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Yield and physiological quality of common bean grains as a function of boron application in the soil

Amanda Magalhães Bueno, Aline Fanciel de Andrade, Aline dos Santos de Carvalho, Rilner Alves Flores*, Klaus de Oliveira Abdala, Glenio Guimarães Santos, Marcio Mesquita

Federal University of Goiás (UFG), College of Agronomy, Esperança avenue, Campus Samambaia, 74690-900, Goiânia, GO, Brazil

***Corresponding author: rilner@ufg.br**

Abstract

We carried out a field experiment to evaluate the effects of soil application of sources and doses of boron (B) on production yield and quality of grains of *Phaseolus vulgaris* (BRS Estilo) grown in an irrigated system. The factorial design was 4x5, being four sources of boron (boric acid, borax, borogran, and FTE BR12) and five doses (0, 1, 2, 3, and 4 kg ha^{-1}) (three replications). We evaluated relative chlorophyll index (RCI), leaf B content, yield, seed viability, and economic value. The data were subjected to analysis of variance, and when significant, evaluated by Tukey test (qualitative) and regression (quantitative). Boron sources affected the RCI 28 days after emergence (DAE). The results for boric acid, borogran, and FTE BR12 were significantly higher (3%, $p_{value}<0.05$) than the results for borax. At 46 DAE, boric acid resulted in a RCI 5% higher than the other sources. Borax and boric acid promoted high leaf B contents (126.11 and 105.63 mg dm^{-3}, respectively). The maximum yield (2,224.03 kg ha^{-1}) was obtained by using 2.21 kg ha^{-1} of B, regardless of the source. Seed viability showed a linear behavior by using borax and boric acid and a quadratic behavior by using borogran and FTE BR12. The dose that resulted in the highest differential profit return (US$ 398.00) was 3.00 kg ha^{-1}. Based on the productive, physiological, and economic results, the dose of 3.00 kg ha^{-1} provides the highest profit margin for common bean producers.

Keywords *Phaseolus vulgaris*; Nutritional efficiency; Borate fertilization; Plant nutrition; Micronutrient.
Abbreviation ABef_absorption efficiency; B_Boron; BAS_Boron accumulation in the shoot; BAP_Boron accumulation in the whole plant; CEC_Cation exchange capacity; DAE_Days after emergence; KCl_Potassium chloride; RCI_Relative chlorophyll index; TRef_Transport efficiency; UTef_Use efficiency for conversion to dry matter.

Introduction

Brazil cultivated an area of 1,614.9 million hectares in the 2019/20 harvest, making it the world's largest producer of common beans (*Phaseolus vulgaris* L.). In 2021, the estimated production is 1,851.40 thousand tons and the estimated productivity is 1.43 tons per hectare (CONAB 2020). Beans play an important social role in developing countries. It is normally cultivated by small farmers and promote socioeconomic sustainability. Also, it is a source of protein in food security programs in emerging countries (Flores et al., 2017a).

Despite the high importance of beans in the Brazilian scenario, there are some aspects of the production system that may limit grain productivity in Brazil. Such aspects are mainly nutritional crop requirements and the effects resulting from mineral sources and doses applied (Flores et al., 2019). The doses of macronutrients applied to crops are currently well known. However, the micronutrient recommendation needs to be better understood, since a correct quantity may provide positive responses to several crops grown under the Cerrado's edaphoclimatic conditions, even if plants require small quantities of micronutrients (Nakao et al., 2018).

Boron (B) is an essential micronutrient for plant growth and metabolism. It acts in physiological processes such as cell wall formation, plasma membrane integrity, sugar translocation, carbohydrate, nitrogen metabolism, hormone activity, and synthesis of nucleic acids (Marenco and Lopes 2013; Taiz et al., 2017; Nejad and Etesami 2020). Fertilization with B has a positive effect on root growth, resulting from necessary cell division and expansion processes. On the other hand, deficiency of B inhibits the development of roots (Trautmann et al., 2014). B also plays an important role in plant reproduction by stimulating flowering and in the growth of pollen tubes, thus increasing the yield and quality of agricultural products (Kumar et al., 2018). B also contributes to fixing pods and increasing the mass of grains per plant, resulting in improvements in productivity (Nakao et al., 2018).

When the concentration of B in the soil is below 0.20 mg dm^{-3}, plants may respond to the application of B. In most plants, B deficiency occurs when its contents in plant tissues are lower than 15.00 mg kg^{-1} (Nejad and Etesami 2020). In dicots, critical deficiency levels vary between 25.00 and 100.00 mg kg^{-1} (Marenco and Lopes 2013). However, there is a very narrow range between a critical level of deficiency and a toxicity state (Flores et al., 2018; Viçosi et al., 2020).

B toxicity occurs mainly in arid regions, especially in alkaline soils with a clayey texture (Nejad and Etesami 2020). Under these conditions, B mobility is almost nonexistent, for it concentrates in the root zone (Dechen et al., 2018). On the other hand, deficiency is common in areas with high rainfall volumes (Nejad and Etesami 2020), in sandy texture soils because these soils are subject to leaching of moving elements (Dechen et al. 2018), and in soils with a low organic matter content (<1.5%), which is the main source of availability of B to plants (Das et al., 2019). The extensive use of fertilizers containing B, such as boric acid, colemanite, ulexite, thermophosphate, borogran, borax, among others, has led to a diversified market of fertilizer products. However, two products are mainly used: boric acid (17% of B) and borax (10% of B), which are solid and low-cost sources because they have a high concentration of B (Nejad and Etesami 2020). However, the use of these fertilizers is restricted to sandy soils and to irrigated production systems due to their easy leaching (Flores et al., 2017; Trautmann et al., 2014). In addition, due to the narrow range between deficiency and toxicity, its high solubility may lead to toxicity, especially in susceptible plants (Nejad and Etesami 2020). In this sense, studies investigating the dynamics of B in the soil-plant system are important to improve productive efficiency mainly in irrigated systems, where the losses of B by leaching are commonly high. Thus, this study evaluates the effects of soil application of different boron sources and B doses on yield and grain quality of common beans grown in an irrigated system.

Results

There are significant differences in the relative chlorophyll index (RCI) of common bean plants as a function of different sources and doses of boron, as Table 1 shows. When evaluating different sources at 28 DAE, the highest rates were for boric acid (36.44 µg cm^{-2}), borogran (36.62 µg cm^{-2}), and FTE BR 12 (36.85 µg cm^{-2}), regardless of the dose. The dose differed statistically for borax (35.57 µg cm^{-2}). At 46 DAE, boric acid (38.25 mg kg^{-1}) obtained the highest RCI value (5% higher than the average of other fertilizers).According to polynomial regression analysis at 28 DAE (Fig. 2a), there were significant increases in RCI. All sources fitted a second-order polynomial equation. Boric acid, borogran, FTE BR 12, and borax obtained the maximum estimated RCI values with the application of 1.81 (38.12 µg cm^{-2}), 1.98 (37.62 µg cm^{-2}), 1.37 (37.43 µg cm^{-2}) and 1.52 (36.52 µg cm^{-2}) kg ha^{-1} of B, respectively. There was a similar behavior according to the evaluation performed at 46 DAE, except for borogran, which did not show significant increases and presented an average RCI of 36.44 µg cm^{-2}, as Fig. 2b shows.The type of source applied to the soil affected the boron content accumulated in leaves of bean plants. The extraction order was borax>boric acid>FTE BR12>borogran, and their average levels were 126.11, 105.63, 97.23, and 92.84 mg kg^{-1}, respectively (Table 1). The polynomial regression analysis of the effects of B doses on the boron contents in leaves showed that the absorption of B by the bean crop had a similar behavior: all fitted linearly and significantly, that is, the boron content in leaves increased with a greater supply of this nutrient to the soil (Fig. 3), except for FTE BR12, whose doses exerted no effects and were on average 97.23 mg kg^{-1}. The increases in B content in leaves were 128.66, 48.96, and 73.48% using borax, boric acid, and borogran, respectively. The application of the maximum dose (4.00 kg ha^{-1}) was the control treatment (no application of B).Bean grain yield did not suffer a significant effect ($p > 0.05$) of boron sources applied to the soil (Table 1) and presented an average productivity of 1,984.49 kg ha^{-1}. However, the effects of B doses on this variable stand out. The polynomial regression showed significant increases and a quadratic fitting regardless of the source applied (Fig. 4). The maximum grain yield (2,224.03 kg ha^{-1}) was obtained using the dose of 2.21 kg ha^{-1} of B. Fig. 4 shows that there was a decrease in bean yield with the dose of 4.00 kg ha^{-1} of B, meaning a 19% reduction in yield. Regarding the quality of grains regardless of sources and doses of B applied to the soil, the weight of 1,000 grains showed no significant differences ($p > 0.05$) (Table 2). It presented an average value of 21.08 g. Also, seed germination did not differ statistically as a function of sources of B. However, B doses significantly affected seed germination following a significant quadratic fitting. With the dose of 1.80 kg ha^{-1} of B, the seeds presented 98.14% of germination (Fig. 5). On the other hand, the application of different doses of B affected seed viability, which is calculated by the tetrazolium test (Table 2). The highest rates resulted from using borax (87.20%) and FTE BR12 (86.00%), regardless of the dose. Fig. 6 shows that the maximum viability of seeds occurred by applying FTE BR 12 at the dose of 2.43 kg ha^{-1} of B. Fig. 6 also shows that the maximum viability of seeds occurred by applying FTE BR 12 at the dose of 1.84 kg ha^{-1} of B, fitting a second-order polynomial equation. However, for borax and boric acid, the significant fitting was linear, that is, more viable seeds (89.53 and 89.00%) were obtained at the highest dose (4.00 kg ha^{-1} of B) (Fig. 6).All doses were economically efficient. There is a positive differential profit compared to the control (Fig. 7). The dose that obtained the greatest differential profit return was 3 kg ha^{-1}, which resulted in a net benefit of US$ 398.00 over not using the nutrient in the fertilization process.

Discussion

Plants fertilized with boron showed a high RCI when the dose was 1.67 kg ha^{-1}. At 46 DAE, the evaluated beans obtained the highest RCI due to the application of 2.44 kg ha^{-1} of B as boric acid.Flores et al. (2017a; 2019) observed that a leaf B application of up to 8.00 kg ha^{-1} of boron as borax, boric acid, or FTE BR12 did not influence the RCI of beans at 28 DAE. On the other hand, Flores et al. (2017b) conducted a study on cv. BRS Estilo and reported that beans responded to the application of 4.39 kg ha^{-1} of B in the soil.

Plants adequately treated with boron may show significant increases in relative chlorophyll index. This is due to B participation in nitrogen metabolism (Dechen et al., 2018) and because this element is directly associated with uracil synthesis (in plant cells), which is one of the nitrogenous bases of ribonucleic acid (RNA).

The presence of high levels of chlorophyll correlates with a better nutrition of nitrogen because in each chlorophyll molecule, there are four externally bound N atoms (Taiz et al., 2017). Sepaskhah and Maftoun (1994) evaluated responses of fertilizers containing nitrogen on pistachio plants grown under a high soil boron content and showed that plants had fewer symptoms of toxicity by this micronutrient when subjected to nitrogen fertilization. These results show that a

Table 1. Relative chlorophyll index (RCI), leaf boron content, and grain yield of common bean (*Phaseolus vulgaris* L.) as a function of boron sources and doses. Plants grown in a central-pivot irrigated system in a tropical region.

Treatments	RCI[1]	RCI[2]
Sources (S)	-----------μg cm^{-2}-----------	
Borax	35.57b	36.76b
Boric Acid	36.44a	38.25a
Borogran	36.62a	36.44b
FTE BR 12	36.85a	35.95b
Test F	9.69**	15.60**
Doses of B (D) (kg ha^{-1})		
0	35.69	35.15
1	37.61	36.66
2	37.66	37.64
3	35.71	38.34
4	35.18	36.46
Test F	34.24**	18.70**
S x D	3.93**	2.29*
C.V.(%)	1.91	2.64

CV: coefficient of variation; RCI[1] and RCI[2] - evaluations performed at 28 and 46 days after emergence, respectively. The same lowercase letters in the same row do not differ at 5% probability by Tukey test. ns, *, and ** - not significant at 5%, significant at 5%, and significant at 1% probability by F test, respectively.

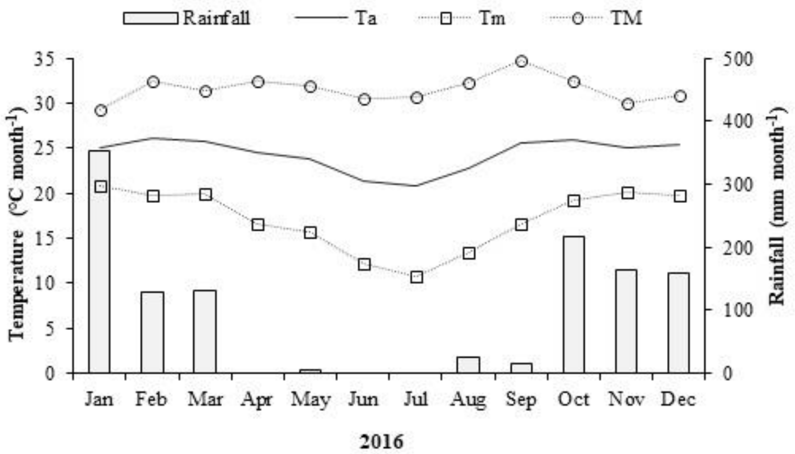

Fig 1. Maximum (TM), minimum (Tm), and average air temperature (Ta); rainfall monthly volume from January 2016 to December 2016, measured at the College of Agronomy, Federal University of Goiás, Goiânia, GO, Brazil.

Table 2. Leaf boron content and grain yield of common bean (*Phaseolus vulgaris* L.) as a function of boron sources and doses. Plants grown in a central-pivot irrigated system in a tropical region.

Treatments	B content (mg kg^{-1})	Yield (kg ha^{-1})
Sources (S)		
Borax	126.11a	2,030.21a
Boric Acid	105.63b	1,954.21a
Borogran	92.84c	1,960.91a
FTE BR 12	97.23bc	1,992.64a
Test F	27.49**	0.61^{ns}
Doses of B (D) (kg ha^{-1})		
0	81.41	1,636.76
1	95.08	2,066.67
2	103.89	2,140.74
3	117.22	2,286.56
4	129.67	1,791.72
Test F	35.65**	28.35**
S x D	6.27**	1.00^{ns}
C.V.(%)	10.34	8.68

CV: coefficient of variation. The same lowercase letters in the same row do not differ at 5% by Tukey test. ** and ^{ns} - significant at 1%, and not significant at 5% probability by F test, respectively.

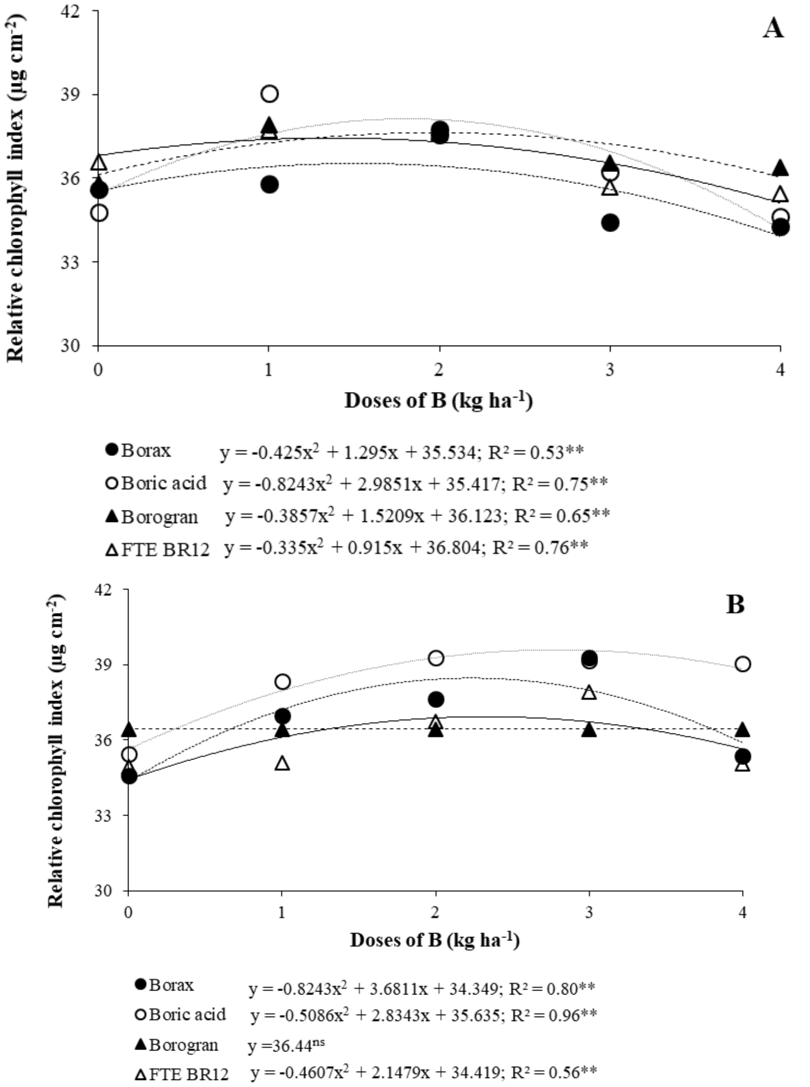

Fig 2. Chlorophyll relative index at 28 (A) and 46 (B) DAE of common beans (*Phaseolus vulgaris* L.) as a function of sources and doses of boron. Plants grown in a central-pivot sprinkler irrigation system in a tropical region. ^{ns} and ** - not significant at 5% and significant at 1% probability by F test, respectively.

Table 3. Grain quality analysis of common beans (*Phaseolus vulgaris* L.) as a function of boron sources and doses. Plants grown in a central-pivot irrigated system in a tropical region.

Treatments	Germination	Tetrazolium	Weight 1,000 grains
Sources (S)	------------%------------		g
Borax	98.23a	87.20a	21.23a
Boric Acid	98.67b	82.33b	21.22a
Borogran	98.10a	81.87b	21.23a
FTE BR 12	98.73a	86.00a	20.74a
Test F	1.16^{ns}	12.42**	1.35^{ns}
Doses of B (D) (kg ha^{-1})			
0	98.08	79.33	20.78
1	98.87	84.08	20.84
2	98.96	86.92	21.55
3	98.54	87.50	21.57
4	97.71	83.92	21.28
Test F	2.66*	14.83**	1.13^{ns}
S x D	0.90^{ns}	728**	1.24^{ns}
C.V.(%)	1.15	3.45	5.82

CV: coefficient of variation. The same lowercase letters in the same column do not differ at 5% probability by Tukey test. **, * and ^{ns} - significant at 1 and 5%, and not significant at 5% probability by F test, respectively.

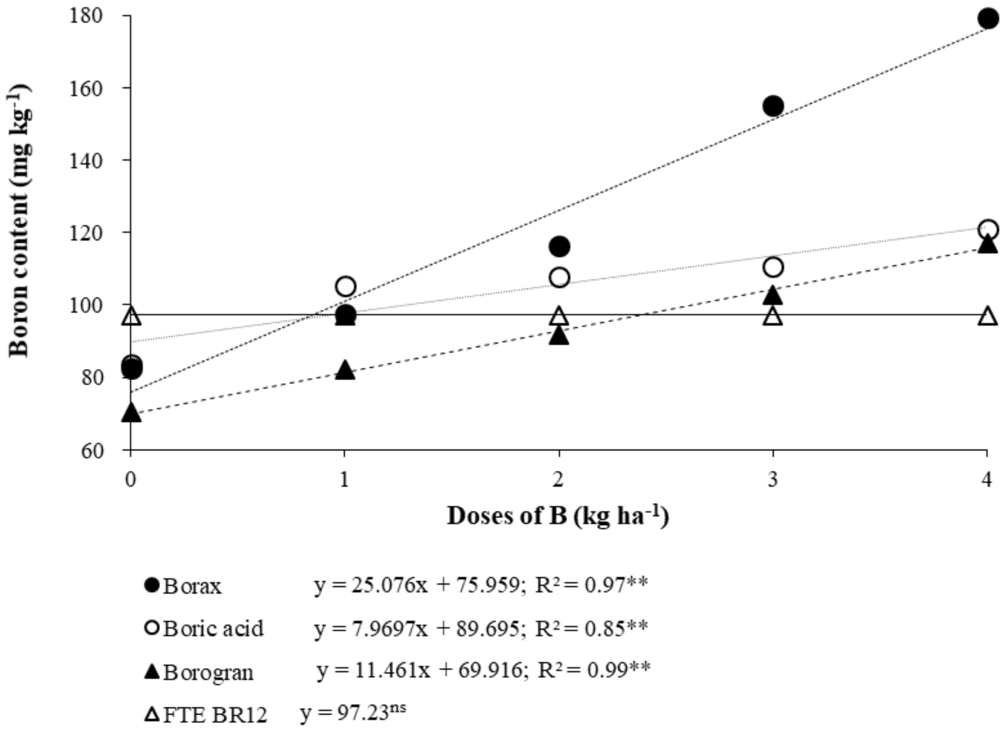

Fig 3. Leaf B content of common beans (*Phaseolus vulgaris* L.) as a function of boron sources and doses. Plants grown in a central-pivot sprinkler irrigation system in a tropical region. ^{ns} and ** - not significant at 5% and significant at 1% probability by F test, respectively.

Table 4. Soil analysis at a depth 0.00-0.20 m. Common beans (*Phaseolus vulgaris* L.) analyzed as a function of boron sources and doses. Plants grown in a central-pivot irrigated system in a tropical region.

pH	OM	Ca^{2+}	Mg^{2+}	K^{+}	$H+Al^{3+}$	P (Mehlich 1)
($CaCl_2$)	g dm^{-3}	$cmol_c$ dm^{-3}	$cmol_c$ dm^{-3}	mg dm^{-3}	$cmol_c$ dm^{-3}	mg dm^{-3}
5.20	32.00	2.80	1.12	83.00	2.80	1.50
B	Cu^{2+}	Fe^{3+}	Mn^{3+}	Zn^{2+}	V%	CEC
mg dm^{-3}	mg dm^{-3}	mg dm^{-3}	mg dm^{-3}	mg dm^{-3}		$cmol_c$ dm^{-3}
0.15	2.40	72.00	48.00	1.30	59.60	6.90

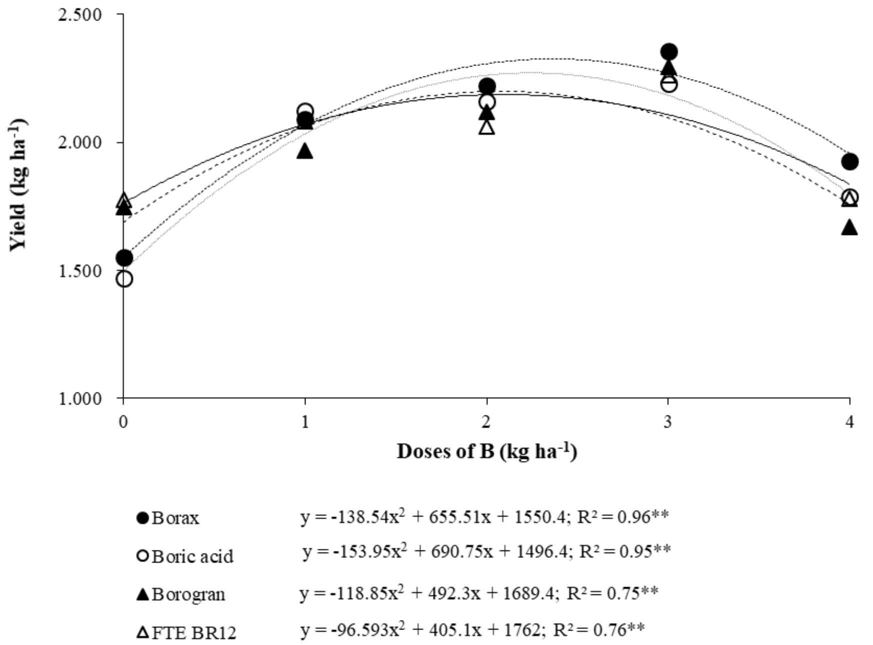

Fig 4. Yield of common bean (*Phaseolus vulgaris* L.) as a function of boron doses. Plants grown in a central-pivot sprinkler irrigation system in a tropical region. ** - significant at 1% probability by F test, respectively.

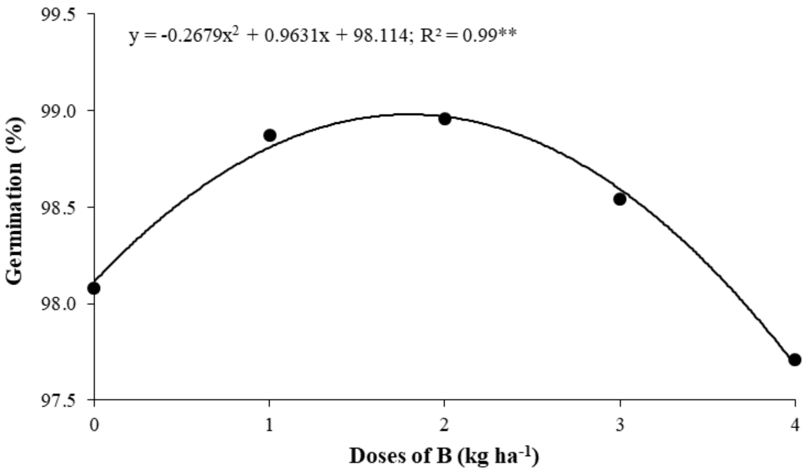

Fig 5. Seed germination (%) of common beans (*Phaseolus vulgaris* L.) as a function of boron doses. Plants grown in a central-pivot sprinkler irrigation system in a tropical region.

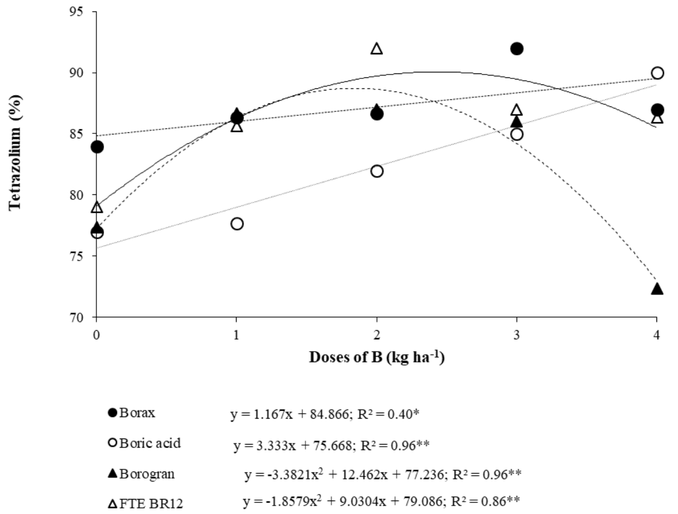

Fig 6. Seed viability (%) of common beans (*Phaseolus vulgaris* L.) as a function of boron sources and doses. Plants grown in a central-pivot sprinkler irrigation system in a tropical region.

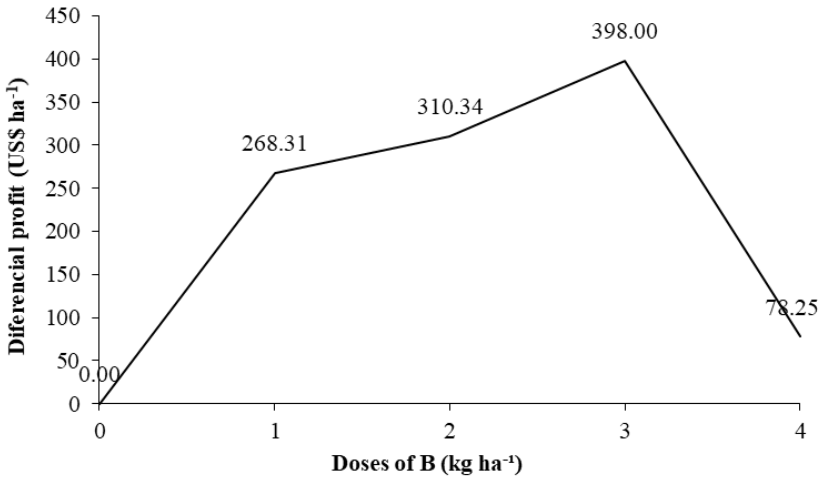

Fig 7. Differential profits of common beans (*Phaseolus vulgaris* L.) grown in a central-pivot sprinkler irrigated system as a function of sources and doses of boron applied to the soil.

high nitrogen content in the plant may favor tolerance to the harmful effects of boron.

Flores et al. (2018b) evaluated the effects of fertilizing common beans with boron. The most soluble sources of B (boric acid and borax) led to increases in leaf B contents with the application of up to 4.00 kg ha^{-1}. In a study on the effects of B on soybean crops, Trautmann et al. (2014) found leaf B levels of 176.86 mg kg^{-1} using boric acid as a source (2 mg dm^{-3}). The authors observed that there was an increase of 43.70 mg kg^{-1} in B content for each mg dm^{-3} of applied B and that there were typical toxicity symptoms.

Because we conducted this study in a clayey soil (480 g kg^{-1} clay), the risks of toxicity increased. This is because, in this condition, B has little soil mobility, concentrating in the root zone, and fertilizers are high soluble in this type of soil, thus facilitating absorption (Nejad and Etesami 2020).

According to Nejad and Etesami (2020), boron toxicity occurs in the field when the concentration in the tissues is greater than 200 mg kg^{-1}. However, the non-uniform dispersion of B within the amplitude range of different species, varieties, and plant cultivars makes it difficult to determine a critical universal level of toxicity. For dicots, the range 25 to 100 mg of B kg^{-1} of dry mass is considered a critical level (Marenco and Lopes 2013). Flores et al. (2018) observed that high levels of B in leaves may indicate a toxicity by this element to common beans (cv. BRS Esplendor).

The highest yield of common beans subjected to borate fertilization (2,325.79 kg ha^{-1}) occurred by applying borax at a dose of 2.37 kg ha^{-1} of B. This fertilizer also led to the highest B contents in bean leaves. The application of boric acid also resulted in a high productivity, reaching 2,271.20 kg ha^{-1} with the application of 2.24 kg ha^{-1} of B. Both fertilizers have a high-water solubility and are highly efficient in environments with an adequate irrigation management. However, the application of doses higher than those cause a reduction in grain yield. The application of high doses to the soil (up to 6.00 kg ha^{-1} of B) when bean plants are still at the beginning of their development contributes to causing a moderate toxicity, which interrupts plant development and reduces biomass production by up to 30% and the efficiency of using B by up to 75% (Flores et al., 2018).

Flores et al. (2017a) reported a linear increase in productivity with leaf application of borax up to a dose of 8.00 kg ha^{-1} of B. The productivity was about 8% higher using fertilization with this same dose of boric acid. Due to the high solubility, it caused toxicity to beans, which initially appeared as leaf chlorosis and later caused a low productivity. According to Flores et al. (2019), leaf fertilization containing more soluble borate fertilizers, such as borax, up to a dose of 8 kg ha^{-1} may linearly reduce the productivity of common beans. FTE BR12, a less soluble source, provided the maximum production (4,102.00 kg ha^{-1}) with one leaf application of 4.50 kg ha^{-1}.

B is essential for the germination of pollen grains and the growth of pollen tubes. It increases the development of flowers and granulation and reduces grain hatching (Malavolta 2006). Such a direct influence of B on the reproductive attributes of plants is related to its effects on reducing flower abortion, providing a greater production of future pods and grains. It also induces the production of phytohormones such as auxin (indole acetic acid, IAA) (Zhou et al., 2016).

The production of indoleacetic acid or auxin affects plant roots. It increases root size and surface contact with the soil, contributing to the absorption of nutrients, improving plant nutrition and growth capacity (Shi et al. 2010), and providing a greater weight and number of branches. Therefore, its demand is evident at the reproductive phase, as it contributes to the formation and development of reserve organs (Carvallho and Nakagawa 2000). It is also responsible for increasing grain yield and biomass in dicots (Flores et al., 2017; Flores et al., 2018).

Although B has a low mobility in the phloem in the presence of carbohydrates, such as sorbitol, mannitol, NAD+, glycerol, fructose, glycoproteins, and glycolipids that bind to the B molecule, there is an increase in cell permeability that facilitates B redistribution throughout the plant (Schnurbusch et al. 2010). It can thus uptake sugars, phenols, and other polymers, which then become energy sources and increase plant reserves.

Fertilization via soil using different sources and doses of B did not present any determinant interactions as for germination percentage and grain weight. However, the application of B from different sources affected seed viability. As described in Brasil (2009), the germination percentage required as a standard for seeds cannot be lower than 80%. In the present study, all treatments showed germination results above 97%, which are within the standards of the Brazilian legislation. Santos-Moura et al. (2019) applied B in a common bean seed treatment (cv. IPA10) and observed that B accounted for 87% of the germination rate and the growth and development of the embryonic axis.

The highest percentage of viable seeds obtained by tetrazolium test occurred when applying FTE BR 12. 90% of seeds were viable following the application of borogran (89%). For borax and boric acid, the effect was linear. There were higher percentages of viable seeds by applying the highest dose of B in the soil, resulting in values of 90 and 89%, respectively. As Embrapa (2013) described, the tetrazolium test calculates seed viability. Seeds are considered non-viable when they present mechanical damage from harvesting or processing, damage from moisture, and insect attacks. Bean seeds of plants fertilized with B were significantly superior to seeds of the control treatment. This shows that this micronutrient promotes a greater resistance of seeds to mechanical damage and pressures by pests and diseases.

According to Marschner (2012), plants demand more in terms of B nutrition during the grain formation phase. Therefore, plants better nourished with this micronutrient tend to present high levels of seed germination and seed vigor.

Flores et al. (2017a) studied the economic viability of the production of *Phaseolus vulgaris* (cv. BRS Estilo) in an irrigated system as a function of the application of boron in leaves and concluded that the application of boric acid is not profitable compared to the control treatment. There was a negative differential profit in all doses evaluated. However, all doses of borax promoted a positive differential profit. The dose 4.00 kg ha^{-1} was more efficient than the other doses. According to Richetti and Ito (2015), micronutrients represent approximately 0.7% of the total production costs. Thus, the application of boron at the dose of 3.00 kg ha^{-1} is highly recommended and may increase grain production, providing a differential profit of US$ 398.00 per hectare compared to systems without the application of B.

Materials and methods

The experiment was conducted by growing beans of the cultivar BRS Estilo in the winter harvest of 2016 in Brazil (16°35'48.38" S and 49°16'63.46" W, approximately 730 m of altitude) in an area with a central pivot irrigation.

According to the Köppen climate classification, the region's climate is Aw (megathermal) with hot and rainy summers and mild and dry winters. The municipality records an average annual rainfall of 1,494.7 mm distributed from October to April (Casaroli et al., 2018). Fig. 1 shows climatic data.

"(Fig. 1)"

The soil was classified as a Ferralsol with a clayey texture (480, 250, and 270 g kg^{-1} of clay, silt and sand, respectively) (Teixeira et al., 2017). Before the beginning of the experiment, the soil chemical contents were determined at the depth 0-0.20 m, according to the methodology proposed by Teixeira et al. (2017) (Table 4).

The experiment was randomized blocks in a 4x5 factorial design, being four sources of boron (borax 10%, boric acid 17%, borogran 10%, and FTE BR12 1.8%) and five doses of B (0, 1, 2, 3, and 4 kg ha^{-1}), with three repetitions. The experimental units were five rows containing bean plants spaced 0.45 m apart. The lines had 2.00 m in length, making up an area of 4.50 m^2. The three central rows were considered as a useful area; 0.50 m was discarded at each end, totaling a useful area of 1.35 m^2.

The experiment was implemented on June 1, 2016. The doses of boron using the different sources were applied to the soil in the planting furrows, as Flores et al. (2018a) performed. Planting fertilization was 20 kg ha^{-1} of N, 120 kg of P_2O_5, and 60 kg ha^{-1} of K_2O as urea ($CO(NH_2)_2$ – 45% N), simple superphosphate (18% of P_2O_5), and potassium chloride (58% of K_2O), respectively. The cover fertilization was 80 kg ha^{-1} of N divided into two equal applications of 40 kg ha^{-1} of N as urea 20 and 40 days after seedling emergence (DAE) (Sousa and Lobato 2004).

The evaluations of RCI were conducted at 28 and 46 DAE using the penultimate fully developed trifoliate leaf over the entire leaf blade, except for the ribs, following the recommendation of Barbosa Filho et al. (2008).

The nutritional status of B was determined at the beginning of flowering. Twenty diagnostic leaves were collected (leaf +3, first ripen leaf from the tip of the branch) in each plot according to procedures laid out by Souza et al. (2011) for common bean crops. The boron content was determined by the dry digestion method and using a spectrophotometer with azomectin-H following the methodology described by Silva (2009).

When the crop reached physiological maturity, 1.00 m from each of the three central rows in each plot was harvested manually. The grains were weighed to determine yield (kg ha^{-1}).

The harvested seeds were submitted to physiological quality analysis at the Seed Laboratory. The tetrazolium test calculated the weight of 1,000 grains, germination, and seed viability. These assessments were carried out according to the criteria established by the Rules for Seed Analysis (Brasil 2009).

For economic analysis, the partial budgeting technique was used (Noronha 1987). By considering differential costs and revenues, the differential profit is calculated considering the reference treatment (control). For this study, the differential costs resulting from the application of each dose were calculated, as well as the differential revenues from changes in land productivity resulting from the applications of B. The differential revenue (Rd) in each treatment was obtained by multiplying the variation in land productivity obtained for the control by the price received by bean producers in the state of Goiás, according to Equation 1.

Equation 1:

$Rd = Dp * P$

Where: Dp = Difference in productivity (kg ha^{-1});

P = average price received by producers in the state of Goiás (US$ kg^{-1});

The average price of the last ten years (2010-2020) was used as a reference. Its value is US$ 38.15 bag^{-1} of 60 kg (Agrolink 2020), considering an exchange rate of US$ 1 = R$ 5.30.

The cost of sources of B was obtained in the market and converted to dollars. Since boron is incorporated into the formulation of fertilizers, it does not incur in operational costs of application at the producer level. Therefore, the added costs are equivalent to the dose value of the commercial product.

The results of statistical analyses show that there is no significant difference between sources of boron. Therefore, the economic analysis was performed for the lowest-cost source, that is, borogran (Bg). Its cost was US$ 5.07 x D, where D is the boron dose in each treatment (kg ha^{-1}). The other sources had costs higher than that of the reference source (Bg) in the following order: boric acid = 1.03 (Bg), borax = 1.80 (Bg), and FTE BR12 = 4.02 (Bg) for each dose applied.

The differential profit (Ld) was the difference between the differential revenues and the differential costs of applying boron doses compared to the control treatment, according to Equation 2:

Equation 2:

$Ld = Rd – Cd$

Where: Rd: differential revenue (Rdti - RdIt0), Cd: differential costs (Cdti - Cdt0); ti: treatment i, and t0: control treatment.

Data were subjected to analysis of variance (F test) and when significant, evaluated by Tukey test ($p \leq 0.05$) (qualitative data: B sources). For boron doses (quantitative data), the linear and quadratic models were tested (polynomial regression) by applying models that obtained the best data fitting. The statistical analyses were performed using the software AgroEstat® (Barbosa and Maldonado Júnior, 2015).

Conclusions

Common beans have a high boron extraction due to the application of more soluble fertilizers following this order: borax>boric acid>FTE BR12>borogran, with average leaf B contents of 126.11, 105.63, 97.23, and 92.84 mg kg^{-1}, respectively. Common beans do not present differences in crop productivity as a function of source applied. The maximum grain yield is 2,244.03 kg ha^{-1}, obtained with the application of 2.21 kg ha^{-1} of B regardless of the source. The application of the maximum B dose (4.00 kg ha^{-1}) results in a 19% decrease in bean yield and in a decrease of 0.23 kg ha^{-1} of grains for each gram of nutrient above the maximum dose (2.21 kg ha^{-1} of B). The application of B is economically viable at all tested doses. The dose 3.00 kg ha^{-1} results in a great profit margin for the producer. This dose is then recommended to meet the productive and economical demands of cultivation of common beans in tropical soils.

Declaration of interest statement

The authors declare no conflicts of interest.

References

Agrolink (2020) Price history. access in 02/08/2021 available in: https://www.agrolink.com.br/cotacoes/graos/feijao/

Barbosa Filho MP, Cobucci T, Fageria NK, Mendes PN (2008) Determinação da necessidade de adubação nitrogenada de cobertura no feijoeiro irrigado com auxílio do clorofilômetro portátil. Cienc Rural 38:1843–1848.

Barbosa JC, Maldonado Júnior W (2015) Experimentação agronômica & Agroestat - Sistema para análises de ensaios agronômicos, 1 th. Funep.

Brasil (2009) Regras para análises de sementes. MAPA, Brasília.

Casaroli D, Rodrigues TR, Martins APB, Evangelista AWP, Júnior JA (2018) Rainfall and evapotranspiration patterns in Goiânia, GO. Rev Bras Meteorol 33:247–256.

CONAB (2020) Acompanhamento da Safra Brasileira de grãos. Brasília.

Das R, Mandal B, Sarkar D, Pradhan AK, Datta A, Padhan D, Seth A, Kumar R, De N, Mishra VN, Polara KB, Sharma S, Thakur NP, Kachroo D, Ray M, Sharma A, Patel KP, Garnayak LM, Narkhede WN (2019) Boron availability in soils and its nutrition of crops under long-term fertility experiments in India. Geoderma 351:116–129.

Dechen AR, Nachtigall GR, Carmello QA de C, Santos LA, Sperandio MV (2018) Micronutrientes. In: Fernandes MS, Souza SR de, Santos LA (eds) Nutrição Mineral de Plantas, 2 th. Sociedade Brasileira de Ciência do Solo, Viçosa, MG, pp 491–562.

Embrapa (2013) Testes para Avaliação da Qualidade de Sementes de Feijão Comum 90

FAO (2014) World reference base for soil resources 2014. International soil classification system for naming soils and creating legends for soil maps

Flores RA, da Cunha PP, Damin V, Abdala K de O, Maranhão DDC, dos Santos MM, Neto LRG, Donegá MC, Rodrigues RA (2019) Physiological quality and grain production of Phaseolus vulgaris (cv. BRS Pérola) using boron (B) application under irrigatation system. Aust J Crop Sci 13:520–528.

Flores RA, Rodrigues RA, da Cunha PP, Damin V, Arruda EM, de Oliveira Abdala K, Donegá MC (2018a) Grain yield of phaseolus vulgaris in a function of application of boron in soil. J Soil Sci Plant Nutr 18:144–156.

Flores RA, Silva RG da, Cunha PP da, Damin V, Abdala K de O, Arruda EM, Rodrigues RA, Maranhão DDC (2017a) Economic viability of Phaseolus vulgaris (BRS Estilo) production in irrigated system in a function of application of leaf boron. Acta Agric Scand Sect B Soil Plant Sci 67:697–704.

Flores RA, Silva Junior AR, Damin V, Arruda EM, Prado ER, Araújo CE (2017b) Nutrition and Production of Phaseolus vulgaris (BRS estilo) Following Boron Application on Soil. Commun Soil Sci Plant Anal 48:1409–1416.

Flores RA, Silva TV, Damin V, Marques Carvalho R de C, Pereira DRM, Souza Junior JP de (2018b) Common Bean Productivity Following Diverse Boron Applications on Soil. Commun Soil Sci Plant Anal 49:725–734.

Gomes I da S, Benett CGS, Silva RL, Xavier RC, Benett KSS, da Silva AR, Coneglian A (2017) Boron fertilisation at different phenological stages of soybean. Aust J Crop Sci 11:1026–1032.

Kaleri AA, Laghari GM, Gandahi AW, Kaleri AH, Nizamani MM (2019) Integrated foliar fertilizer effects on growth and yield of sunflower. 1072:25–28

Kumar S, Phogat M, Lal M (2018) Response of Pulse and Oilseed Crops to Boron Application: A Review. Int J Curr Microbiol Appl Sci 7:669–675.

Malavolta. E (2006) Manual de Nutrição Mineral de Plantas. Editora Agronômica Ceres Ltda.

Marenco RA, Lopes NF (2013) Fisiologia Vegetal: fotossíntese, respiração, relações hídricas e nutrição mineral, 3 th. Editora UFV, Viçosa, MG.

Marschner (2012) Mineral Nutrition of Higher Plants, 3rd edn. Copyright © 2012 Elsevier Ltd. All rights reserved.

Nakao AH, Costa NR, Andreotti M, Souza MFP, Dickmann L, Centeno DC, Catalani GC (2018) Características agronômicas e qualidade fisiológica de sementes de soja em função da adubação foliar com boro e zinco. Cult Agronômica 27:312–327.

Nejad SAG, Etesami H (2020) The Importance of Boron in Plant Nutrition. In: Deshmukh R, Tripathi DK, Guerriero G (eds) Metalloids in Plants, 1 th. Wiley, pp 433–449.

Noronha JF (1987) Projetos agropecuários: administração financeira, orçamento e viabilidade econômica, 2 th. Atlas, São Paulo, SP.

Peter H Raven, Ray F Evert SEE (2014) Biologia Vegetal, 8 ed. Gen-Koogan, Grupo.

Prado R de M (2008) Nutrição de Plantas, 1 th. São Paulo, SP.

Richetti A, Ito MA (2015) Viabilidade econômica da cultura do feijão-comum, safra da seca de 2016, em Mato Grosso do Sul. Embrapa, Comunicado Técnico 208, Dourados, MS.

Santos-Moura S da S, Pereira Gonçalves E, Silva Viana J, Guimarães Paiva L, Farias de Moura M (2019) Potencial fisiológico de sementes de feijão tratadas com micronutrientes. Divers J 4:1119–1129.

Schnurbusch T, Hayes J, Sutton T (2010) Boron toxicity tolerance in wheat and barley: Australian perspectives. Breed Sci 60:297–304.

Sepaskhah AR, Maftoun M (1994) Seedling growth and chemical composition of two pistachio cultivars as affected by boron and nitrogen application. J Plant Nutr 17:155–171.

Shi CL, Park HB, Lee JS, Ryu S, Ryu CM (2010) Inhibition of primary roots and stimulation of lateral root development in arabidopsis thaliana by the rhizobacterium serratia marcescens 90-166 is through both auxin-dependent and -independent signaling pathways. Mol Cells 29:251–258.

Silva FC da (2009) Manual of chemical analyzes of soils, plants and fertilizers, 2 th. Embrapa Informação Tecnológica, Brasília, DF.

Sousa DMG de, Lobato E (2004) Cerrado: Correction of soil and fertilization, 2 th. Planaltina, DF.

Souza HA de, Hernandes A, Romualdo LM, Rozane DE, Natale W, Barbosa JC (2011) Folha diagnóstica para avaliação do estado nutricional do feijoeiro. Rev Bras Eng Agric e Ambient 15:1243–1250.

Taiz L, Zeiger E, Møller I, Murphy A (2017) Fisiologia e desenvolvimento vegetal. Artmed Editora.

Teixeira PC, Donagemma GK, Fontana A, Teixeira WG (eds) (2017) Manual de métodos de análise de solo, 3 th. Embrapa, Brasília, DF.

Trautmann RR, Lana M do C, Guimarães VF, Gonçalves Jr AC, Steiner F (2014) Potencial de água do solo e adubação com boro no crescimento e absorção do nutriente pela cultura da soja. Rev Bras Cienc do Solo 38:240–251.

Viçosi KA, Carvalho AS, Silva DC, Almeida FP, Ribeiro D, Flores RA (2020) Foliar Fertilization with Boron on the Growth, Physiology, and Yield of Snap Beans. J Soil Sci Plant Nutr. 20: 917-924.

Zhou T, Hua Y, Huang Y, Ding G, Shi L, Xu F (2016) Physiological and transcriptional analyses reveal differential phytohormone responses to boron deficiency in Brassica napus genotypes. Front Plant Sci 7:1–16.