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100 Years on Boron Research in Plants – Research article

Soil organic matter influences the agronomic efficiency of boron fertilizers in sandy Oxisol cultivated with soybean

Leonardo Fernandes Sarkis[1], Flávio Henrique Silveira Rabêlo[1*], Franz Walter Rieger Hippler[2], Douglas Guelfi[1]

[1]Universidade Federal de Lavras – Depto. de Ciência do Solo, Trevo Rotatório Professor Edmir Sá Santos s/n – 37203-202 – Lavras, MG – Brasil.
[2]Yara International – Yara Agronomy and R&D, Hanninghof 35 – 48249 – Dülmen – Germany.
*Corresponding author <flavio.rabelo@ufla.br>

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ABSTRACT: Boron (B) is readily leached from the soil, depending on the soil texture, soil organic matter (OM) content, and the fertilizer source used. This can restrict B uptake by plants. Therefore, we investigated the most adequate B source for soybeans grown in soils with contrasting textures and OM contents. The plants were cultivated for 55 days in columns filled with clayey or sandy Oxisols with low or high OM contents. The clay contents (%) in the soils were as follows: clayey soil with low OM = 64; clayey soil with high OM = 67; sandy soil with low OM = 4; and sandy soil with high OM = 15. The B sources tested comprised the control (no B supply), ulexite, zinc borate, boric acid, and B-monoethanolamine (B-MEA), with the equivalent of 6 kg B ha^{-1} applied. Boron leaching from ulexite was lower than other B fertilizers in the sandy soil with high OM content. Boron leaching was higher in sandy than in clayey soils. Boron accumulation in shoots was lower when boric acid was applied to the sandy soil with low OM content than the other B fertilizers. In this same soil, the agronomic efficiency and recovery of B applied by plants supplied with ulexite and zinc borate were higher compared to boric acid and B-MEA. In conclusion, the use of ulexite and zinc borate is more appropriate for soybean fertilization in sandy soils with low OM content, while B-MEA is more suitable for sandy soils with high OM content.

Keywords: *Glycine max*, B-monoethanolamine, boric acid, ulexite, zinc borate

Introduction

Boron (B) is a micronutrient that frequently limits crop growth and yield in tropical and subtropical soils. This is due to its ability to induce deficiency or toxicity (Dhassi et al., 2019). Boron exhibits high vertical mobility in the soil profile due to its predominant form ($H_3BO_3^0$) at the pH range observed in tropical and subtropical soils. This form is chemisorbed with less intensity to soil solid components than its anionic form ($H_4BO_4^-$) (Sá and Ernani, 2016). Consequently, the high mobility of B makes it susceptible to leaching, which can induce B deficiency in plants. However, B is also susceptible to accumulation in the root growth zone in low rainfall areas, which can result in B toxicity (Dhassi et al., 2019; Castro et al., 2020).

The factors that affect B leaching include soil texture, soil organic matter (OM) content, rainfall frequency, and B sources. Boron leaching is higher in sandy than in clayey soils, particularly in regions with high average annual rainfall, where B may reach the subsoil quickly (Sá and Ernani, 2016). Such leaching can be increased when conventional fertilizers, such as boric acid (H_3BO_3), which has high solubility, are applied in agriculture (Castro et al., 2020). Nevertheless, very little is known about B fertilizers containing new technologies. Another factor favoring B leaching is the low OM content frequently found in tropical and subtropical soils. In such circumstances, there is a low degree of B complexation by OM, which results in a reduced capacity to supply B to plants, thus requiring more frequent fertilizations with B (Gu and Lowe, 1990).

Although the leaching of B can be affected by soil texture and OM content, to the best of our knowledge, there are no studies that have evaluated the most appropriate B source to be applied to soybean (*Glycine max* L.) cultivation in soils presenting low or high clay contents associated with low or high OM contents. For instance, in clayey soil (51 %) presenting 3.81 dag OM kg^{-1}, there was no difference in the growth of soybean plants fertilized with boric acid or ulexite. However, further soil conditions and B sources must be evaluated to improve B nutrition in soybeans.

Boron deficiency or toxicity in soybean is a frequent problem, as this crop exhibits high sensitivity to this micronutrient (Dameto et al., 2023). Soybean is the most economically important leguminous crop and one of the most widely grown worldwide (FAO, 2023). Thus, improving the use efficiency of B by this crop is essential. We hypothesize is that soils with low clay and OM contents favor B leaching due to the low B adsorption; however, the use of fertilizers of lower solubility in this condition can minimize this problem while meeting the B requirement of soybean plants. This study aimed to identify the most suitable B source for soybean cultivation in soils with contrasting textures and OM contents. We measured B leaching, shoot biomass, B accumulation in the plant shoots, agronomic efficiency index (AEI), and applied B recovery (ABR) to achieve this.

Materials and Methods

Study site and experimental design

The study was conducted in a greenhouse located at the Departamento de Ciências do Solo of the Universidade Federal de Lavras (21°13′34″ S, 44°58′45″ W, altitude 919 m), Lavras, Minas Gerais states, Brazil. Soybean cv. 95R90IPRO plants were cultivated (28.5 ± 8 °C and 69 ± 21 %) in cylindrical polyvinyl chloride (PVC) columns filled with 12 kg of contrasting soils in terms of texture and organic matter (OM) content (Table 1). The soils were selected to evaluate B dynamics in relation to these attributes. The treatments were composed of an evaluation of five B sources, including a control (without B supply), ulexite ($NaCaB_5O_9.8H_2O$, 10 % B), zinc borate in a suspension concentrate formulation ($2ZnO_3B_2O_3.3.5H_2O$, 14 % B; YaraVita PROCOTE™, Yara International), boric acid (H_3BO_3, 17 % B), and B-monoethanolamine (B-MEA) in solution formulation (10 % B). These treatments were conducted on the four soil types of nutrient leaching and soybean growth (Table 1). For fertilization and the simulation of B leaching in the soil profile, 6 kg B ha^{-1} (0.02 g per column) was applied, per the recommendations for soybean (Seixas et al., 2020). The columns were distributed in a completely randomized design, with four replications per treatment.

Columns building and soil treatment

We built leaching columns with a height of 60 cm by stacking six PVC rings with a height of 10 cm and a diameter of 200 mm to simulate a soil profile up to 60 cm deep. The base of the leaching columns was drilled to accommodate the installation of a polyethylene hose, which was used to collect the leached solution from the soil profile using PET bottles with a capacity of 2 L. The hose holes were covered with a protective screen to prevent the loss of soil particles. To fill the leaching columns, the soils collected at depths of 0.0-0.2, 0.2-0.4, and 0.4-0.6 m were crushed, sieved, and subjected to liming using CaO and MgO to increase the base saturation (BS) to 70 % (except for the sandy soil with high OM, which already presented BS of 80 %), as recommended for soybean cultivation (Seixas et al., 2020). The soil was maintained at a constant level of 70 % of the maximum water-holding capacity for 30 days following the application of lime.

Subsequently, the soils were irrigated to reach 100 % of their maximum water holding capacity. This was achieved by irrigating the columns once a day with deionized water until leaching in the collection hose, and the stabilization of the soil structure was perceived, which lasted approximately four days. Next, the basic fertilization was performed following the recommendations for soybean cultivation, with the application of the nutrient solution at the following concentrations: 200 mg P dm^{-3}; 129 mg Ca dm^{-3}; 26 mg Mg dm^{-3}; 39 mg S dm^{-3}; 5 mg Zn dm^{-3}; 0.1 mg Mo dm^{-3}; 1.5 mg Cu dm^{-3}; and 3 mg Mn dm^{-3}.

Plant growth and B supply

Six soybean seeds were planted in each leaching column following the initial fertilization. Ten days after emergence (DAE), the seedlings were thinned, with only three per column remaining. During the subsequent plant growth period, four rainfall simulations were

Table 1 – Classification and physical-chemical characterization of soils used in the study.

Soil type	Soil classification	Physical-chemical characterization (0.0-0.2 m depth)	Sampling point
Clayey soil with low OM	Anionic Acrudox	OM = 1.01 dag kg^{-1}; pH (H_2O) = 4.8; Ca = 0.55 $cmol_c$ dm^{-3}; Mg = 0.1 $cmol_c$ dm^{-3}; K = 5.75 mg dm^{-3}; Al^{3+} = 0.01 $cmol_c$ dm^{-3}; H + Al = 1.82 $cmol_c$ dm^{-3}; SB = 0.66 $cmol_c$ dm^{-3}; CEC = 2.48 $cmol_c$ dm^{-3}; BS = 26.8 %; m = 1.49 %; P = 0.49 mg dm^{-3}; rem-P = 3.55 mg L^{-1}; Zn = 0.3 mg dm^{-3}; Fe = 27.53 mg dm^{-3}; Mn = 5.4 mg dm^{-3}; Cu = 1.3 mg dm^{-3}; B = 0.01 mg dm^{-3}; sandy = 19 %; silty = 17 %; clayey = 64 %.	Lavras, Brazil
Clayey soil with high OM	Anionic Acrudox	OM = 2.37 dag kg^{-1}; pH (H_2O) = 5.5; Ca = 0.88 $cmol_c$ dm^{-3}; Mg = 0.71 $cmol_c$ dm^{-3}; K = 33.27 mg dm^{-3}; Al^{3+} = 0 $cmol_c$ dm^{-3}; H + Al = 4.2 $cmol_c$ dm^{-3}; SB = 1.68 $cmol_c$ dm^{-3}; CEC = 5.88 $cmol_c$ dm^{-3}; BS = 28.5 %; m = 0 %; P = 0 mg dm^{-3}; rem-P = 7 mg L^{-1}; Zn = 0.9 mg dm^{-3}; Fe = 37 mg dm^{-3}; Mn = 25 mg dm^{-3}; Cu = 4.4 mg dm^{-3}; B = 0.05 mg dm^{-3}; sandy = 17 %; silty = 16 %; clayey = 67 %.	Lavras, Brazil
Sandy soil with low OM	Typic Hapludox	OM = 1.49 dag kg^{-1}; pH (H_2O) = 6.4; Ca = 1.48 $cmol_c$ dm^{-3}; Mg = 0.6 $cmol_c$ dm^{-3}; K = 34.57 mg dm^{-3}; Al^{3+} = 0.09 $cmol_c$ dm^{-3}; H + Al = 1.27 $cmol_c$ dm^{-3}; SB = 2.17 $cmol_c$ dm^{-3}; CEC = 3.44 $cmol_c$ dm^{-3}; BS = 63.04 %; m = 3.98 %; P = 6.3 mg dm^{-3}; rem-P = 44.74 mg L^{-1}; Zn = 0.2 mg dm^{-3}; Fe = 11.6 mg dm^{-3}; Mn = 3.3 mg dm^{-3}; Cu = 0.19 mg dm^{-3}; B = 0.07 mg dm^{-3}; sandy = 94 %; silty = 2 %; clayey = 4 %.	Itutinga, Brazil
Sandy soil with high OM	Typic Hapludox	OM = 4.98 dag kg^{-1}; pH (H_2O) = 6.2; Ca = 6.08 $cmol_c$ dm^{-3}; Mg = 1.92 $cmol_c$ dm^{-3}; K = 376.12 mg dm^{-3}; Al^{3+} = 0.17 $cmol_c$ dm^{-3}; H + Al = 2.22 $cmol_c$ dm^{-3}; SB = 8.96 $cmol_c$ dm^{-3}; CEC = 11.18 $cmol_c$ dm^{-3}; BS = 80.18 %; m = 1.86 %; P = 69.64 mg dm^{-3}; rem-P = 44.36 mg L^{-1}; Zn = 8.58 mg dm^{-3}; Fe = 264.47 mg dm^{-3}; Mn = 52.09 mg dm^{-3}; Cu = 2.17 mg dm^{-3}; B = 0.07 mg dm^{-3}; sandy = 70 %; silty = 15 %; clayey = 15 %.	Carrancas, Brazil

OM = organic matter; SB = sum of bases (Ca + Mg + K); CEC = total cation exchange capacity (Ca + Mg + K + H + Al); BS = base saturation (SB × 100 / CEC); m = saturation by aluminum [Al × 100 / (Ca + Mg + K + Al)]; rem-P = remaining P. The pH (H_2O), Al^{3+}, Ca and Mg (extraction with 1 mol L^{-1} KCl), OM (oxidation with 0.2 mol L^{-1} $K_2Cr_2O_7$), potential acidity (H + Al; extraction with 0.5 mol L^{-1} $Ca(OAc)_2$), P, K, Cu, Fe, Mn and Zn (extraction with Mehlich-1), B (hot water) and rem-P (P in equilibrium solution) were determined according the recommendations of Soil Fertility Commission from the State of Minas Gerais (Ribeiro et al., 1999). Granulometric fractions (sand, silt and clay) were obtained by the densimeter method (EMBRAPA, 2009).

conducted to evaluate the impact of precipitation on B leaching and plant yield (Silva et al., 2018). In the first and fourth rainfalls, the water volume was equivalent to 95.49 mm each, whereas in the second and third rainfalls, the water volume was equivalent to 127.5 mm each. The first rainfall simulation was carried out at 25 DAE. A 10-day interval between rainfalls was applied to simulate a conventional crop with constant rainfall throughout the crop development cycle. This approach was taken to avoid rapid B leaching in a sole rainfall.

Boron sources were applied in accordance with the manufacturer's recommendations for each fertilizer at the vegetative stage V3 (18 DAE). Ulexite, boric acid, and B-MEA were applied directly to the soil, while zinc borate was combined with potassium chloride (KCl) for application to the soil surface. Consequently, K fertilization was performed on this same date (18 DAE) for all treatments. At 55 DAE, the plant shoots were harvested and dried in a forced ventilation oven at 65 °C for 72 h.

Determining B leaching in the soils

The leached liquid was collected on the day following each rainfall simulation to ensure sufficient time for leaching the soil solution exceeding the field capacity of each soil type. The leached volume from each collecting bottle was measured, and an aliquot was collected for the chemical analysis of B concentration. The vials containing the aliquots were stored in a refrigerator until the analyses were carried out.

The samples were subjected to nitric-perchloric digestion (HNO_3 65 % and $HClO_4$ 70 %) to determine the concentration of B in the leached liquid. Blank reagent samples were used during digestion to verify the absence of contamination. Subsequently, the extracts were analyzed by inductively coupled plasma optical emission spectrometry (ICP-OES).

Determining B accumulation in plant shoots

After drying, the shoots of soybean plants were ground in a Wiley-type mill to determine the concentration of B, which occurred after nitric-perchloric digestion by using HNO_3 65 % and $HClO_4$ 70 %. Blank reagent samples were used during digestion to verify the lack of contamination. The extracts were then analyzed by ICP-OES. Finally, B accumulation was determined by multiplying the B concentration by the dry mass of the respective tissue.

Calculating efficiency indexes

From the B accumulation in the plant shoots, we calculated two indices: i) Agronomic Efficiency Index (AEI) (Baligar et al., 2001); and ii) Applied B Recovery (ABR) (Baligar et al., 2001). These indices were calculated using the equations described in Eq. (1) and (2), respectively:

$$\text{AEI}(\%) = \left(\frac{\text{B acc. in the treament} \times - \text{B acc. in the control}}{\text{B acc. in the boric acid treament} - \text{B acc. in the control}}\right) \times 100 \quad (1)$$

$$\text{ABR}(\%) = \left(\frac{\text{B acc. in the treament} \times - \text{B acc. in the control}}{\text{B dose applied}}\right) \times 100 \quad (2)$$

where: acc. = accumulation; and B dose applied = 6 kg B ha^{-1} (0.02 g per column).

Statistical analysis

Normality (Shapiro-Wilk test) and homoscedasticity (Levene's test) were checked prior to data analyses. Afterward, the data were submitted for variance analysis, and the means were compared using the Scott-Knott test at 5 % of probability. The statistical analyses were performed using SISVAR® v. 5.3 (Ferreira, 2014). The results were expressed as means ± standard error of the mean (SEM).

Results

We observed that variation between B sources on nutrient leaching in response to four simulated rainfalls was insignificant in the clayey soil with low and high OM content (Figure 1A and B). Conversely, the effect of different B sources on B leaching in the sandy soil with low and high OM contents showed a higher level of variation between the B sources compared to the clayey soils (Figure 1A-D). A comparison of the soils revealed that B leaching was more significant in the sandy soil than the clayey soil, especially in the soil with low OM content (Figure 1A-D).

After the last simulated rainfall, the accumulated B leached was quantified and the means from each B source were compared (Figure 2A-D). The results showed that the B sources did not effect on the leaching of B in the clayey soil with low and high OM content and in the sandy soil with low OM content (Figure 2A-C). In contrast, in the sandy soil with high OM content, B leaching from ulexite was 27, 36, and 48 % lower than that from zinc borate, boric acid, and B-MEA, respectively (Figure 2D).

Although some differences were observed in B leaching due to the use of different B sources, there was no effect of B sources on the shoot biomass yield of soybean (Figure 3A-D). The shoot biomass yield observed in the clayey soil with low and high OM content and in the sandy soil with low OM content was found to be very similar but lower than that observed in the sandy soil with high OM content (Figure 3A-D). This soil presented the best chemical characterization (Table 1).

Despite the absence of differences in shoot biomass yield due to the use of different B sources, B accumulation in the shoot of soybean plants was affected by the different B sources supplied in the clayey soil with high OM content and in the sandy soils with low and high OM contents (Figure 4A-D). In the

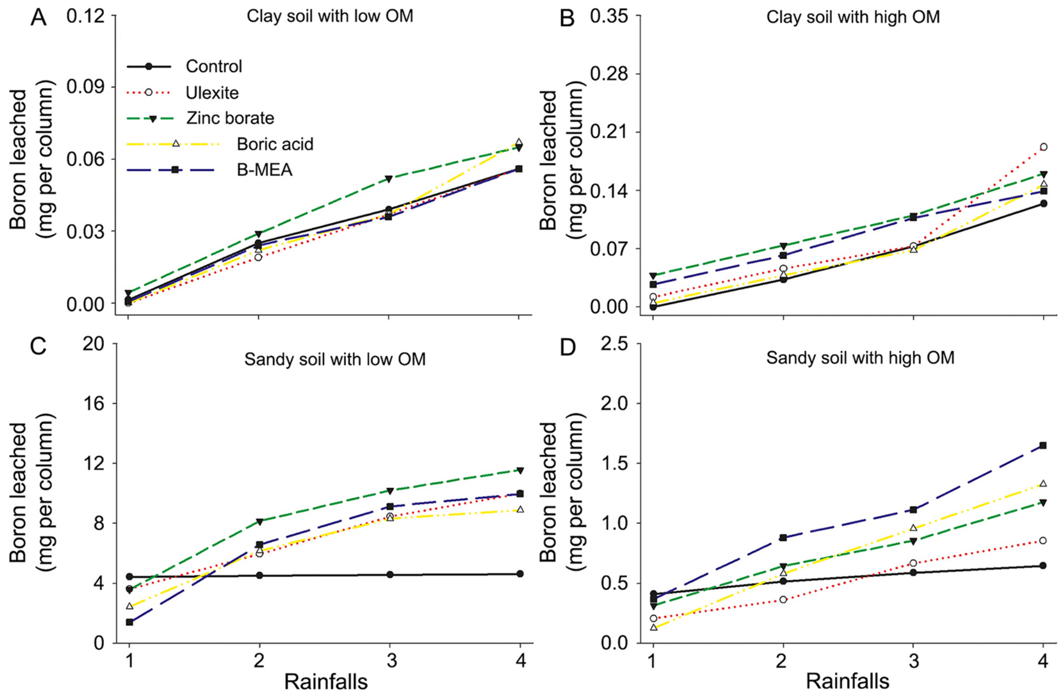

Figure 1 – Boron leached along of four simulated rainfalls in soils contrasting as texture (A and B = clay; C and D = sandy) and organic matter (OM) content (A and C = low OM; B and D = high OM) from the application of different Boron sources (B-MEA = B-monoethanolamine).

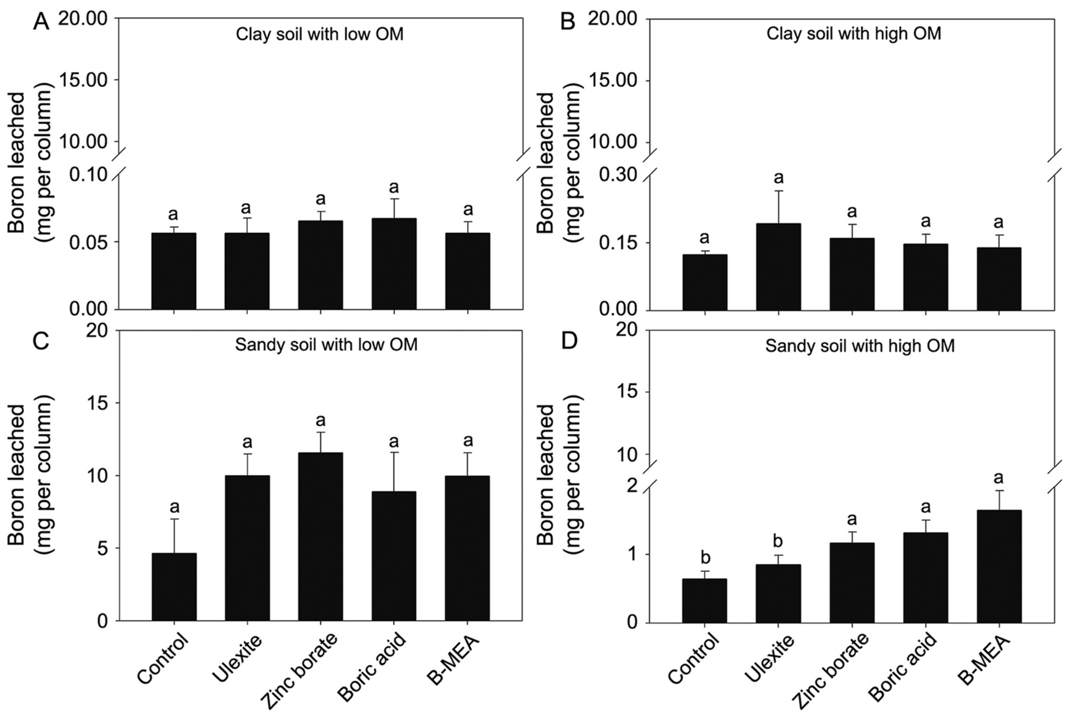

Figure 2 – Accumulated Boron leached in soils contrasting as texture (A and B = clay; C and D = sandy) and organic matter (OM) content (A and C = low OM; B and D = high OM) from the application of different Boron sources (B-MEA = B-monoethanolamine). Distinct letters on the bars ± standard error of the mean indicate difference between the means (Scott-Knott, $p < 0.05$).

clayey soil with high OM content, the supply of ulexite, zinc borate, boric acid, and B-MEA resulted in higher B accumulation than the control (Figure 4B). In the sandy soil with low OM content, using ulexite, zinc borate, and B-MEA resulted in higher B accumulation compared to boric acid, presenting a B accumulation

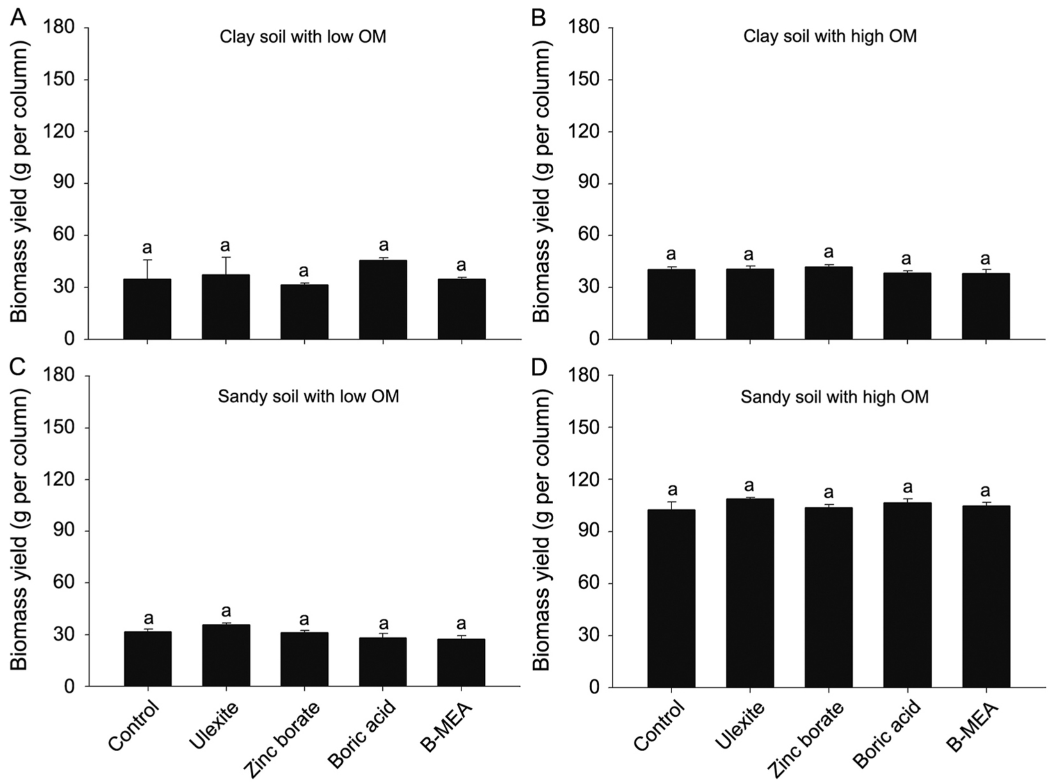

Figure 3 – Shoot biomass yield of soybean growth in soils contrasting as texture (A and B = clay; C and D = sandy) and organic matter (OM) content (A and C = low OM; B and D = high OM) from the application of different Boron sources (B-MEA = B-monoethanolamine). Distinct letters on the bars ± standard error of the mean indicate difference between the means (Scott-Knott, $p < 0.05$).

149 % higher than the control (Figure 4C). Lastly, in the sandy soil with high OM content, using B-MEA resulted in the highest B accumulation, followed by ulexite, zinc borate, and boric acid (Figure 4D). When comparing the soils, we observed that the highest B accumulation occurred in the sandy soil with high OM content, regardless of the B sources used (Figure 4A-D). This can be attributed to the higher shoot biomass yield in this soil (Figure 3D).

We calculated AEI (Figure 5A-D) and ABR (Figure 6A-D) from the B accumulation data. To proceed with the AEI calculation, we used boric acid as a reference between the B sources applied. In the clayey soils with low and high OM content, there was no difference in the AEI values for the B sources (Figure 5A-B). On the other hand, in the sandy soil with low OM content, the use of ulexite and zinc borate resulted in the highest AEI, which were 113 and 130 % higher, respectively, compared to boric acid (Figure 5C). In the sandy soil with high OM, using B-MEA resulted in the highest AEI, which was 84 % higher than boric acid (Figure 5D). Generally, the AEI was higher in the sandy soils than in the clayey soils (Figure 5A-D).

The different B sources did not affect the ABR in the clayey soils with low and high OM content and the sandy soil with high OM content (Figure 6A-D). However, in the sandy soil with low OM content, the use of ulexite and zinc borate resulted in higher ABR compared to boric acid and B-MEA (Figure 6C). As observed for AEI, the ABR values were higher than those in the sandy soils compared to the clayey soils (Figure 6A-D).

Discussion

Soil texture, soil OM content, and fertilizer sources have been identified as factors influencing soil B leaching and the capacity of fertilizers to supply B to plants (Dhassi et al., 2019; Castro et al., 2020). Consequently, in order to identify the most suitable B source for each soil condition evaluated in our study, it is necessary to investigate the processes occurring in the soil and how they affect the plants and the environment. This involves interpretating parameters from the B leaching to ABR by soybean. Therefore, it is essential to better understand the interaction between these factors not only to boost growth and yields but also to reduce environmental problems resulting from B leaching (Castro et al., 2020; Dameto et al., 2023).

In our study, we observed a minimal variation in the efficiency of B sources on soil B leaching across four simulated rainfalls in the clayey soils, regardless

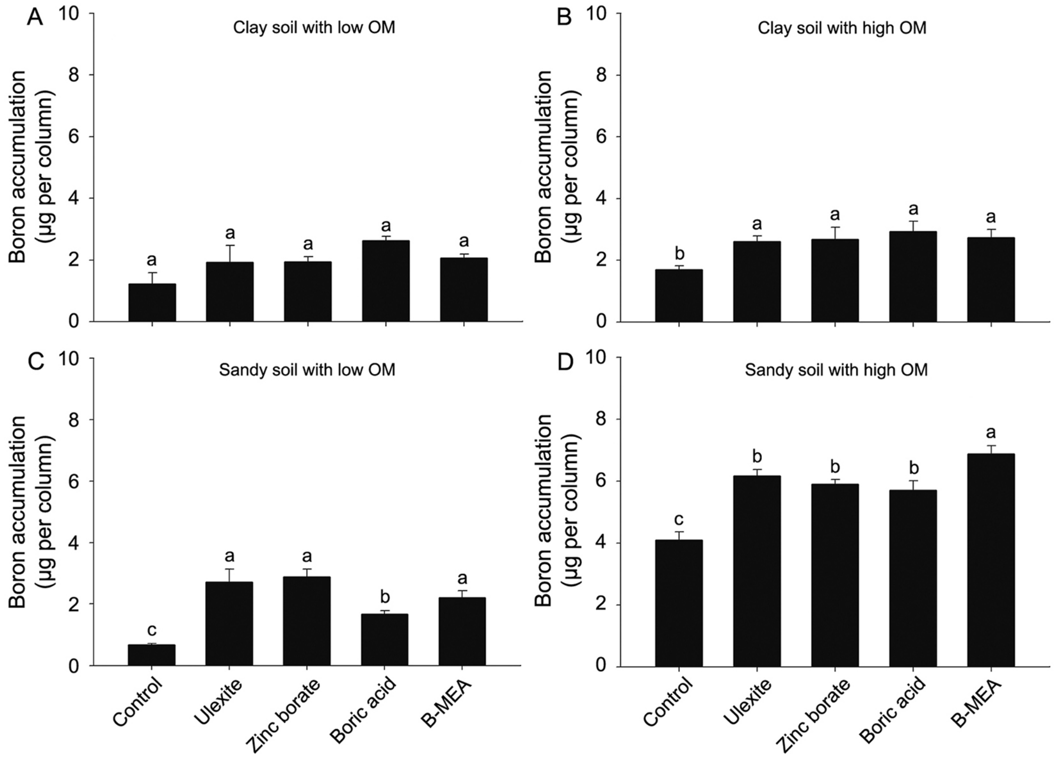

Figure 4 – Boron accumulation in the shoot of soybean growth in soils contrasting as texture (A and B = clay; C and D = sandy) and organic matter (OM) content (A and C = low OM; B and D = high OM) from the application of different Boron sources (B-MEA = B-monoethanolamine). Distinct letters on the bars ± standard error of the mean indicate difference between the means (Scott-Knott, $p < 0.05$).

of the OM content (Figure 1A and B). After the fourth simulated rainfall, B sources had no observable effect on B leaching in the clayey soils with low or high OM contents (Figure 2A and B). However, in the sandy soils, we observed a higher variation between the sources of soil B leaching (Figure 1C and D). In the sandy soil with high OM content, B leaching resulting from using ulexite was lower than using zinc borate, boric acid, and B-MEA (Figure 2D). This result can be explained by the lower solubility of ulexite in relation to other B sources (Mortvedt and Woodruff, 1993; Degryse, 2017). Other studies have also reported that ulexite presents lower soil B leaching compared to other B sources (Silva et al., 2021).

In this study, we observed that B leaching was significantly higher in sandy soil compared to clayey soil, mainly in soil with low OM content (Figure 1A-D). Our findings align with those reported by Communar and Keren (2006) and Dhassi et al. (2019), who similarly found higher B leaching in sandy soils (especially in soils with low OM content) compared to clayey soils. Boron adsorption by soil components is generally weak, but it may occur on phyllosilicate clays, oxides and hydroxides, carbonate minerals, and OM (Goldberg and Glaubig, 1985; Goldberg and Forster, 1991; Goldberg et al., 1993; Gu and Lowe, 1990). As sandy soils typically exhibit low contents of phyllosilicate clays, oxides, hydroxides, andcarbonate minerals, compared to clayey soils, B leaching is likely to be higher in sandy soils, particularly when the OM content is low. Consequently, it is paramount to pay special attention to B fertilization in sandy soils to prevent environmental issue, while ensuring that B nutrition requirements of plants are met.

The application of B sources to the soil did not result in any observable effects on the shoot biomass yield of soybean (Figure 3A-D). However, differences were observed in B leaching due to the use of different fertilizer sources (Figures 1A-D and 2A-D). The B requirement for soybean plants is known to increase from 60 DAE (Oliveira Junior et al., 2016). The harvest of plants in this study was carried out at 55 DAE. Therefore, the B concentration in the soils tested (Table 1) and the level of this nutrient from the seeds were sufficient to meet the initial requirement of plants not supplied with B. This resulted in the absence of a difference between the sources of shoot biomass yield of soybeans (Figure 3A-D). It can be further postulated that genotype 95R90IPRO presents high B use efficiency. An alternative hypothesis is that soils of low fertility, such as Oxisols, may restrict the response of soybean to B fertilization in the first year of the crop, as reported by Rosolem et al. (2008). However, this assumption is less likely to have occurred in our

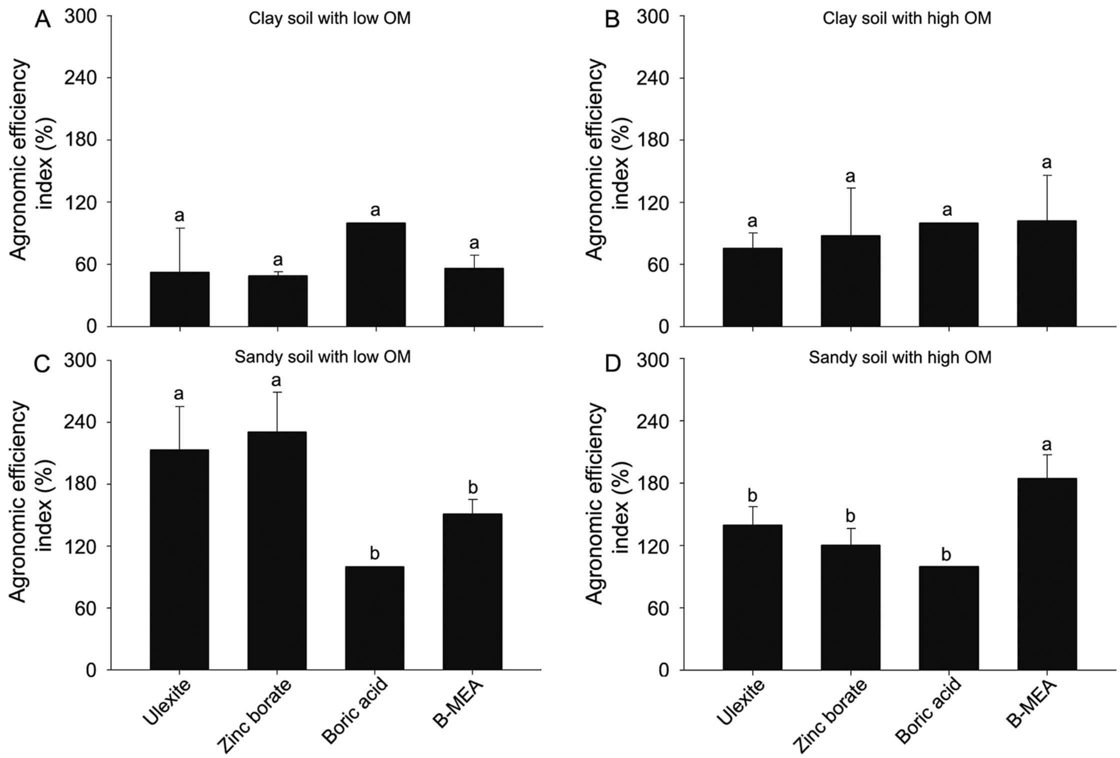

Figure 5 – Agronomic efficiency index of the different Boron sources on the soybean growth in soils contrasting as texture (A and B = clay; C and D = sandy) and organic matter (OM) content (A and C = low OM; B and D = high OM). Distinct letters on the bars ± standard error of the mean indicate difference between the means (Scott-Knott, $p < 0.05$). B-MEA = B-monoethanolamine.

study, given that a complete fertilization was carried out. Nevertheless, shoot biomass yield in the sandy soil with high OM content was higher than in the other soils tested (Figure 3A-D), likely related to its greater soil fertility (Table 1). Higher P and K concentrations, as observed in sandy soil with high OM content, are essential to increase soybean biomass yield (Rosolem et al., 2008).

Although differences were not detected in the shoot biomass yield of soybean due to the use of different B sources (Figure 3A-D), shoot B accumulation of soybean grown in the clayey soil with high OM content was higher with the supply of ulexite, zinc borate, boric acid, and B-MEA compared to the control (Figure 4B). This could be expected since the control treatment did not receive B fertilization. The highest B accumulation in soybean grown in the sandy soil with low OM content was observed with the supply of ulexite, zinc borate, and B-MEA (Figure 4C). The lower B accumulation resulting from the use of boric acid compared to other B sources in this soil is possibly due to its higher solubility (Mortvedt and Woodruff, 1993; Degryse, 2017). Boron was possibly percolated to the deep soil layers within the column, as Silva et al. (2021) observed, which restricted B uptake by the roots of plants supplied with boric acid and resulted in lower nutrient accumulation in the shoots. Although B-MEA is a H_3BO_3-based fertilizer, stabilizers, and complexing agents of hydroxy amine and hydroxycarboxylic acids groups are used in B-MEA production by the industry, which may reduce B mobility in specific soil conditions and favor B uptake by plants. Boron accumulation by plants grown in the sandy soil with a high OM content was significantly higher than in the other soils (Figure 4A-D). The use of B-MEA resulted in the highest shoot B accumulation by plants grown in the sandy soil with a high OM content, followed by the use of ulexite, zinc borate, and boric acid (Figure 4C and D). The highest B accumulation observed in the sandy soil with high OM content can be attributed to two factors. First, the high shoot biomass yield found in this condition (Figure 3D) is a contributing factor, as B accumulation is the product of biomass yield × tissue B concentration. Second, the higher OM content in the soil reduces B leaching in relation to soils with lower OM content (Figure 2C and D) due to the formation of nutrient complexes with ligands, such as $RCOO^-$ and RO^- (Van Duin et al., 1984). Furthermore, organic matter plays a role in occluding B on clay reactive sites, thereby reducing B leaching (Gu and Lowe, 1992).

The use of B sources that reduce the nutrient leaching losses and prolong its availability is essential for B nutrition of soybean. However, in the clayey soils, B sources had no effect on AEI and ABR, regardless of

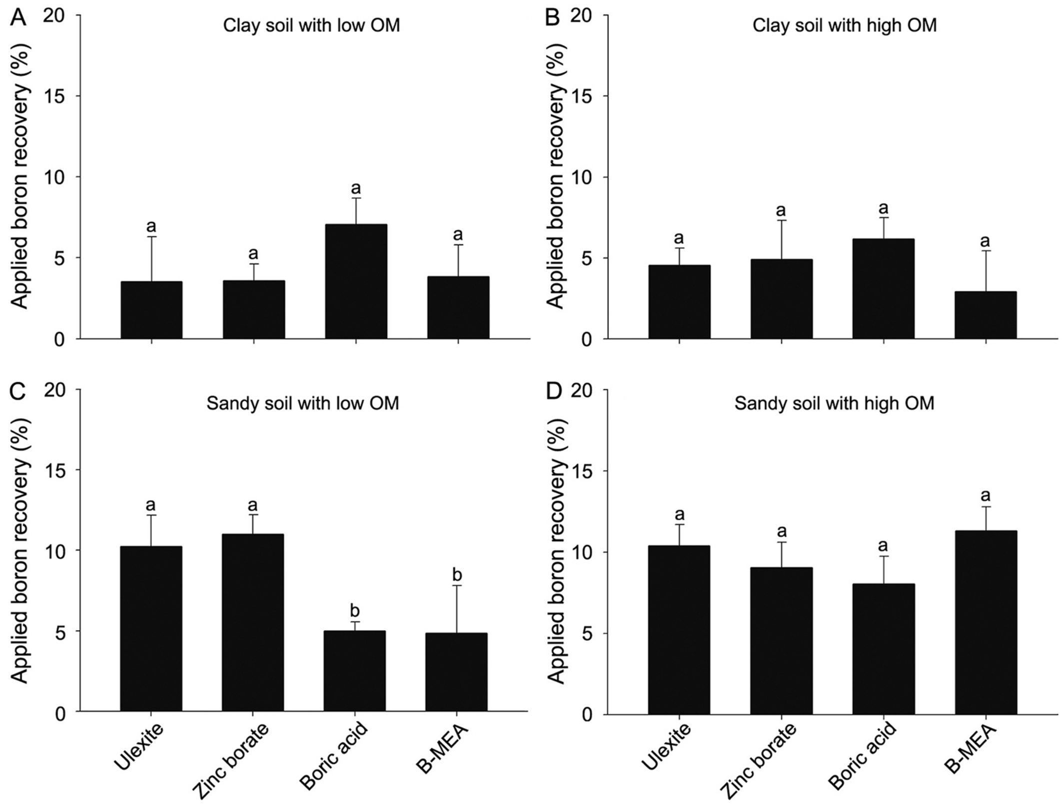

Figure 6 – Applied boron recovery by soybean growth in soils contrasting as texture (A and B = clay; C and D = sandy) and organic matter (OM) content (A and C = low OM; B and D = high OM) from the application of different Boron sources. Distinct letters on the bars ± standard error of the mean indicate difference between the means (Scott-Knott, $p < 0.05$). B-MEA = B-monoethanolamine.

the OM content (Figures 5A-B and 6A-B). In soils with a high clay content and a high concentration of oxide minerals, such as the clayey soils tested in this study, B adsorption is rapid, and B is subjected to a slow fixation over time (Goldberg, 1997). This process contributes to a reduction in B leaching, as observed in Figure 2A and B, but it can also reduce B availability to plants, as shown in Figure 4A and B. It can be postulated that differences between B sources from the second crop season onward in clayey soils (residual B availability) are more likely to be observed. In silty and clayey soils, even soluble B fertilizers may have a substantial residual effect due to the retention of B in the soil. However, in sandy and/or acidic soils, B is leached easily, and the residual effects of soluble sources are expected to be small in regions with considerable rainfall (Degryse, 2017). The residual availability of B was of great importance for the nutrition of sunflower plants (*Helianthus annuus* L.), and the use of B sources other than boric acid was indicated for sandy soils (Castro et al., 2020).

Indeed, the AEI and ABR of plants supplied with ulexite and zinc borate were higher than those of H_3BO_3-based fertilizers in the sandy soil with a low OM content (Figures 5C and 6C). Although B-MEA presents stabilizers and complexing agents of hydroxy amine and hydroxycarboxylic acids groups in its composition, H_3BO_3-based fertilizers are more subjected to leaching over time in soils with low capacity to retain $H_3BO_3^0$ compared to other B sources (Silva et al., 2021; Betiol et al., 2023). This results in a low capacity to supply B to plants, as observed in peanut (*Arachis hypogaea* L.) (Betiol et al., 2023). Conversely, in the sandy soil with a high OM content, the application of B-MEA resulted in the highest AEI (Figure 5D). This finding indicates that B-MEA was the most efficient in such conditions in supplying B to plants per unit of B applied. It is therefore probable that some interaction between B-MEA and OM has occurred in the sandy soil with a high OM content, which favored B accumulation by soybean plants, resulting in a higher AEI compared to other B sources (Figure 5D). Nevertheless, the process of B adsorption-desorption by OM is highly complex (Goldberg and Suarez, 2012), and thus, further investigation of this interaction is required, given that B-MEA may be a valuable source of B for plants grown in soils with a high OM content.

Generally, the AEI and ABR were higher in the plants growing in sandy soils than clayey soils (Figures 5A-D and 6A-D). This indicates that B was more available in the sandy soil solution than in clayey soils when soybean was grown for a single cycle. This result can be considered a positive indicator in that B deficiency can limit soybean yield and the low clay content would not limit the plant's ability to absorb the nutrient (Dameto et al., 2023). In contrast, two negative aspects must be considered. First, the highest soil B availability can induce B toxicity in soybean, depending on B dose applied (Dameto et al., 2023). Second, the highest soil B availability can result in an increased B leaching in sandy soils, as observed in this study (Figure 2C-D). Consequently, soybeans will require more frequent fertilization with B in sandy soils, particularly in those with a low OM content.

In conclusion, the variation in B leaching resulting from using distinct B sources was absent in the clayey soils and the sandy soil with a low OM content and was minimal in the sandy soil with a high OM content. Boron leaching was considerably influenced by soil texture, yet soil OM content significantly impacted the AEI of B sources in the sandy soil. Therefore, soil OM content must be considered when selecting the most suitable B source for soybean cultivation in sandy soils. As soybean biomass yield was not impacted by any B source tested and AEI of B sources assessed in the sandy soils was affected by soil OM content, our findings suggest that ulexite and zinc borate are more recommended for fertilization of soybean cultivated in sandy Oxisol with low OM content. At the same time, B-MEA is more suitable for sandy Oxisol, which presents high OM content. To the best of our knowledge, only a few studies have evaluated the effectiveness of B-MEA in supplying B to plants. However, our results indicated that B-MEA is a good source of B for soybean cultivation in sandy Oxisol. Therefore, further studies are required to confirm these findings.

Authors' Contributions

Conceptualization: Hippler FWR, Guelfi D. **Data curation:** Sarkis LF. **Formal analysis:** Sarkis LF, Rabêlo FHS. **Investigation:** Sarkis LF. **Methodology:** Sarkis LF, Guelfi D. **Supervision:** Guelfi D. **Writing-original draft:** Rabêlo FHS. **Writing-review & editing:** Sarkis LF, Hippler FWR, Guelfi D.

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