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Research Article

Leaching potential and soybean responses to pre-sowing application of different sources of boron

Potencial de lixiviação e respostas da soja à aplicação pré-semeadura de diferentes fontes de boro

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ABSTRACT

In southern Brazil, the high annual rainfall and soil pH conditions increase the potential for boron (B) leaching. This study aimed to examine B dynamics in soil and the responses of soybean (*Glycine max* (L.) Merr.) crops to surface application of B sources with different solubilities on two clay soils in southern Brazil. The following B sources were used: boric acid (17% B), ulexite (10% B), and disodium octaborate (21% B). Two experiments were conducted, one in soil columns and the other in the field. B leaching along soil columns under simulated edaphoclimatic conditions was not influenced by B source at the tested rate (1.1 kg ha^{-1} B). The three sources were effective in raising B content in the 0.00–0.20 m layer. On average, 60% of the added B remained in the soil following percolation with distilled water. In the field experiment, plots treated with ulexite or disodium octaborate at a rate of 1 kg ha^{-1} B had higher soybean yield than the untreated control. The results indicate that other factors besides solubility can influence the effectiveness of pre-sowing application of sources of B to improve soybean nutrition and yield.

KEYWORDS: Boron losses. Boron nutrition. *Glycine max.* Micronutrient. Grain yield.

RESUMO

No sul do Brasil, a elevada precipitação anual e as condições de pH do solo aumentam o potencial de lixiviação de boro (B). Este trabalho teve como objetivo examinar a dinâmica do B no solo e as respostas da cultura de soja (*Glycine max* (L.) Merr.) à aplicação superficial de fontes de B com diferentes solubilidades em dois solos argilosos no sul do Brasil. As seguintes fontes de B foram utilizadas: ácido bórico (17% B), ulexita (10% B) e octaborato dissódico (21% B). Dois experimentos foram conduzidos, um em colunas de solo e o outro no campo. A lixiviação de B ao longo das colunas de solo sob condições edafoclimáticas simuladas não foi influenciada pela fonte de B na taxa testada (1,1 kg ha^{-1} B). As três fontes foram eficazes em aumentar o teor de B na camada de 0,00–0,20 m. Em média, 60% do B adicionado permaneceu no solo após a percolação com água destilada. No experimento de campo, parcelas tratadas com ulexita ou octaborato dissódico na dose de 1 kg ha^{-1} B apresentaram maior produtividade de soja do que o controle. Os resultados indicam que outros fatores, além da solubilidade, podem influenciar a eficácia da aplicação em pré-semeadura de fontes de B na melhoria da nutrição e produtividade da soja.

PALAVRAS-CHAVE: Perdas de boro. Nutrição de boro. *Glycine max.* Micronutriente. Rendimento de grãos.

INTRODUCTION

Boron (B) is a micronutrient that participates in important physiological processes in plants (DECHEN et al. 2018). In soybean (*Glycine max* (L.) Merr.), B deficiency can impair biomass growth, nodule development, and seed production (DAMETO et al. 2023, PAWLOWSKI et al. 2019). Although it is not common to observe symptoms of B deficiency in soybean in Brazil, studies showed that application of boron fertilizers increased grain yield by improving photosynthetic activity and water use efficiency (FUJIYAMA et al. 2019, GALERIANI et al. 2022).

The form and availability of B in soil are influenced by several factors, such as soil pH, texture, iron and aluminum oxides and hydroxides, and soil organic matter (SOM) (DAS et al. 2019, SARKIS et al. 2024). SOM is the main source of B for plants (NOVAIS et al. 2007). However, tropical and subtropical soils typically have low SOM levels, as a result of climatic factors and land use (PEIXOTO et al. 2020). Consequently, these soils tend to contain lower levels of available B. Given the predominantly acidic pH of Brazilian soils, B is found in the form of boric acid (H_3BO_3). As it is electrically neutral, H_3BO_3 has a high leaching potential. Nutrient leaching reduces nutrient availability in the root growth zone and may cause environmental impacts by groundwater contamination (BOLAN et al. 2023).

Several sources of B have been investigated for their potential to enhance soybean development in no-till systems, such as boric acid, disodium octaborate, and ulexite. Traditionally, B fertilizers are applied to the soil or directly to plant leaves. Although soil application is a common practice, it poses challenges in achieving a uniform distribution of the micronutrient, which plants require in small quantities (1 to 2 kg ha^{-1} B) (PAULETTI et al. 2019, OLIVEIRA JUNIOR et al. 2020). With foliar treatment, the challenge lies in providing a sufficient supply of the micronutrient, given its limited mobility in plants (WILL et al. 2011). In view of these limitations, studies have recommended that B fertilizers, particularly boric acid, be applied at pre-sowing together with herbicide sprays, either alone or as a complementary fertilizer (OLIVEIRA JUNIOR et al. 2020). Several types and formulations of B fertilizers are available in the market, each having a different composition and, therefore, different solubility. Consequently, these products may elicit distinct responses after soil application (DAMETO et al. 2023).

This study examined the hypothesis that boric acid and disodium octaborate, highly soluble sources of B, are more susceptible to leaching losses and have lower efficiency in improving soybean nutrition and yield than ulexite, a low-solubility source of B, when applied as liquid fertilizers at the pre-sowing stage. The aims were to assess B dynamics in soil and soybean responses to surface application of liquid B sources with different solubilities on two clay soils in southern Brazil. Thus, the current study comprises two experiments, one conducted in soil columns and the other in the field.

MATERIAL AND METHODS

The first experiment was conducted in a greenhouse over a five-week period. B leaching from B fertilizers was measured by applying distilled water to soil columns, simulating local rainfall conditions (BAMBERG et al. 2012). Rainfall simulation consisted of weekly drip applications of a water volume equivalent to 189 mm. This water volume corresponds to the average monthly rainfall recorded in the three summer cropping seasons (October to February) prior to the experiment (2016–2017, 2017–2018, and 2018–2019) (INSTITUTO NACIONAL DE METEOROLOGIA 2020) in Paraná State, Brazil.

The experimental units consisted of polyvinyl chloride (PVC) columns measuring 0.65 m in height and 0.10 m in inner diameter. The upper part of each column had a 0.05 m free wedge to facilitate water application. At the bottom, columns were equipped with a PVC plug with a central hole to which a rubber hose was attached. The hose was used to drain the percolated solution into plastic bottles. The base of the PVC plug was lined by paper filter to prevent the loss of soil material and maintain the percolated solution filtered and clear.

Columns were gradually filled with soil, starting from the base upward. Deformed soil samples collected from the 0.60–0.40, 0.40–0.20, 0.20–0.10, and 0.10–0.00 m layers were sequentially added to replicate the original soil profile at the collection site. The soil was a Rhodic Kandiudalf with a high clayey content collected from a soybean–second-crop maize system (23°23′54.91″ S and 51°57′05.56″ W). Soil chemical and textural properties are presented in Table 1.

Table 1. Soil chemical and textural properties in the soil columns experiment.

Soil attributes[a]	**Soil layer (m)**			
	0.00–0.10	**0.10–0.20**	**0.20–0.40**	**0.40–0.60**
Sand (%)	9	10	7	7
Silt (%)	17	14	12	12
Clay (%)	74	76	81	81
pH $CaCl_2$[b]	5.60	5.60	5.50	5.60
Ca^{2+} ($cmol_c\ dm^{-3}$)[c]	5.50	5.69	3.96	3.79
Mg^{2+} ($cmol_c\ dm^{-3}$)[c]	1.67	1.74	1.33	1.17
K^+ ($cmol_c\ dm^{-3}$)[d]	0.47	0.28	0.13	0.08
$H^0 + Al^{3+}$ ($cmol_c\ dm^{-3}$)[e]	3.85	4.28	4.00	3.42
Al^{3+}($cmol_c\ dm^{-3}$)[c]	0.00	0.00	0.00	0.00
Organic matter (g kg^{-1})[f]	31.40	34.70	19.40	11.70
P (mg dm^{-3})[d]	2.37	2.11	0.42	0.93
B (mg dm^{-3})[g]	0.33	0.11	0.26	0.18

[a]Soil analysis were performed according to the methods described by SILVA et al. (2009). [b]Determined in 0.01 mol L^{-1} $CaCl_2$. [c]Extracted with 1 mol L^{-1} KCl. [d]Extracted with Mehlich-1 solution. [e]Determined by the Shoemaker–McLean–Pratt (SMP) method. [f]Determined by the Walkley–Black method. [g]Determined by the hot water method.

The experimental design was completely randomized with four replications. Treatments consisted of an unfertilized control (without B application), boric acid (H_3BO_3, 17% B), disodium octaborate ($Na_2B_8O_{13}\cdot 4H_2O$, 21% B), and ulexite ($NaCa_2B_5O_9\cdot 5H_2O$, 10% B). The analyzed variables were cumulative amount of B leached to the percolated water, residual B content in the 0.00–0.10, 0.10–0.20, 0.20–0.40, and 0.40–0.60 m layers after percolations, and recovery of B fertilizer added to the soil.

Soil moisture was standardized by saturating each column with distilled water and draining the excess water for 96 h. The quantities of boric acid, disodium octaborate, and ulexite were 5.07 mg, 4.11 mg, and 8.63 mg, respectively, corresponding to a rate of 1.1 kg ha^{-1} B. All fertilizers were dissolved in 1 mL of distilled water and then applied uniformly to the soil surface with a micropipette (ROSOLEM & BÍSCARO 2007). Boric acid and disodium octaborate were completely dissolved. On the other hand, ulexite was ground, sieved (840 µm), and mixed with the same amount of water used in the other fertilizers (1 mL), forming a suspension, which was stirred immediately before application.

Percolated solutions were collected weekly. First, the volume was measured. Then, the solution was filtered through qualitative filter paper and subjected to B quantification. B contents were determined by microwave plasma atomic emission spectroscopy (MP-AES, Agilent 4200) at 249.772 nm.

The B content at each soil depth was determined after the last weekly application of distilled water. Columns were sectioned into four parts for the collection of soil samples from the 0.00–0.10, 0.10–0.20, 0.20–0.40, and 0.40–0.60 m layers. The soil was dried in an air circulation oven at 45 °C, ground, and sieved through 2 mm mesh sieves. B was extracted by the hot water method and determined by colorimetry using azomethine-H (SILVA et al. 2009).

The cumulative leached B index of B fertilizers was calculated using the following Equation (1):

$$\mathrm{B_l} = \sum_{i=1}^{5} (\mathrm{B_f} - \mathrm{B}_c) \quad (1)$$

where B_l is the sum of the amounts of B fertilizer lost to leaching over the 5 weeks of percolation, B_f is the amount of B (mg) leached from each fertilizer in week *i*, and B_c is the amount of B leached from the unfertilized control (mg) in week *i*. $B_f - B_c$ was calculated within each replication.

The amount of B recovered from soil and leachate was calculated for each fertilizer source according to Equations (2) and (3), respectively, both adapted from calculations of SÁ & ERNANI (2016) and MARANGONI et al. (2019):

$$\mathrm{BR_l}\,(\%) = \left(\frac{\overline{\mathrm{B}_t}}{\mathrm{B_{rate}}}\right) \times 100 \quad (2)$$

$$\mathrm{BR_s}\,(\%) = \frac{\left[\sum_{j=1}^{4}\left(\frac{\overline{\mathrm{B}_j} - \overline{\mathrm{B_c}}}{V_{\mathrm{column}}}\right)\right]}{\mathrm{B_{rate}}} \times 100 \quad (3)$$

where BR_l represents the percentage of B fertilizer recovered in leachate in relation to the rate of B applied; $\overline{\mathrm{B}_t}$ is the cumulative amount of leached B from source *t* (mg), B_{rate} is the ratio of applied B to the column surface area (0.8635 mg to 0.00785 m^2, equivalent to 1.1 kg ha^{-1}), BR_s is the percentage of B fertilizer recovered from each soil layer (0–0.6 m) after 5 weeks of percolation, $\overline{\mathrm{B}_j}$ is the mean B content in soil layer *j* (mg dm^{-3}) (*j* = 0.00–0.10, 0.10–0.20, 0.20–0.40, or 0.40–0.60 m) fertilized with source *t*, $\overline{\mathrm{B_c}}$ is the mean B content in the control soil layer (mg dm^{-3}), V_{column} is the column volume at depth *j* (dm^3). $\overline{\mathrm{B}_j} - \overline{\mathrm{B_c}}$ was calculated within each replication.

The field experiment was conducted in the 2019–2020 growing season in Campo Mourão, Paraná, Brazil (24°04′17.79″ S 52°24′04.43″ W, 591 m a.s.l.). The soil is classified as a Rhodic Hapludox with a high clayey texture. Soil properties at the beginning of the experiment are shown in Table 2. The climate of the experimental region is of the Cfa type (mesothermal humid subtropical), with hot summers and infrequent frosts (KÖPPEN 2011). Climate data for the experimental period were obtained from the Brazilian National Institute of Meteorology (INMET) and are summarized in Figure 1.

Treatments included an unfertilized control (without B application) and applications of 1 kg ha^{-1} B in the form of boric acid, disodium octaborate, or ulexite. Fertilizer applications were performed on November 21, 2019, the same day as soybean sowing. Fertilizers were applied directly on the soil surface by using a CO_2 knapsack sprayer. The spray volume was 120 L ha^{-1}. Prior to application, the fertilizers were prepared in solution or suspension as described in the soil columns experiment.

Table 2. Soil chemical and textural properties in the field experiment.

Soil attributes[a]	Soil layer (m)	
	0.00–0.20	0.20–0.40
Sand (%)	10	9
Silt (%)	10	8
Clay (%)	80	83
pH $CaCl_2$[b]	5.2	4.9
Base saturation (%)	51	33
Al^{3+} (cmol$_c$ dm^{-3})[c]	0.00	0.11
H^0 + Al^{3+} (cmol$_c$ dm^{-3})[e]	5.51	5.80
K^+ (cmol$_c$ dm^{-3})[d]	0.50	0.11
Ca^{2+} (cmol$_c$ dm^{-3})[c]	3.73	1.95
Mg^{2+} (cmol$_c$ dm^{-3})[c]	1.59	0.76
P (mg dm^{-3})[d]	22	3
C (g dm^{-3})[f]	23.87	13.31
B (mg dm^{-3})[g]	0.20	0.09

[a]Soil properties were analyzed according to the methods described by SILVA et al. (2009). [b]Determined in 0.01 mol L^{-1} $CaCl_2$. [c]Extracted with 1 mol L^{-1} KCl. [d]Extracted with Mehlich-1 solution. [e]Determined by the Shoemaker–McLean–Pratt (SMP) method. [f]Determined by the Walkley–Black method. [g]Determined by the hot water method.

Plots were sown with soybean 5D6215 IPRO (Dow Agrosciences, Brazil) at a density of 267,000 pl ha^{-1}. *Bradyrhizobium* spp. were used at a rate of 100 mL 50 kg^{-1} seed. Seed treatment was performed by mixing the inoculant solution and seeds in a plastic bag. Additionally, an in-furrow application of 6.6 kg ha^{-1} N, 66 kg ha^{-1} P_2O_5, and 59 kg ha^{-1} K_2O was provided by applying 330 kg ha^{-1} of 2-20-18 (N-K_2O-P_2O_5) fertilizer. At the V3 stage (FEHR & CAVINESS 1977), plants were treated with 120 kg ha^{-1} K_2O in the form of KCl fertilizer (60% K_2O). Control of weeds, insects, and diseases followed the technical recommendations for the crop (SEIXAS et al. 2020).

The experiment was conducted according to a completely randomized block design with four replications. Each experimental unit consisted of eight 10 m long rows spaced 0.45 m apart, totaling 36 m^2. The analyzed variables were B content in leaves and grains, grain yield, and thousand-grain weight.

When plants reached the R1 stage, 25 trifoliate leaves (without the petiole) were collected from each plot for determination of leaf B content (OLIVEIRA JUNIOR et al. 2020). Leaves were washed with distilled water and dried for 72 h in a forced-air oven at 65 °C. Grains were harvested when plants reached the R8 stage. Harvest was carried out manually along the two central rows of each plot, encompassing an area of 7.2 m^2. Grain moisture was corrected to 130 g kg^{-1}, and grain yield was extrapolated to kg ha^{-1}. Thousand-grain weight was determined from the mean weight of three replications of 50 grains randomly chosen from harvested grains. Moisture content was also corrected to 130 g kg^{-1}.

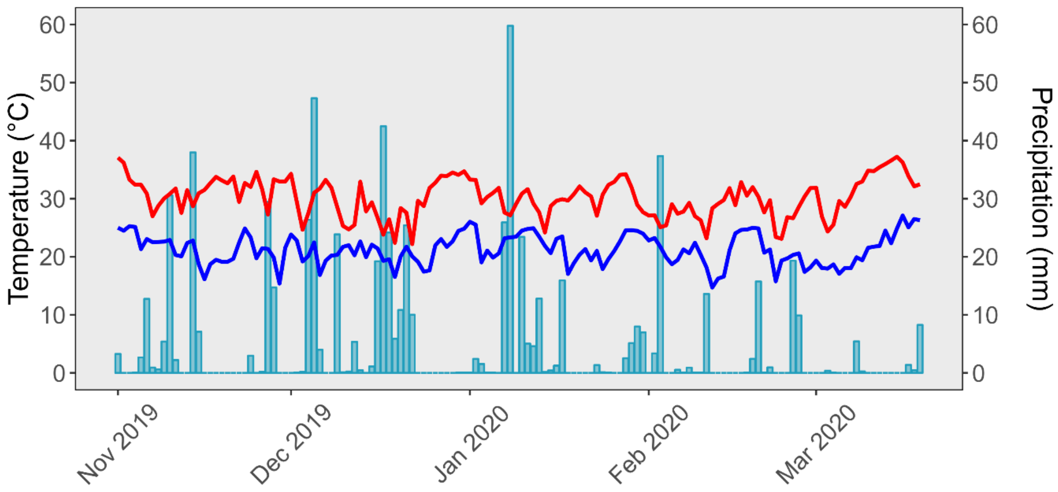

Figure 1. Air temperature (°C) and daily precipitation (mm) during the 2019/2020 cropping season in Campo Mourão, Paraná State, Brazil. Red and blue continuous lines represent the maximum and minimum air temperatures, respectively. Blue bars represent the daily precipitation.

Leaf and grain samples were ground in a Wiley mill, weighed, and treated in a muffle furnace at 550 °C. The resulting ash powders were used for determination of B content by the azomethine-H colorimetric method. Reading was performed at 420 nm by using a digital UV/visible spectrophotometer (Spec-UV-5100, Tecnal), as described by MALAVOLTA et al. (1997).

The data were analyzed using R software (R CORE TEAM 2024). The lme4 package was used to fit mixed linear models to experimental data for cumulative leached B, soil residual B content, leaf and grain B contents, grain yield, and thousand-grain weight (BATES et al. 2015). B sources were treated as fixed effects. For data from the soil columns experiment, replications were treated as random effects. For field data, blocks were treated as random effects. Normality of residuals and homogeneity of variances were verified, and square root transformations were applied when necessary. Fitted models were subjected to type III analysis of variance (ANOVA) using the car package (FOX & WEISBERG 2018). When significant differences were identified ($p < 0.05$), the null hypothesis was rejected and Tukey's test was applied using the multicomp package for comparison of means at $p < 0.05$ (HOTHORN et al. 2008).

RESULTS

B sources did not significantly influence the amount of leached B in percolated solutions ($p > 0.05$) (Figure 2a), with an overall mean of 0.11 mg of B. However, residual B content in surface layers was positively influenced by B fertilization ($p < 0.05$) (Figure 2b). In the 0.00–0.10 m layer, B content increased by about 20% with B application in relation to the initial content, considering the overall mean of B treatments. In the control, by contrast, B content decreased by 45%. In the 0.10–0.20 m layer, boric acid and disodium octaborate application resulted in higher residual B contents than the control, with a 2.4 times higher mean than the initial B content in the layer. Residual B contents in the 0.20–0.40 m and 0.40–0.60 m layers were not influenced by B source, with mean values of 0.24 and 0.30 mg dm^{-3}, respectively.

The total recovery of applied B was observed in the following descending order: boric acid > disodium octaborate > ulexite (Figure 2c). On average, 60% of the applied B remained at the 0.00–0.60 m depth after the simulated rainfall regime. The percentage of recovered B in the percolated solution ranged from 13% to 17% between sources. Disodium octaborate and boric acid showed similar results in terms of B recovery after percolation of 942 mm of water: on average, 65% of the applied fertilizer remained in the soil. In this fraction, the results agreed with the degree of solubility of B sources at 20 °C, namely of 223.65 g L^{-1} for disodium octaborate, 50.27 g L^{-1} for boric acid, and 7.60 g L^{-1} for ulexite.

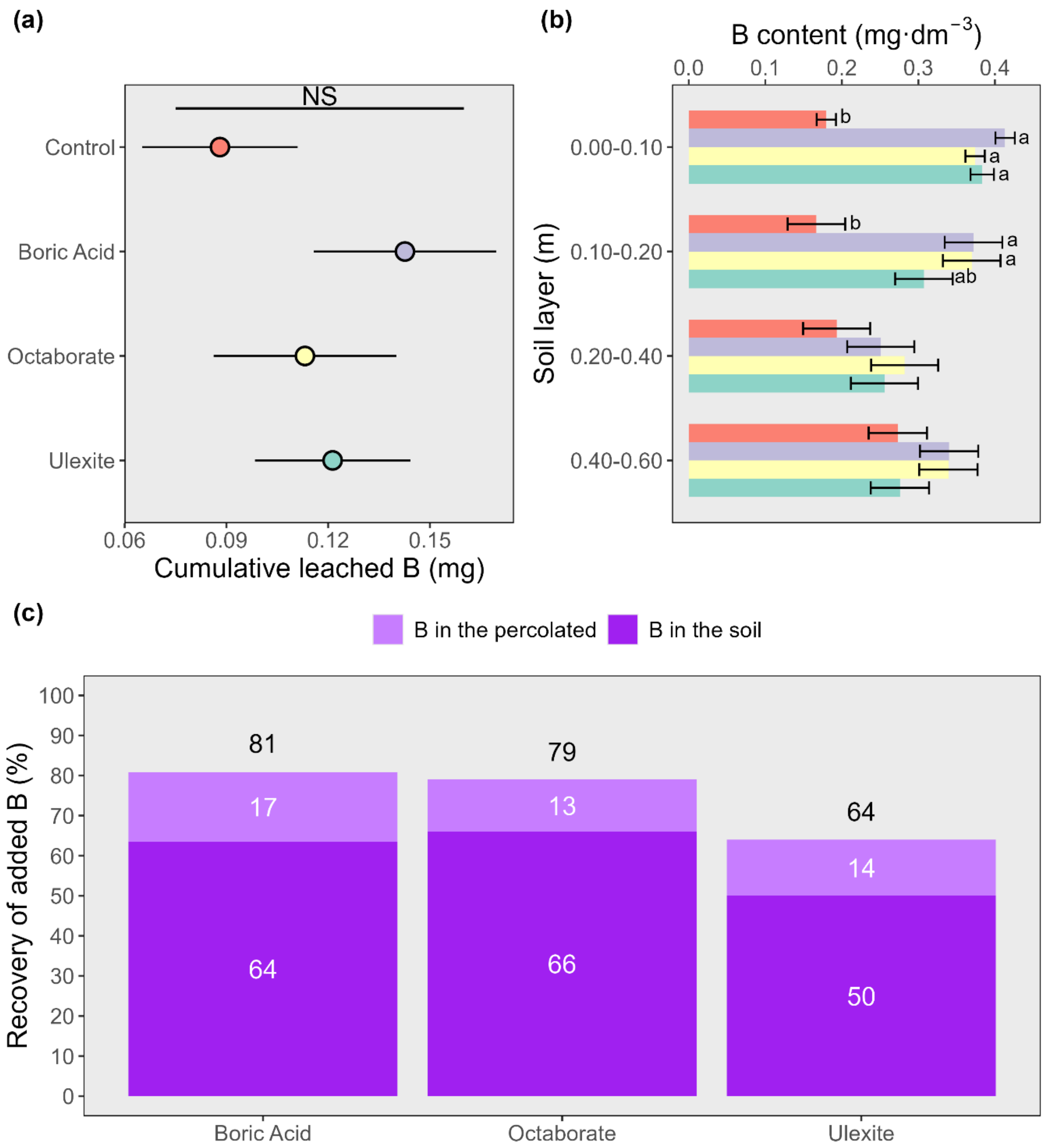

Figure 2. (a) Cumulative amount of boron (B) (mg) leached from soil during percolation of 942 mm of distilled water[1], (b) B content (mg dm^{-3}) along the soil profile after percolation[2], and (c) recovery of added B in the form of three B sources after percolation. Bar colors in panel b represent the same treatments as in panel a. [1]Points represent mean values (n = 4), and error bars represent the standard error. No significant differences (NS) were observed among treatments (analysis of variance, p > 0.05). [2]Within each soil layer, means (n = 4) followed by the same letter are not significantly different at p > 0.05 by Tukey's test. Tukey test results are only displayed when B sources had a significant effect on B content

in individual soil layers.

B levels in soybean leaves did not differ significantly between treatments ($p > 0.05$) (Figure 3a). The mean B content in leaf tissue was 54.7 mg kg^{-1}. By contrast, grain B content was significantly influenced by B fertilization source ($p < 0.05$) (Figure 3b). Plants fertilized with boric acid and disodium octaborate exhibited a 9% higher B accumulation in grains compared with the control.

Grain yield was significantly influenced by B fertilization ($p < 0.05$). Ulexite and disodium octaborate afforded the highest grain yields compared with the control (Figure 3c), with yield gains of 17.6% and 16.3%, respectively. B application also influenced thousand-grain weight ($p < 0.05$). B fertilization at a rate of 1 kg ha^{-1} B provided an increase in the parameter in relation to the control (Figure 3d).

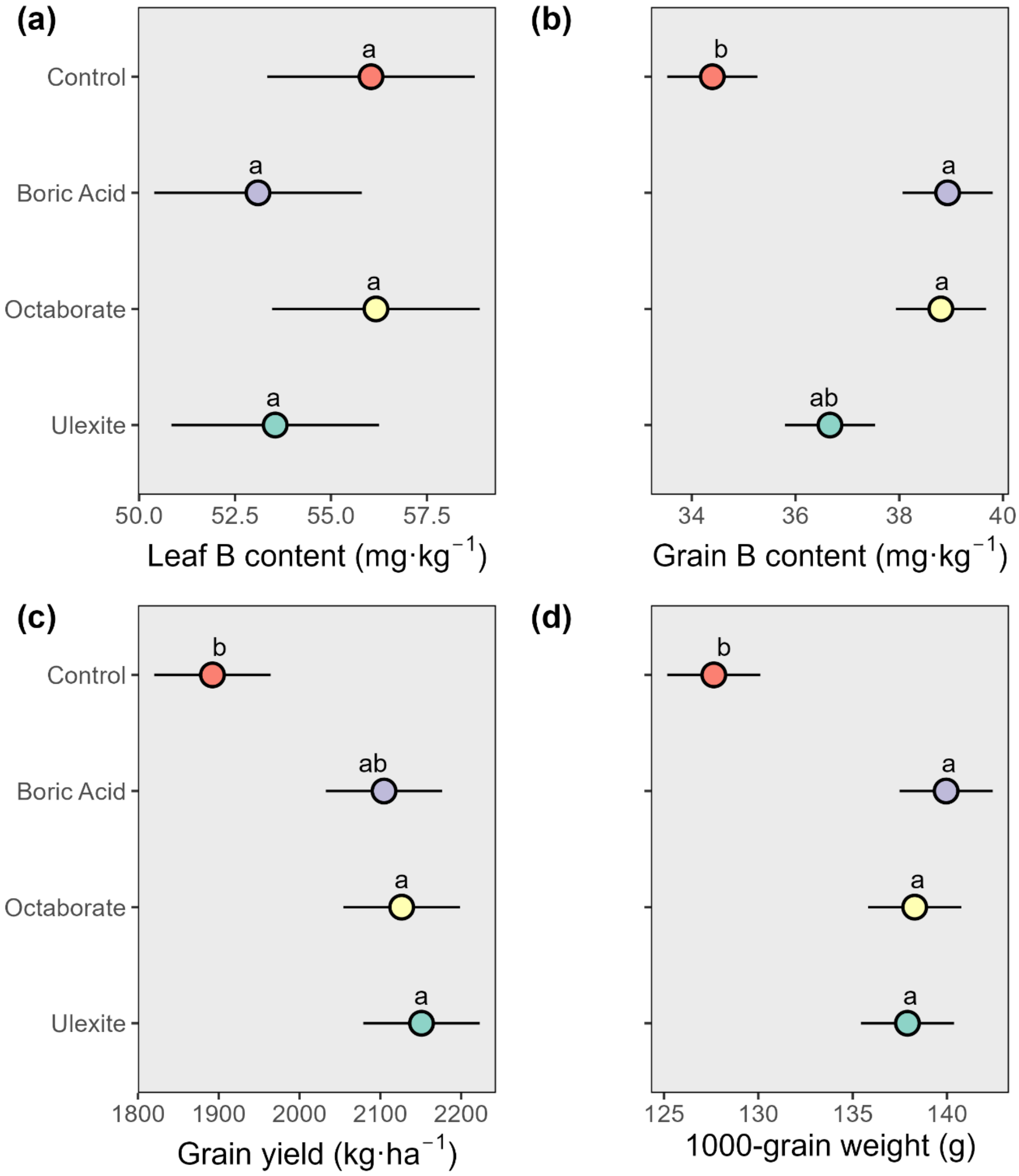

Figure 3. Boron (B) content in (a) soybean leaf and (b) grain, (c) grain yield, and (d) thousand-grain weight. Means ($n = 4$) followed by the same letter are not significantly different at $p > 0.05$ by Tukey's test. Error bars represent the standard error.

DISCUSSION

This study provides novel data on soil B losses and the agronomic response of soybean to B fertilization in clay soils in southern Brazil. The simulated water regime promoted B leaching regardless of the application (1.1 kg ha^{-1}) or not of B fertilizers. Thus, there is a natural propensity for B leaching, even in soils with high clay content. In quantifying B losses via leaching in a Typic Hapludox, ROSOLEM & BÍSCARO (2007) demonstrated that B leaching can occur even without the addition of B fertilizers and that leaching rates are proportional to the amount of percolated water.

Analysis of residual B after percolation showed that B fertilization increased soil B content in the surface layer (0.00–0.20 m). This finding confirms the high mobility of the predominant B species (H_3BO_3) under the studied soil chemical conditions. Similar results were reported by OLIVEIRA NETO et al. (2009) for a Rhodic Eutrudox. The authors attributed these results to the higher SOM content in surface layers, as observed here (Table 1). SOM plays a major role in adsorption processes and represents an important natural source of available B. The results of the 0.20–0.40 m and 0.40–0.60 m layers suggest that the simulated water volume was sufficient to induce the leaching of B fertilizers to 0.10–0.20 m depth. Soil pH conditions likely had little influence on B adsorption (BARROW & HARTEMINK 2023).

Overall, there were high rates of B recovery regardless of B source. Although using higher rates of boric acid, SÁ & ERNANI (2016) and SARKAR et al. (2015) recorded lower recovery rates than those found in this study in unlimed treatments. SÁ & ERNANI (2016) argued that the differences in total applied B and recovered B (in soil and percolates) indicate that the hot water method is not suitable for quantifying available and adsorbed B contents in soil. The results suggest that boric acid and disodium octaborate are viable short-term sources for surface application in liquid form, given their good solubility in water. On the other hand, the low B recovery rate from ulexite application confirms the fertilizer's slow release of B, owing to its reduced solubility. Under the simulated environmental conditions, ulexite would potentially have a longer residual effect in the medium or long term than the other B sources (ABAT et al. 2015).

In the field experiment, the foliar B contents of all soybean treatments were adequate according to national criteria (OLIVEIRA JUNIOR et al. 2020). The lack of difference between treatments and the control indicates that the initial B content in soil, together with B mineralized by organic matter, might have been sufficient to meet the demand of soybean plants up to trifoliate sampling. The B content of soybean trifoliate leaves at the R1 stage is not associated with grain yield (SUTRADHAR et al. 2017). Regarding grain B content, the means of disodium octaborate and boric acid treatments were higher than those of the control, suggesting that the high solubility of the fertilizers contributed to B absorption and accumulation in soybean.

Ulexite and disodium octaborate increased grain yield compared with the control. Nevertheless, responses to B fertilization applied at pre-sowing or early season at rates similar to those tested here have been inconsistent and attributed to specific environments. SUTRADHAR et al. (2017) observed that, in soils with high chemical fertility (unknown clay content and mean initial levels of 0.71 mg kg^{-1} B, 4.7% SOM, and pH in water of 6.7), incorporation of B at a rate of 2.2 kg ha^{-1} at pre-sowing did not increase soybean yield; rather, such fertilization decreased yield due to toxicity effects. ROSS et al. (2006) observed a significant increase in yield with B fertilization (0.28 kg ha^{-1}) in the early season (V2 stage) in only one (8% clay, initial levels of 0.43 mg kg^{-1} B, 2.3% SOM, and pH in water of 7.7) of four environments. Therefore, it can be inferred that the response of soybean yield to B fertilization at pre-sowing and/or early season is more likely to be positive in soils with low B and SOM levels.

In addition to soil chemical properties, soybean genotype can influence the response of grain yield to B fertilization. Recently, LIBÓRIO et al. (2024) assessed the agronomic performance of modern soybean cultivars with and without ulexite application (10% B, rate of 3.19 kg ha^{-1}) at the V3 stage in soils of the Brazilian Cerrado. The authors obtained significant responses in 8 of the 10 cultivars. In two seasons, there were increases of 13% to 51% in mean grain yield with B fertilization, in agreement with the present study. The increase in grain yield was mainly expressed by the contribution of thousand-grain weight, in contrast to that observed by LIBÓRIO et al. (2024).

In the present study, initial soil B levels were low according to regional criteria (PAULETTI et al. 2019). It is believed that surface application of B fertilizers at pre-sowing promotes fertilizer mobility along the soil profile to zones with high root concentrations in no-till systems (MORAES et al. 2020). The laboratory and field experiments conducted here support this hypothesis. Nevertheless, the yield of all fertilized treatments was below the regional mean for the 2019/2020 harvest season (DEPARTAMENTO DE ECONOMIA RURAL 2020), possibly due to the poor rainfall distribution in the region during the soybean cycle.

CONCLUSION

B losses via leaching under the simulated edaphoclimatic conditions did not depend on the application of different B sources at a rate of 1.1 kg ha^{-1}.

Surface application of boric acid, disodium octaborate, or ulexite in liquid form was effective in increasing soil B content in the 0.00–0.20 m layer.

The highest percentages of B recovery were obtained with higher-solubility fertilizers (boric acid and disodium octaborate). However, the findings suggest that factors other than fertilizer solubility influenced the responses of soybean nutrition and yield to B fertilization at pre-sowing on two clay soils in southern Brazil.

NOTES

AUTHOR CONTRIBUTIONS

Conceptualization, methodology, and formal analysis**, Juliana Marques Voroniak, Marcelo Augusto Batista and Tadeu Takeyoshi Inoue**; software and validation**, Lucas Hiroshi Suguiura;** investigation**, Juliana Marques Voroniak**; resources and data curation**, Juliana Marques Voroniak and Paulo Sergio Lourenço de Freitas**; writing-original draft preparation**, Juliana Marques Voroniak and Lucas Hiroshi Suguiura**; writing-review and editing**, Lucas Hiroshi Suguiura, Fernando Marcos Brignoli, João Henrique Vieira de Almeira Jr and Marcelo Augusto Batista**; visualization**, Lucas Hiroshi Suguiura**; supervision, **Paulo Sergio Lourenço de**

Freitas and Tadeu Takeyoshi Inoue; project administration, **Paulo Sergio Lourenço de Freitas**; funding acquisition, **Marcelo Augusto Batista and Tadeu Takeyoshi Inoue**. All authors have read and agreed to the published version of the manuscript.

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INSTITUTIONAL REVIEW BOARD STATEMENT

Not applicable for studies not involving humans or animals.

INFORMED CONSENT STATEMENT

Not applicable because this study did not involve humans.

DATA AVAILABILITY STATEMENT

The data can be made available under request.

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CONFLICTS OF INTEREST

The authors declare no conflict of interest.

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