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Article

Boron topdressing fertilization in sweet cassava cultivars grown in sandy soil: effects on biomass, root yield, and boron uptake and removal

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ABSTRACT: Boron (B) is an important micronutrient for plant root growth and development. However, its benefits for cassava crops remain unknown. We evaluated the effects of B topdressing fertilization on the root yield, biomass, and B accumulation and distribution in five sweet cassava cultivars grown in sandy soil. A randomized block design in a 5 × 3 factorial scheme with four replicates was used. The treatments included five sweet cassava cultivars (IAC 576-70, BRS 396, BRS 399, Palito, and Precoce) and three B rates (0, 1, and 2 kg·ha^{-1}). BRS 399 and Precoce maintained stable biomass regardless of B application. IAC 576-70 increased whole plant and storage root biomass with 2 kg·ha^{-1} B, while the biomass of Palito decreased at this rate. Application of 1 kg·ha^{-1} B improved storage root biomass of the BRS 396 cultivar. BRS 399 cultivar responded positively to topdressing B fertilization; Precoce was unaffected; and 2 kg·ha^{-1} B was excessive in the Palito cultivar. B fertilization increased B uptake only in the Palito and IAC 576-70 cultivars, and B removal was the highest in the BRS 399 and Palito cultivars. Therefore, for soils with limited B availability, it is recommended to fertilize Palito and BRS 396 cultivars with a maximum of 1 kg·ha^{-1} B, and IAC 576-70 and BRS 399 cultivars with 2 kg·ha^{-1} B. These findings emphasize the need for cultivar-specific B fertilization to optimize cassava root production.

Key words: *Manihot esculenta,* boron concentration, carbohydrate remobilization.

INTRODUCTION

Cassava (*Manihot esculenta* Cranz) is the sixth most important crop worldwide, ranking only behind wheat, maize, rice, potatoes, and barley (Lebot 2009). This root crop is the main source of carbohydrates for millions of people in developing countries (Pushpalatha and Gangadharan 2020). In percentage terms, the growth of global cassava production from 1980 to 2015 is comparable to that of maize (Pushpalatha and Gangadharan 2020). However, the cassava yield in Brazil is still low, around 15 Mg·ha^{-1} (IBGE 2024). Brazil's low cassava root yield is due to several factors, including the use of low-quality planting material and landrace cultivars, the incidence of weeds, pests, and diseases, and a lack of investment in fertilization (Albuquerque et al. 2008, Rocha et al. 2021, Bonatti et al. 2022, Oliveira and Diamantino 2022, Saldanha et al. 2020). Therefore, a balanced nutrient supply is one of the ways that can contribute to improving the development and root yield of cassava crops.

Cassava crops take up large amounts of nutrients from the soil, the most important of which are nitrogen (N) and potassium (K) (Lorenzi et al. 1981). Despite being taken up in small amounts, micronutrients are essential for crops' proper growth and yield. Information on the response of cassava to boron (B) fertilization is scarce. B is a fundamental element for root growth and elongation because it plays a structural role in cell division (Gupta and Solanki 2013). The synthesis of carbohydrates in plants and the production of tubers are also affected by B supply (Lenka and Das 2019), with a direct relationship between B and sugar content and their transport in the plant (Gupta 2007). For example, in sweet potatoes and potato crops, B helps prevent tuber cracking and improves shape, color, and tuber yield (Byju et al. 2007, Gupta 2007, Lenka and Das 2019).

B deficiency in cassava crops is most visible in growth zones such as roots, which may not develop and cause apical root death (Hadi et al. 2023). Although cassava is tolerant to low B availability in the soil, its supply in deficient soils, even at low rates, increases root yield and starch content (Hadi et al. 2023, Howeler 2002, Lebot 2009, Sruthi et al. 2019). Cassava is usually grown in sandy soils (Aguiar et al. 2021), which may favor the appearance of B deficiency symptoms in plants. Acidic soils with low organic matter concentrations, leached soils, and highly sandy soils may be deficient in this nutrient (Fuentes-Lara et al. 2019, Gupta and Solanki 2013). Since cassava is typically grown in sandy soils, low B availability may limit the storage root yield.

Therefore, we hypothesized that B fertilization could enhance cassava crops' growth and root yield in B-deficient sandy soils. Therefore, this study aimed to evaluate the effects of B topdressing fertilization on storage root yield, biomass, and B accumulation and distribution in five sweet cassava cultivars grown in sandy soil.

MATERIAL AND METHODS

Site, soil, and climate

The trial was conducted in Ubirajara, São Paulo state, Southeastern Brazil (22°30'31"S, 49°39'45"W; 484 m above sea level) in a cassava farm of the Cooperativa Agroindustrial de Ubirajara from July 2020 to June 2021. According to the Köppen classification system, the region's climate is Cwa (tropical with dry winters and hot, rainy summers). The soil is predominantly red-yellow Ultisol with a sandy-loamy texture (Rossi 2017). The maximum and minimum temperatures and rainfall during the experiment are shown in Fig. 1.

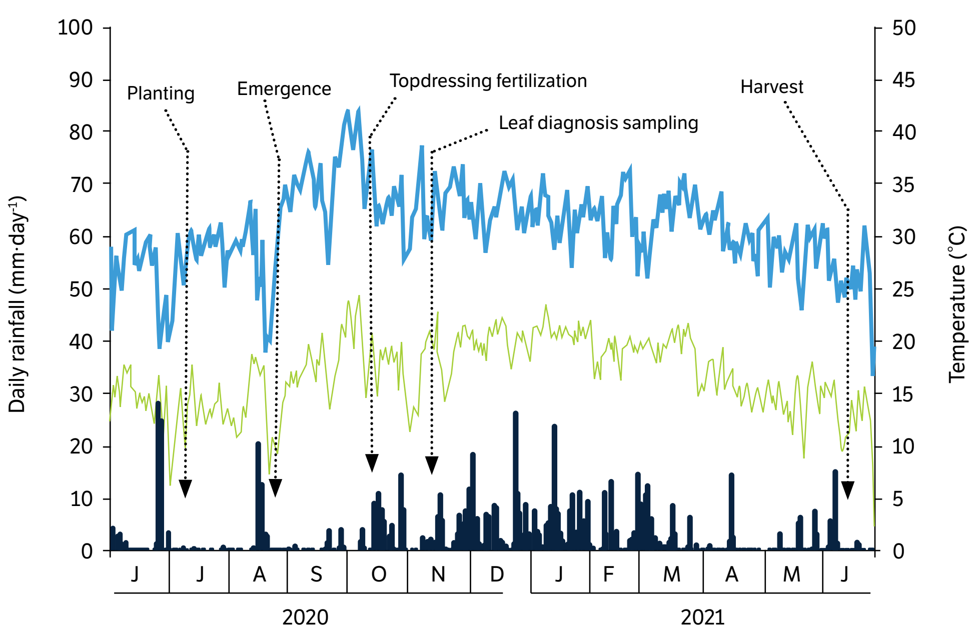

Figure 1. Daily rainfall (mm·day^{-1}), maximum (thick line), and minimum (thin line) temperatures in the experimental area during the period of cassava growing in Ubirajara, SP, Brazil. The moments of planting, emergence, topdressing, diagnostic leaves sampling, and harvest are indicated in the figure.

Experimental design, treatments, and cultivars

The experimental design was a randomized complete block in a 5 × 3 factorial scheme with four replicates. The treatments were represented by five sweet cassava cultivars (IAC 576-70, BRS 396, BRS 399, Palito, and Precoce) and three B rates (0, 1, and 2 kg·ha^{-1}). Each plot consisted of four 5-m-long rows spaced 1.10 m between rows and 0.75 m between plants. Eight plants per plot were evaluated from the two central plant rows.

The IAC 576-70 cultivar exhibits outstanding culinary qualities, including roots with yellow pulp, short cooking time, high yield, and harvesting after nine months of the cycle (Oliveira and Moraes 2009). Similarly, the BRS 396 and BRS 399 cultivars offer high root yield, roots with yellow pulp, fast cooking, and a shorter growing cycle, with harvest from seven to 14 months (FUNDAPAM 2025). Meanwhile, the traditional landraces Precoce and Palito, cultivated by farmers of Ubirajara, produce storage roots with yellow pulp and are harvested from nine to 14 months of cycle.

Soil tillage, cassava planting, and management

The cassava was cultivated in the experimental area during the previous growing season. Soil samples were collected from the experimental area at 0–20 and 20–40 cm depths in June 2020 for chemical analysis following the methodology proposed by Raij et al. (2001). The area did not receive liming because the base saturation was in the range indicated for cassava crops under Brazilian conditions, which is 50% (Table 1) (Lorenzi et al. 1997). The soil B and organic matter concentrations were low (B < 0.20 mg·dm^{-3}; organic matter < 15 g·dm^{-3}) at both depths (Raij et al. 1997, Sobral et al. 2015).

Table 1. Soil chemical characteristics in the experimental area at depths of 0–20 and 20–40 cm before cassava planting.

Soil characteristic	Depth (cm)	
	0–20	20–40
pH (1:2.5 soil/$CaCl_2$ suspension 0.01 mol·L^{-1})	4.9	4.6
Soil organic matter (g·dm^{-3})	11.0	10.0
Presin-extractable (mg·dm^{-3})	5.0	3.0
S-SO_4^{2-} (mg·dm^{-3})	3.0	6.0
K (mmol$_c$·dm^{-3})	1.0	0.64
Ca (mmol$_c$·dm^{-3})	10.5	5.5
Mg (mmol$_c$·dm^{-3})	7.5	3.5
Cation exchange capacity (mmol$_c$·dm^{-3})	32	24
Base saturation (%)	57	37
B (mg·dm^{-3})	0.15	0.20
Cu (mg·dm^{-3})	0.30	0.30
Fe (mg·dm^{-3})	11.00	5.50
Mn (mg·dm^{-3})	8.10	6.50
Zn (mg·dm^{-3})	1.10	0.30

The soil in the area was conventionally tilled by plowing with a disc plow (± 20-cm deep) followed by light harrowing. Planting fertilization was carried out with 264 kg·ha^{-1} of formulated N-P_2O_5-K_2O 4-30-10 + 7% Ca + 3% S. Therefore, 11 kg·ha^{-1} N, 79 kg·ha^{-1} P_2O_5, 26 kg·ha^{-1} K_2O, 18 kg·ha^{-1} Ca, and 8 kg·ha^{-1} S were applied.

Planting was mechanically performed on July 10, 2020, using a cassava planter-fertilizer (Bazuca II model from the Planticenter company). The stems were collected from the middle third of healthy plants that were approximately 12 months old. The planting depth was set at 10 cm. Crop emergence occurred on August 26, 2020, at 47 days after planting (DAP). On October 15, 2020 (98 DAP and 50 days after emergence–DAE), topdressing B fertilization was conducted according to the treatments by applying fertilizers to the soil surface approximately 10 cm from the base of the plant. Boric acid (17% B) was used as the source of B. During topdressing fertilization, all plots received 40 kg·ha^{-1} N, 44 kg·ha^{-1} S (ammonium sulfate, 20% N and 22% S), 60 kg·ha^{-1} K_2O (potassium chloride, 60% K_2O), and 2 kg·ha^{-1} Zn (zinc sulfate, 20% Zn and 16% S). The quantity of fertilizer containing micronutrients per treatment was calculated and weighed, and a known amount of washed and oven-dried sand was added to the measured volume. Subsequently, the mixture was homogenized and weighed, and plastic bags containing the mixture (fertilizer + sand) with the appropriate fertilizer amount per 5-m-long row in each plot were prepared. The mixture was homogenized in bags by agitation before being applied to each plot in the field.

Pest, disease, and weed control were performed according to the recommendations for crops in the region and the criteria adopted by the grower (Vidigal Filho et al. 2022). The cassava was harvested on June 17, 2021 (342 DAP, 295 DAE).

Plant sampling and analysis

On November 14, 2020 (127 DAP, 80 DAE), leaf samples were collected by removing the blades of the 20 youngest, fully expanded leaves (Lorenzi et al. 1997) from each plot to determine the B concentration according to the methodology proposed by Malavolta et al. (1997).

At harvest, the final plant population was evaluated in two central 4-m-long rows of each plot to obtain the mean final plant population. Eight plants in the two central 3-m-long rows from the useful area of each plot were removed. The plants were separated into shoots, planted stem cuttings, and storage roots. Storage roots from all plants were counted and classified as either marketable or unmarketable. The defect-free storage roots, measuring over 10 cm in length and exceeding 4 cm in diameter, were classified as marketable. Subsequently, all storage roots were weighed, and the total and marketable storage root yields were calculated by multiplying the weight per plant by the final plant population (9,466 plants·ha^{-1}).

All plant parts (shoots, planted stem cuttings, and storage roots) were weighed separately (fresh weight), and representative sub-samples of each plant part were separated and dried in a forced air circulation oven at 65°C for 96 hours. After drying, the samples were weighed again (dry weight), and each plant part's dry matter (DM) content was calculated. The amount of biomass (dry biomass) in each plant part was calculated using data on fresh weight per plant, DM content, and final plant population (9,466 plants·ha^{-1}). Biomass accumulation in the whole plant was obtained by summing the biomass in all plant parts.

The samples were ground in a steel mill with a 1-mm sieve and subjected to B analysis (Malavolta et al. 1997). The amount of B accumulated in each part of the plant was obtained by multiplying the B concentration by the amount of accumulated biomass. B uptake was calculated by summing the amount of B accumulated in each plant part, and B removal was defined as the amount of B accumulated in the storage roots. The B use efficiency (BUE) of cassava plants was calculated as described by Fernandes and Soratto (2013).

Data analysis

The data were subjected to an analysis of variance using the statistical software SISVAR (Ferreira 2011), and the means of the treatments were compared using the least significant difference test ($p < 0.05$).

RESULTS

Boron concentration in the diagnostic leaf

Leaf B concentration was affected by the cultivar and B application rate (Table 2). The BRS 399 and BRS 396 cultivars had the highest leaf B concentrations. In contrast, the Precoce cultivar had the lowest leaf B concentration (Fig. 2). The Palito and IAC 576-70 cultivars showed intermediate leaf B concentrations. Topdressing B fertilization with 2 kg·ha^{-1} B increased the leaf B concentration compared to the control, whereas treatment with 1 kg·ha^{-1} B resulted in intermediate concentrations of this nutrient in the leaves (Fig. 2).

Table 2. Analysis of variance (*p*-values) for cassava crop traits between the cultivar, boron application rate, and cultivar × boron application rate interactions.

Characteristics	Source of variation		
	Cultivar (C)	Boron rate (B)	C × B
Leaf B concentration	0.001	0.002	NS
Shoot B concentration	< 0.001	< 0.001	0.001
Planted stem cutting B concentration	< 0.001	0.001	< 0.001
Storage roots B concentration	< 0.001	< 0.001	0.020
Shoot biomass	< 0.001	0.013	0.021
Planted stem-cutting biomass	< 0.001	0.032	0.005
Storage root biomass	< 0.001	0.004	0.008
Whole plant biomass	< 0.001	NS	0.001
B uptake	< 0.001	0.003	< 0.001
B removal	< 0.001	< 0.001	0.046
B use efficiency	< 0.001	< 0.001	0.006
Total storage root yield	< 0.001	0.043	0.002
Marketable storage root yield	< 0.001	NS	0.004

NS: not significant.

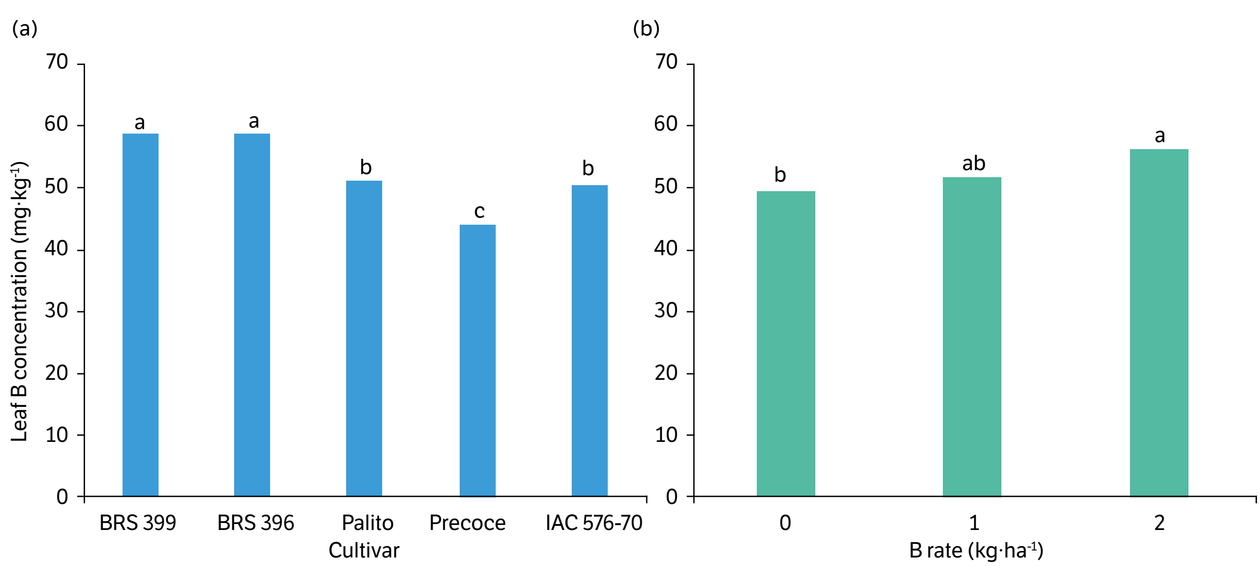

Figure 2. Effects of (a) cultivar and (b) boron (B) rate on B concentration in the diagnostic leaves of five cassava cultivars. Different letters indicate a significant difference between cultivar or B rates at $p < 0.05$ according to the least significant difference test.

Biomass yield and distribution, total and marketable storage root yield

The amount of biomass accumulated in different cassava plant parts was influenced by the cultivar × B application rate interaction (Table 2). The application of 1 or 2 kg·ha^{-1} B did not alter the shoot biomass of the BRS 396 and Palito cultivars, but it decreased the shoot biomass of the Precoce cultivar (Fig. 3a). In the IAC 576-70 and BRS 399 cultivars, shoot biomass was the lowest at rates of 1 and 2 kg·ha^{-1} B, respectively. Overall, in the control and 1 kg·ha^{-1} B treatments, the BRS 399 cultivar showed the highest shoot biomass, whereas the BRS 396 and Palito cultivars had the lowest values. At the 2 kg·ha^{-1} B rate, the BRS 399 and IAC 576-70 cultivars showed the highest shoot biomass, whereas the BRS 396 cultivars showed the lowest biomass.

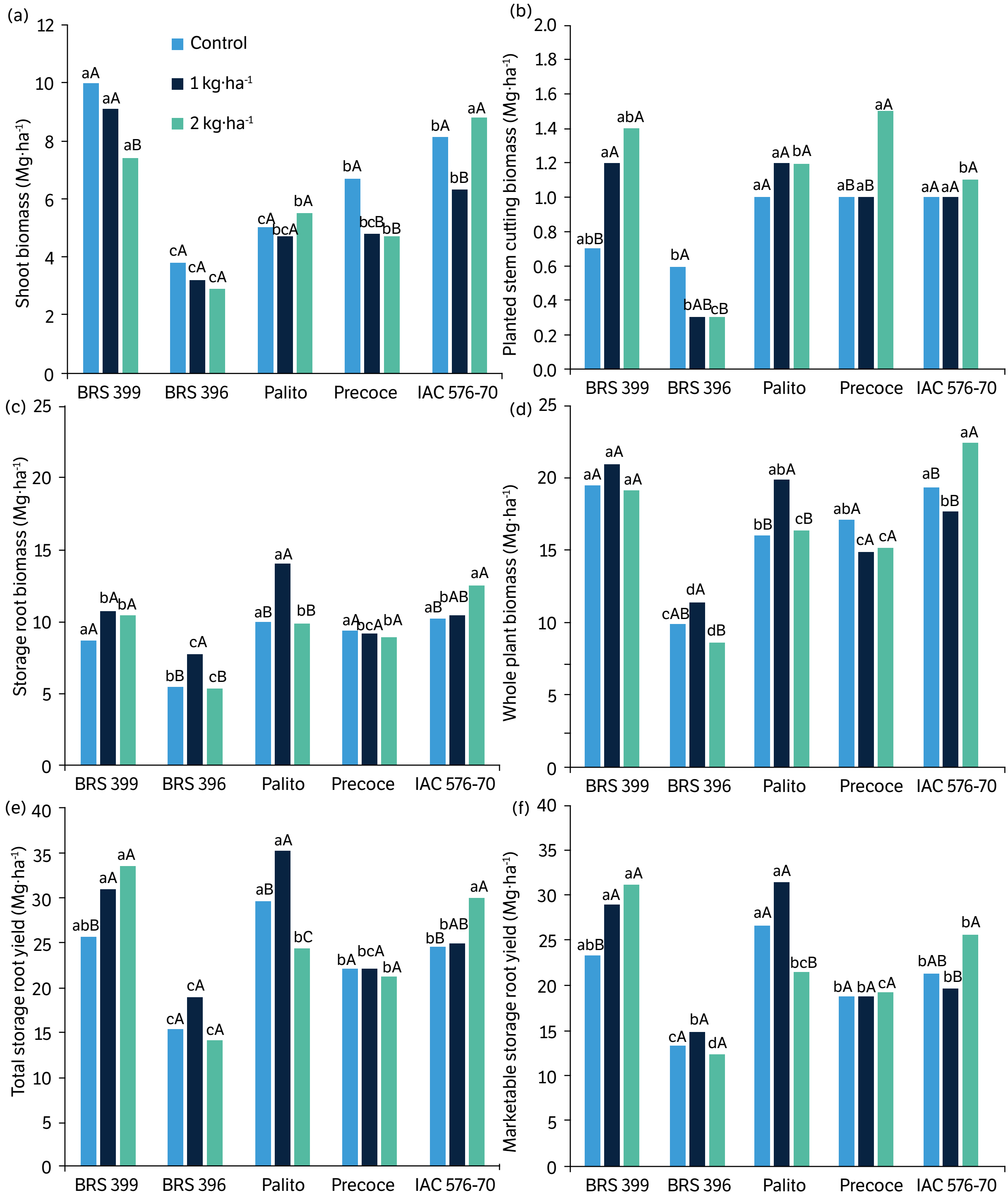

Figure 3. Cultivar × boron (B) rate interaction for biomass accumulation in the (a) shoot, (b) planted stem cutting, (c) storage roots, (d) whole plant, (e) total fresh storage root yield, and (f) marketable fresh storage root yield of five cassava cultivars. Different lowercase letters indicate a significant difference between cultivars in the same B rate, whereas different uppercase letters indicate a significant difference among B rates in the same cultivar at $p < 0.05$ according to the least significant difference test.

Boron supply did not affect biomass accumulation in the planted stem cuttings in the Palito and IAC 576-70 cultivars, while it increased in the BRS 399 and Precoce cultivars (Fig. 3b). In contrast, the application of 2 $kg{\cdot}ha^{-1}$ B decreased the planted stem-cutting biomass of the BRS 396 cultivar. The planted stem-cutting biomass was lower at all B rates in the BRS

396 cultivar. In contrast, the biomass of the other cultivars was similar, especially in the control and 1 $kg \cdot ha^{-1}$ B treatments. At the highest B application rate, the Precoce cultivar accumulated more biomass in planted stem cuttings than the BRS 396, Palito, and IAC 576-70 cultivars.

B supply did not affect the storage root biomass of BRS 399 and Precoce cultivars (Fig. 3c). The application of 1 $kg \cdot ha^{-1}$ B increased the storage root biomass of the BRS 396 cultivar, and the highest B application rate increased the storage root biomass of the IAC 576-70 cultivar compared with that of the control. The BRS 396 cultivar showed the lowest storage root biomass accumulation at all B application rates. In the control treatment, storage root biomass did not differ among the BRS 399, Palito, Precoce, and IAC 576-70 cultivars. Palito and IAC 576-70 cultivars had the highest storage root biomass at 1 and 2 $kg \cdot ha^{-1}$ B rates, respectively.

The whole-plant biomass of the BRS 399 and Precoce cultivars was not affected by the B application rates (Fig. 3d). The application of 2 $kg \cdot ha^{-1}$ B increased the plant biomass of the IAC 576-70 cultivar and decreased the plant biomass of the BRS 396 cultivar compared with the B rate of 1 $kg.ha^{-1}$. Applying 1 $kg \cdot ha^{-1}$ B increased the whole-plant biomass of the Palito cultivar. In general, the plant biomass of the BRS 399, Precoce, and IAC 576-70 cultivars did not differ from the control treatment and was greater than that of the BRS 396 cultivar. The BRS 399 and Palito cultivars showed the highest whole-plant biomass at the rate of 1 $kg \cdot ha^{-1}$ B. However, the plants with the highest biomass at the rate of 2 $kg \cdot ha^{-1}$ B were from the IAC 576-70 cultivar.

The total and marketable fresh storage root yields were affected by the cultivar × B rate interaction (Table 2). B application did not change the total and marketable fresh storage root yields in the BRS 396 and Precoce cultivars (Fig. 3e and 3f). In the Palito cultivar, a B application rate of 1 $kg \cdot ha^{-1}$ significantly increased the total fresh storage root yield without significantly altering the marketable storage root yield. Conversely, higher B application rates (2 $kg \cdot ha^{-1}$) reduced this cultivar's total and marketable storage root yields. In general, the highest total and marketable root yields in the BRS 399 and IAC 576-70 cultivars occurred at the 2 $kg \cdot ha^{-1}$ B rate. In the control and 1 $kg \cdot ha^{-1}$ B treatments, the total and marketable root yields of the Palito and BRS 399 cultivars were higher than those of the other cultivars. However, at the highest B rate, only the BRS 399 cultivar showed superior yields compared to the other cultivars. Overall, the lowest fresh storage root yields were observed in the BRS 396 cultivar, especially in the control and at the highest B application rate.

Boron concentration, uptake, removal, and use efficiency

The B concentration in the plant parts was affected by the cultivar × B application rate interaction (Table 2). Application of 1 or 2 $kg \cdot ha^{-1}$ B increased the B concentration in the shoots only in the Palito and IAC 576-70 cultivars (Fig. 4a). In the control, B concentrations in the shoots of the BRS 399 cultivar were higher than those in the shoots of the BRS 396 and Precoce cultivars. However, at the 1 $kg \cdot ha^{-1}$ B rate, Palito showed higher B concentrations in the shoots, whereas at the 2 $kg \cdot ha^{-1}$ B rate both Palito and IAC 576-70 cultivars showed the highest B concentrations in the plant shoots.

The application of B increased the B concentration only in the planted stem cuttings of the Palito and Precoce cultivars (Fig. 4b). Overall, in the control treatment, B concentrations in the planted stem cuttings were higher in the Precoce and IAC 576-70 cultivars, but, at the rate of 1 $kg \cdot ha^{-1}$, the highest B concentrations were observed in the Palito, Precoce, and IAC 576-70 cultivars. At the highest B application rate (2 $kg \cdot ha^{-1}$), the planted stem cuttings of the Palito cultivar showed higher B concentrations than the other cultivars.

The supply of B increased its concentration in storage roots only in the BRS 399, Palito, and Precoce cultivars (Fig. 4c). The B concentrations in the storage roots of the BRS 399, BRS 396, and Palito cultivars did not differ in the control treatment and were higher than those in the other cultivars. In general, at the rates of 1 and 2 $kg \cdot ha^{-1}$ B, the B concentration in the storage roots of the BRS 399 and Palito cultivars was higher than that in the other cultivars.

The amount of B taken up and removed, as well as the B-use efficiency of cassava, was affected by the cultivar × B rate interaction (Table 2). B fertilization did not increase B uptake in BRS 396 and Precoce cultivars (Fig. 4d). However, the application of 2 $kg \cdot ha^{-1}$ B decreased B uptake by the BRS 399 cultivar compared to the application of 1 $kg \cdot ha^{-1}$ B, but without differ from the control. The application of 2 $kg \cdot ha^{-1}$ B increased the amount of B taken up by the Palito and IAC 576-70 cultivars. IAC 576-70 cultivar took up the highest amount of B in the treatment fertilized with 2 $kg \cdot ha^{-1}$ B. The BRS 396 cultivar took up the lowest amount of B regardless of B fertilization. The Palito and Precoce cultivars took up intermediate amounts of B compared to the IAC 576-70 cultivar at the rate of 2 kg·ha^{-1}, the BRS 399 cultivar at rates of 0 and 1 kg·ha^{-1}, and the BRS 396 cultivar across B rates.

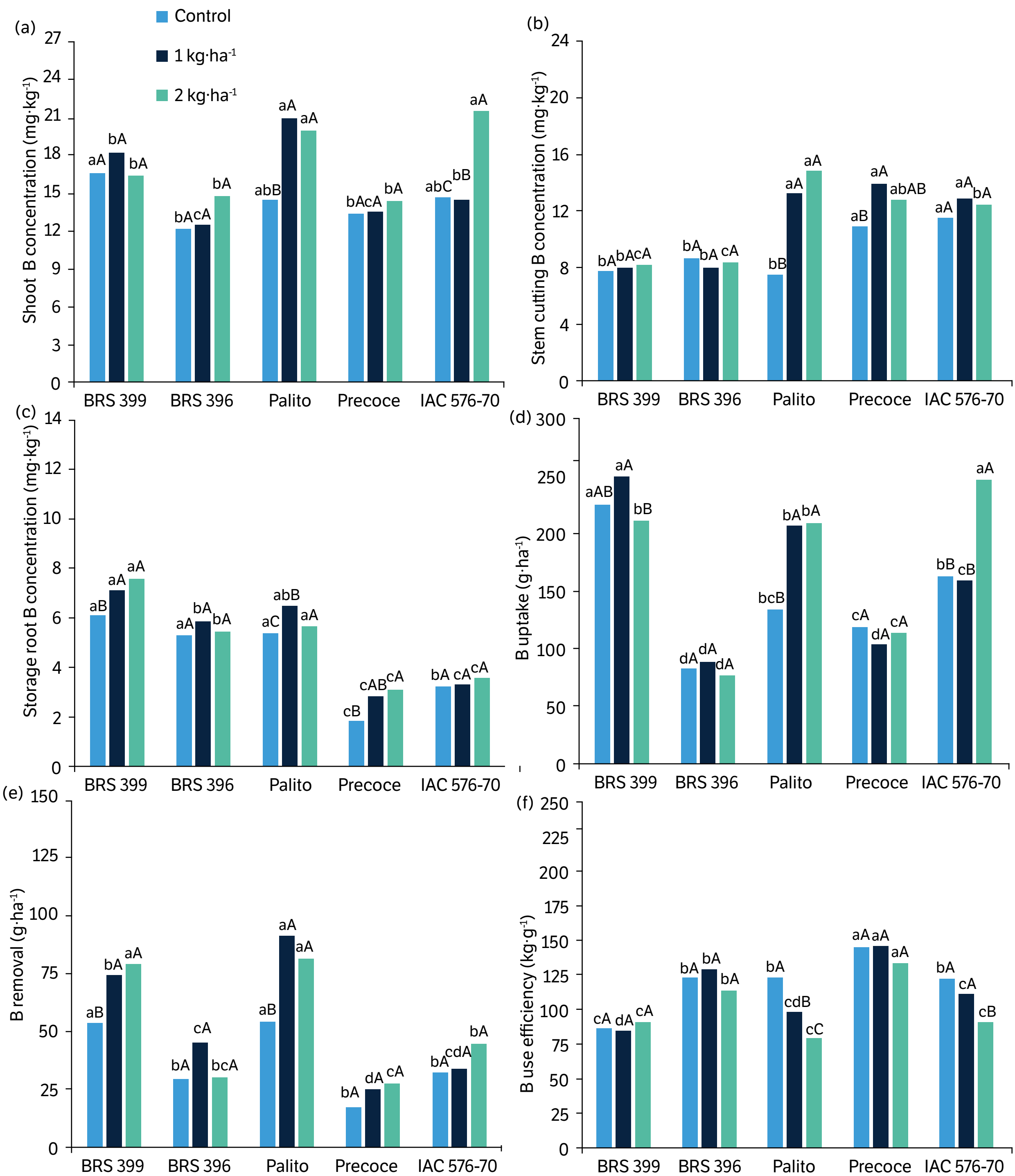

Figure 4. Cultivar × boron (B) rate interaction for B concentration in the (a) shoot, (b) planted stem cutting, and (c) storage roots, (d) B uptake, (e) B removal, and (f) B use efficiency for biomass yield in five cassava cultivars. Different lowercase letters indicate a significant difference between cultivars in the same B rate, whereas different uppercase letters indicate a significant difference among B rates in the same cultivar at $p < 0.05$ according to the least significant difference test.

Only the BRS 399 and Palito cultivars exhibited increased B removal in response to B fertilization (Fig. 4e). In the control and 2 $kg \cdot ha^{-1}$ B treatments, B removal by the BRS 399 and Palito cultivars was higher than that by the other cultivars. At the rate of 1 $kg \cdot ha^{-1}$ B, B removal by the Palito cultivar exceeded that of the other cultivars. The lowest B removal occurred in the Precoce cultivar when 1 or 2 $kg \cdot ha^{-1}$ B was applied.

The increase in B application did not alter the BUE of BRS 399, BRS 396, and Precoce cultivars. However, in the Palito and IAC 576-70 cultivars, there was reduction in BUE with the application of the highest B rates (Fig. 4f). The highest BUE at all B rates occurred in the Precoce cultivar. In contrast, the BRS 399 cultivar showed the lowest BUE at 0 and 1 $kg \cdot ha^{-1}$ B rates. The lowest BUE at the highest B application rate was observed in the BRS 399, Palito, and IAC 576-70 cultivars.

DISCUSSION

Evaluating the nutrient concentration in the diagnostic leaves allowed us to determine whether the amount of nutrients supplied through fertilization was sufficient to adequately nourish the plants. Although B concentrations in the leaves of the Palito, Precoce, and IAC 576-70 cultivars were lower than those in the BRS 399 and BRS 396 cultivars, only the leaf B concentration range in the Precoce cultivar was considered adequate for cassava (15–50 $mg \cdot kg^{-1}$; Feltran et al. 2022). In the other cultivars, leaf B concentrations were above the adequate range. However, no visual symptoms of B toxicity were observed in any cultivar throughout the developmental cycle. Even with low B availability in the soil (< 0.20 $mg \cdot dm^{-3}$; Raij et al. 1997), the leaf B concentrations were considered adequate for the crop, and it was necessary to apply 2 $kg \cdot ha^{-1}$ B to increase the leaf B concentrations by 14%. This may indicate that cassava is tolerant to low B availability in the soil (Aprianti et al. 2022), as deficiencies are uncommon in the field (Howeler et al. 1982). This suggests that the leaf B concentration range for cassava must be updated. Howeler et al. (1982) linked symptoms of B deficiency in cassava with leaf concentrations below 30 $mg \cdot kg^{-1}$ B and toxicity symptoms with leaf concentrations above 100 $mg \cdot kg^{-1}$ B. Furthermore, variations in leaf nutrient concentrations have been observed in the literature and the present study (Burns et al. 2012, Imakumbili et al. 2020).

In the present study, biomass accumulation in cassava plants was affected differently by B topdressing fertilization in the cultivars (Table 2). The BRS 399 and Precoce cultivars maintained the whole plant, and storage root biomass accumulation unchanged regardless of B supply. The B supply did not alter the BUE of these cultivars either, indicating that biomass production per unit of B taken up did not change with increased nutrient availability.

In contrast, the whole plant and storage root biomass of IAC 576-70 were greater when 2 $kg \cdot ha^{-1}$ B was applied, indicating that this cultivar was more responsive to B topdressing fertilization than cultivars Palito and BRS 396. B plays a role in cell division and promotes shoot development and root elongation (Dear and Weir 2004). Therefore, if a cultivar has a high demand for B, an adequate supply is essential to increase root development. The whole plant and storage root biomass of the Palito cultivar was unaltered by applying 2 $kg \cdot ha^{-1}$ B, but increased under the 1 $kg \cdot ha^{-1}$ B supply. This showed that increasing the B supply beyond 1 $kg \cdot ha^{-1}$ did not enhance biomass production in the Palito cultivar. Being a landrace, the Palito cultivar may lack the genetic adaptations necessary to effectively demand by high B supply, resulting in a limited response to fertilization. A higher B supply in the Palito cultivar reduced the BUE without increasing plant growth (Figs. 3c, 3d, and 4f). Forno et al. (1979) also found that high B supply reduced the growth of cassava plants, with an effect related to lower shoot biomass production.

In the BRS 396 cultivar, only 1 $kg \cdot ha^{-1}$ B was sufficient to increase storage root biomass, indicating a lower B requirement, despite being a cultivar considered to be a shorter cycle (FUNDAPAM 2025). Other studies have shown that the B supply is crucial for increasing cassava plant biomass (Forno et al. 1979), but our results indicated that the demand for B can vary across cultivars. For example, despite showing the highest BUEs under all three B availability conditions, the Precoce cultivar did not accumulate the most biomass or have the highest fresh storage root yield. The lower production of plant biomass or fresh storage roots may be because this cultivar has not been genetically improved for these traits.

Despite the growth being altered by the B application, there was no increase in B uptake in the BRS 396, Precoce, and BRS 399 cultivars in response to the B application. Generally, the amounts of B taken up by cassava plants ranged from 75.8 to 249.3 g·ha^{-1}. B uptake values between 157.4 and 430.8 g·ha^{-1} were observed by Parry et al. (2005) in different planting seasons and residual fertilization treatments. Other studies have indicated that the nutrient uptake rate increases with B fertilization (Aprianti et al. 2022), but we observed this only in some cultivars. For example, in the Palito and IAC 576-70 cultivars, the application of B increased its uptake by plants. At the highest B application rate, the IAC 576-70 cultivar took up more B than the other cultivars. However, under a low B supply, the BRS 399 cultivar showed the highest B uptake.

Therefore, the lack of growth response in the BRS 399 cultivar to B application may be related to its greater capacity for B uptake under deficient soil conditions, as it did not show the highest B-use efficiencies. The mineralization of organic matter may have contributed to the B supply for cassava cultivars because organic matter can be a significant source of B for plants in soils with low B availability (Bell et al. 2002).

In this study, this contribution may have been high despite the low initial soil organic matter concentration (< 15 g·dm^{-3}; Sobral et al. 2015) (Table 1). Organic matter can bind up to 8.6% of the total soil B concentration (Fontes et al. 2001). Thus, organic matter decomposition in 40 cm of topsoil, where 63.6% of the absorbent cassava roots are concentrated (Souza et al. 2006), could release up to 0.9 mg·dm^{-3} B. This potential for B release may have partially supplied the demand for B in cassava crops, reducing its response to B fertilization.

The BRS 399 cultivar showed a fresh storage root yield similar to that of the Palito cultivar at the lowest B supply rates, but greater than that of the Precoce cultivar at all B supply rates. Furthermore, when the highest B application rate (2 kg·ha^{-1}) was applied, the marketable storage root yield of the BRS 399 cultivar was higher than that of the other cultivars. This response may be related to the shorter cycle of this cultivar (FUNDAPAM 2025). Each cultivar's genetic traits lead to different storage root yield levels (Fuhrmann et al. 2019, Mendonça et al. 2020). However, in this study the cultivars respond differently to B supply in B-deficient soils, probably due to differences in the growth cycle and volume of soil exploration by the absorbent root system, capable of absorbing the mineralized B from soil organic matter. For example, in the BRS 396 and Precoce cultivars, B topdressing fertilization did not increase the marketable storage root yield.

In contrast, in the Palito cultivar, a high B supply reduced the marketable storage root yield. These results indicated that the BRS 399 cultivar was more responsive to topdressing B fertilization regarding fresh storage root yield. The Precoce cultivar did not respond to B supply, and the rate of 2 kg·ha^{-1} B was excessive for the storage root yield of the Palito cultivar. However, at this rate, it took up the same amount of B at the rate of 1 kg·ha^{-1}, which significantly improved the storage root yield; this indicates that, although a higher B application rate did not increase B uptake, it decreased BUE and was excessive for the storage root yield of the Palito cultivar. Howeler et al. (1982) achieved a storage root yield of 60 Mg·ha^{-1} with the application of 1 kg·ha^{-1} B, but in a study carried out by Hadi et al. (2023) storage root yield of 10 cassava genotypes increased only up to a rate of 0.79 kg·ha^{-1} B and decreased at higher B rates, i.e., results similar in part to those obtained for the Palito cultivar in this study.

Nutrient removal depends on storage root yield levels, dry matter content of the storage roots, and soil fertility (Howeler 1991), which are reflected in the nutrient concentrations in the plant parts. B removal increased with topdressing fertilization only in the BRS 399 and Palito cultivars, which consistently removed more B than the BRS 396, Precoce, and IAC 576-70 cultivars across all B rates. The increased B removal in the BRS 399 cultivar resulted from increased root B concentration and yield. In contrast, in the Palito cultivar, an increase in root B concentration had a greater effect on B removal. Forno et al. (1979) observed an increase in B removal in response to increased B application rates in cassava crops, as it was verified in the present study for some cultivars. Generally, B concentrations in cassava storage roots are lower than those in the shoots under conditions of low B supply. However, under high B supply, storage root B concentrations can increase and become higher than those in plant shoots (Forno et al. 1979). In this study, B removal ranged from 17.5 to 92 g·ha^{-1} depending on the cultivar and B fertilization rate applied, i.e., values lower than the mean values of 132.6 and 134.2 g·ha^{-1} obtained by Parry et al. (2005) for the Olho Verde cultivar.

CONCLUSION

BRS 399 and Precoce cultivars maintained stable biomass regardless of B supply. IAC 576-70 cultivar increased storage root and plant biomass with 2 kg·ha^{-1} B, while the biomass of Palito cultivar decreased at this rate. Root biomass of BRS 396 cultivar improved with 1 kg·ha^{-1} B.

BRS 399 cultivar responded positively to B topdressing, Precoce remained unaffected, and Palito was negatively impacted by 2 kg·ha^{-1} B. B uptake increased significantly by B supply only in the Palito and IAC 576-70 cultivars. B removal was the highest in the BRS 399 and Palito cultivars driven by increases in root yield or B concentration in the storage roots.

This study highlighted significant cultivar-specific variation in B uptake (75.8 to 249.3 g·ha^{-1}) and removal (17.5 to 92 g·ha^{-1}). Therefore, for soils with limited B availability, it is recommended to fertilize Palito and BRS 396 cultivars with a maximum of 1 kg·ha^{-1} B, and IAC 576-70 and BRS 399 cultivars with 2 kg·ha^{-1} B. These findings emphasize the need for cultivar-specific B fertilization to optimize cassava root production.

CONFLICT OF INTEREST

Nothing to declare.

AUTHORS' CONTRIBUTION

Conceptualization: Piroli, V. L. B. and Fernandes, A. M.; **Methodology:** Piroli, V. L. B., Silva, R. M., Guedes, P. T. P., Figueiredo, R. T. and Rodrigues, F. E.; **Investigation:** Silva, R. M., Guedes, P. T. P. and Figueiredo, R. T.; **Writing – Original Draft:** Piroli, V. L. B. and Rodrigues, F. E.; **Writing – Review and Editing:** Fernandes, A. M. and Piroli, V. L. B.; Su**pervision:** Fernandes, A. M.; **Final approval:** Fernandes, A. M.

DATA AVAILABILITY STATEMENT

Data will be made available on request.

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