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Soil boron fertilization: the role of nutrient sources and rootstocks in citrus production

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Abstract

Boron (B) is a key element for citrus production, especially in tropical regions, where the nutrient availability is commonly low in the soil. In addition, information about doses, fertilizer sources, methods of application and, particularly, differential nutrient demand of scion/rootstock combinations are required for efficient fertilization of commercial groves. In a non-irrigated sweet orange orchard (*cv.* Natal), grafted onto Rangpur lime, Swingle citrumelo or Sunki mandarin, we studied the application of two sources of B: boric acid (17% B, soluble in water) and ulexite (12% B, partially soluble in water) at four levels of supply (control without B, and soil application of 2, 4 and 6 kg ha^{-1} yr^{-1} of B). The experiment was carried out for three years. Boron availability in the soil and concentration in the leaves, as well as the fruit yield and quality of trees were evaluated. Soil B extracted with hot water and total leaf B positively correlated with doses of the nutrient applied to the trees. Levels of B in the soil and in the leaves did not vary with fertilizer sources. Fruit yield of trees grafted onto Rangpur lime and Swingle citrumelo was more responsive to B doses than those grafted onto Sunki mandarin. Maximum fruit yield of trees grafted onto Swingle was obtained with 3.2 kg ha^{-1} yr^{-1} of B, and leaf B level of 280 mg kg^{-1} what point out to a highest demand for B when this combination was compared with other rootstocks. Furthermore, fertilization with B did not affect the quality of fruits, but correlated with B and potassium (K) concentrations in the leaves. These results also support that the current recommendations for levels of B in leaves should be revisited.

Keywords: boric acid, ulexite, fertilization via soil, leaf analysis, fruit quality, citrus

1. Introduction

Boron (B) deficiency has affected a significant area of citrus orchards in the world (Liu *et al.* 2014; Zhou *et al.* 2014; Wang *et al.* 2015), especially those in the tropical regions. This is a consequence of lower availability of this nutrient in soil and longer periods of drought or excess rainfall, which reduce the absorption of this nutrient by plants (Huang *et al.* 2005). In recent years, the citriculture in the State of São Paulo, the major producing region in Brazil, has moved to less traditional growing region in the South, where temperatures are milder and rainfall more abundant, compared to the North and Northwest. In such new area, plant transpiration rates are lower and, consequently, the

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B deficiency is more severe.

B absorbed by roots is transported *via* xylem, mostly driven by plant transpiration, and then distributed to all plant tissues (Huang *et al.* 2005; Mertens *et al.* 2011; Wimmer and Eichert 2013; Mesquita *et al.* 2016). However, this nutrient exhibits low mobility in the phloem of citrus (Boaretto *et al.* 2008) and, consequently, limited redistribution in the trees (Liu *et al.* 2012). Such characteristic interferes with the definition of best nutrient management practices in orchards (Mattos *et al.* 2005). Basing on the closed correlation beg tween the dose of B applied to the soil and the fruit yield of sweet oranges (*Citrus sinensis* (L.) Osbeck), maximum fruit yield is estimated at a dose of 4 kg ha^{-1} of B and soil levels at ~1.0 mg dm^{-3} of B in the 0–20 cm depth layer (Quaggio *et al.* 2003). Moreover, the application of B on the soil is more efficient than leaf fertilization (Boaretto *et al.* 2011). Taking these information together, official guidelines for nutrient recommendation for citrus growers has been revised and B supply via soil in citrus orchards recommended. Thereafter, more data on nutrient sources and horticultural responses of rootstock varieties are still required to improve the efficiency of soil B applications.

Borax ($Na_2B_4O_7 \cdot 10H_2O$) and boric acid (H_3BO_3) are the most common fertilizers that contain B, which are soluble in water. Others, such as ulexite ($NaCaB_5O_9 \cdot 8H_2O$) and colemanite ($Ca_2B_6O_{11} \cdot 5H_2O$) are less soluble in water (Bell and Dell 2008; Abat *et al.* 2015). Then, different water solubility of these sources could be important for management of fertilization, since soil application of the more soluble sources could increase the risk of B losses from the soil profile by leaching (Brennan *et al.* 2015; Sá and Ernani 2016) or cause toxicity when applied in high doses in regions with low rainfall (Gimeno *et al.* 2012).

The availability of a micronutrient for agricultural crops is determined primarily by the texture, pH and the content of organic matter in the soil, as well the water availability for the plants. Over the last few decades there has been a necessity to substitute the rootstocks commonly used in the Brazilian citriculture, such as the Rangpur lime and Volkamer lemon (*C. volkameriana* V. Ten. & Pasq.), due to diseases that appeared during the 1970s and late 1990s, for example citrus blight and citrus sudden death (Bassanezi *et al.* 2003). Swingle citrumelo (*C. paradisi* Macfad.×*Poncirus trifoliata* (L.) Raf.) and the mandarins Cleopatra (*C. reshni* hort. ex Tanaka) and Sunki (*C. sunki* (Hayata) hort. ex Tanaka) are tolerant to these diseases (Pompeu and Blumer 2008).

Besides rootstock varieties optimize plant tolerance to biotic and abiotic stresses (Syvertsen and Garcia-Sanches 2014), they also affect physiological and nutritional characteristics of trees (Quaggio *et al.* 2010; Hippler *et al.* 2016; Mesquita *et al.* 2016). In sweet oranges, a higher nutritional demand for B was verified when scions were grafted onto Swingle compared to Rangpur lime (Boaretto *et al.* 2008; Mattos *et al.* 2008). Additionally, observations taken from commercial citrus orchards showed that B deficiency symptoms were more frequent in trees grafted onto Swingle. Poorly developed plants characterize these symptoms, which also present small leaves on shortened branches coming from excessive sprouting of axillary buds due to the loss of stem apical dominance (Mattos *et al.* 2005; Liu *et al.* 2012). Fruits from deficient trees can also appear deformed and prematurely drop off (Wang *et al.* 2015).

The present research tested the hypothesis that differences in the water solubility of B fertilizer sources and the horticultural characteristics of the rootstocks affect fruit yield of orange trees in response to B applied via soil. Therefore, this study was carried out with the objective to evaluate the fertilization efficiency with B applied to the soil surface at four doses of the nutrient supplied by two sources and the fruit yield of sweet orange trees grafted onto three different rootstocks. We also sought to establish calibration curves between soil and leaf analyses, and fruit quality and production of orange trees.

2. Material and methods

The experiment was carried out in the municipality of Bebedouro-SP, 20°54´30.5´´ S, 48°30´57.34´´ W, in a dystrophic Oxisol with a medium texture (pH ($CaCl_2$)=5.7; cation exchange capacity (CEC)=55 mmol$_c$ dm^{-3} and B=0.2 mg dm^{-3} in the 0–20 cm soil layer). Before setting up the experiment, dolomitic limestone was applied (acid neutralizing capacity of 70%) to elevate the soil base saturation to 70% (Quaggio *et al.* 2010). The climate in the region by the Köppen classification is Cwa, a dry winter and a hot and humid summer with an average annual temperature of ≥23°C.

The experiment was set up in a three-year-old orchard of sweet orange trees *cv.* Natal (*C. sinensis* (L.) Osbeck), planted at 7 m×4 m and grafted onto the rootstock Rangpur lime (*C. limonia* Osbeck), Swingle citrumelo (*P. trifoliata* (L.) Raf.×*C.paradisi* Macf.) or Sunki mandarin (*C. sunki* (Hayata) hort. ex. Tanaka). The treatments were constituted by the three rootstock varieties distributed in blocks; two sources of the fertilizer containing B, applied to the soil [boric acid (H_3BO_3) and ulexite ($NaCaB_5O_9 \cdot 8H_2O$)) and four doses of the micronutrient (control without B, 2, 4 and 6 kg ha^{-1} yr^{-1}; or 5.5, 11.0 and 16.5 g tree^{-1}, respectively). The experiment was set up in a 3×2×4 factorial design with four replicates, each consisting of 24 plants. The experimental plots defined by three planting rows, with six trees each; the four central trees from each plot were used to assess the studied variables.

The doses of B were evenly distributed onto the soil surface in a 1.5 m wide fertilization band on both sides of the tree, and the total dose was split and applied three times during the year: from beginning the spring to the end of summer. The sources of the fertilizer were analyzed to estimate the total concentration and the proportion of the nutrient that was soluble in water (Vale and Alcarde 1999). Boric acid presented a total concentration of 17.5 and 17% soluble in water, whereas ulexite had a total concentration of 12%, but only 3% soluble in water. Orchard fertilization, with the exception of B, followed the recommendations of Quaggio *et al.* (2010).

The evaluations were made in the second and third years after fertilization containing B was initiated. The first fruit harvest was not considered due to the relatively young age of the orchard, as the largest variations occur in young trees.

Each year at the end of the summer (March–April), leaf samples were collected from the intermediate part of the tree from branches that had one terminal fruit (~3 cm in diameter), for chemical analyses to determine total nutrient levels (Bataglia *et al.* 1983). Soil samples were taken each year in July from the 0–20 cm, 20–40 and 40–60 cm soil depth layers and chemically analyzed (Raij *et al.* 2001). In the third year, soil samples were also taken from the 80–100 cm layer only in those plots that received B doses of 2 and 6 kg ha^{-1} yr^{-1}. To determine B in the soil, we used the hot water extraction method according to Abreu *et al.* (1994).

Fruit quality was assessed by sampling five oranges per tree, in a total of 20 fruits per plot, to determine fresh weight, mean height and width, juice percentage, acidity, soluble solids (SS) (°Brix), SS/acidity ratio and yield of SS per 40.8 kg box (Redd *et al.* 1992).

The studied variables were analyzed using variance analysis (rootstock, B Sources and B Doses) and their interactions using the F test. Regressions with simple correlation analysis were used to describe relationships between variables.

3. Results

The level of B in the soil increased linearly as the fertilizer dosage increased along two years of evaluation, reaching 2.8 mg dm^{-3} in the 0–20 cm layer, with the application of 6 kg ha^{-1} yr^{-1} of B (Fig. 1). In the control treatment, which did not receive fertilization with B, the levels extracted in hot water were similar to those observed in the initial analysis of the experimental area: approximately 0.3 mg kg^{-1} (Fig. 1). Soil application, in both cases (boric acid and ulexite), produced similar increases in the extractable B levels in the soil profile, independent of the dose applied (Fig. 1).

Four years after starting B applications, micronutrient movement through the soil profile was observed increasing the fertilization level in a direct proportion to the tested doses (Figs. 1 and 2) and independently of the fertilizer sources.

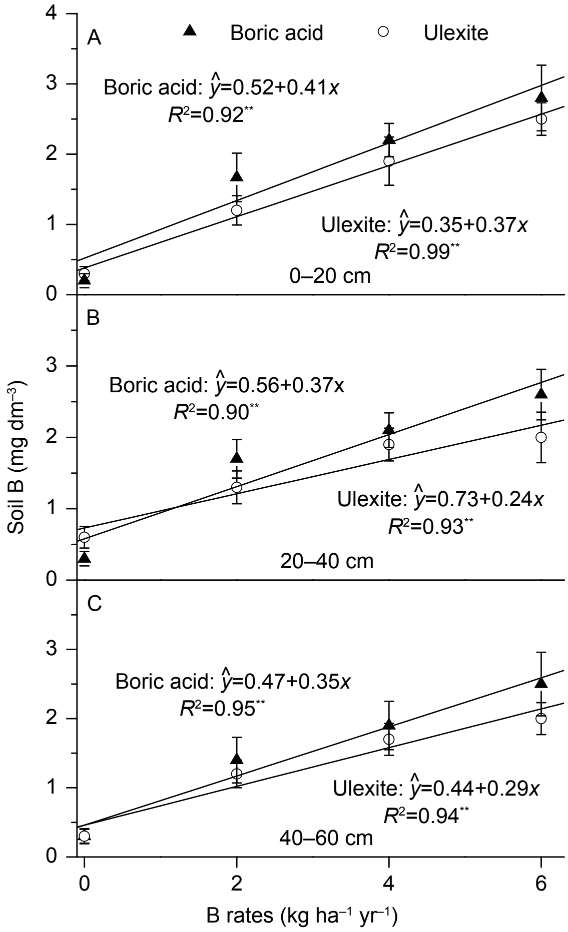

Fig. 1 Soil level of boron (B)(mean values for each rootstock over two years) in the 0–20 cm (A), 20–40 cm (B) and 40–60 cm (C) layers after the application of different sources and doses of the nutrient onto the soil. The vertical bars represent the standard deviation of the mean (n=24). **, p<0.01.

With application of 2 kg ha^{-1} yr^{-1} of B was applied, the B level in the topsoil (0–20 cm) was 1.3 mg dm^{-3} reaching 0.7 mg dm^{-3} in the deepest layer sampled (80–100 cm). On the other hand, when 6 kg ha^{-1} yr^{-1} of B was applied, the levels of B were twice as high (2.7 mg dm^{-3}) in the superficial layer and approximately three times higher (2.1 mg dm^{-3}) in the 40–60 cm layer when compared to the treatment that received 2 kg ha^{-1} yr^{-1}. Moreover, at 6 kg ha^{-1} yr^{-1} of B, the levels found in the 40–60 cm layer were similar to those in the 80–100 cm layer (Fig. 2).

Correspondingly to that verified in the soil, the average increase in the level of B in the leaves for the rootstock was linear with the increase in the dose of the nutrient applied: control treatment (65 mg kg^{-1}), 2 kg ha^{-1} yr^{-1} (186 mg kg^{-1}), 4 kg ha^{-1} yr^{-1} (~300 g kg^{-1}) and 6 kg ha^{-1} yr^{-1} (>400 mg kg^{-1}). There was no difference between the sources with respect to B levels in the leaves; however, trees grafted onto Sunki presented lower levels in the leaves (208 mg kg^{-1})

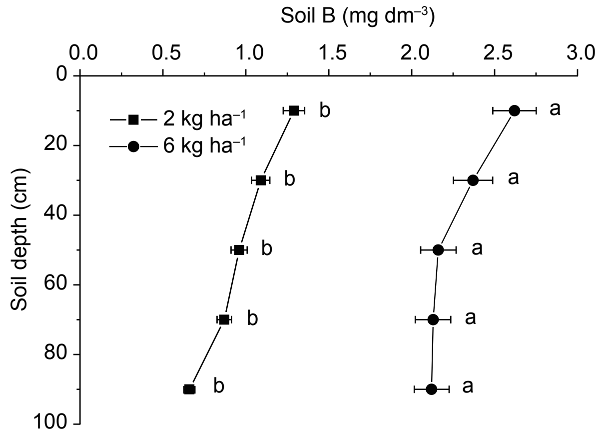

Fig. 2 Concentration of B in the soil (extracted with hot water) at different depths in the second year of evaluation after fertilizer application to the soil. Horizontal bars represent the standard deviation of the mean of the sources of boron (n=24).

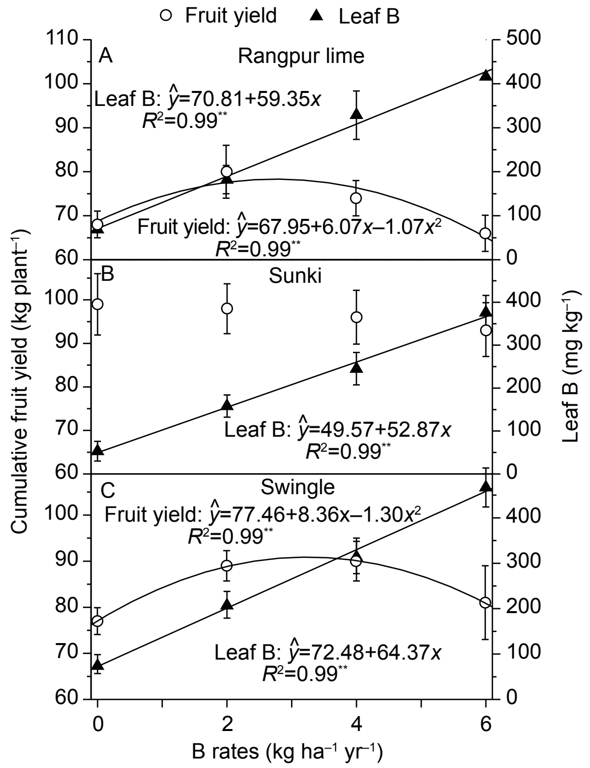

Fig. 3 The relationship between the doses of boron (B) applied to the soil, the accumulated fruit production over the two years of evaluation and the level of the nutrient in the leaves of the Natal sweet orange grafted onto: A, Rangpur lime; B, Sunki mandarin; C, Swingle citrumelo. Vertical bars represent standard deviation of the mean (n=16). **, p<0.01.

when compared to those grafted onto Rangpur lime (249 mg kg^{-1}) or Swingle citrumelo (266 mg kg^{-1}) (p<0.05), using data pooled across the B fertilizer doses observed during the two years of analyses (Fig. 3).

Trees grafted onto Sunki produced the greatest fruit yields during the experimental period, with the average of the treatments being 51.0 kg per tree yr^{-1}. Those grafted onto Swingle produced an intermediate average yield of 42.2 kg per tree yr^{-1}, while those onto Rangpur lime produced the lowest average yield of 36.0 kg per tree yr^{-1} (p<0.05). On the other hand, there was a difference between the rootstocks regarding response to B; the maximum average yield occurred at 2.8 kg ha^{-1} yr^{-1} for trees on the Rangpur lime and 3.2 kg ha^{-1} yr^{-1} for those onto Swingle, which corresponded to leaf levels of 230 and 280 mg kg^{-1} of the nutrient, respectively. No significant difference was observed between the doses for those grafted onto Sunki (Fig. 3).

Similarly to the levels in leaves and soil, no effect of the fertilizer source was observed on fruit yield of trees grafted onto either rootstocks (Fig. 3). A positive correlation was observed between the levels of B and potassium (K) in the leaves for all the rootstocks studied (Fig. 4). No parameter for fruit quality was altered for either of the two fertilizer sources. The reduction in fruit size (height and width) and weight, and an increase in acidity from the first to the second year of evaluation likely resulted from seasonal weather patterns (Table 1).

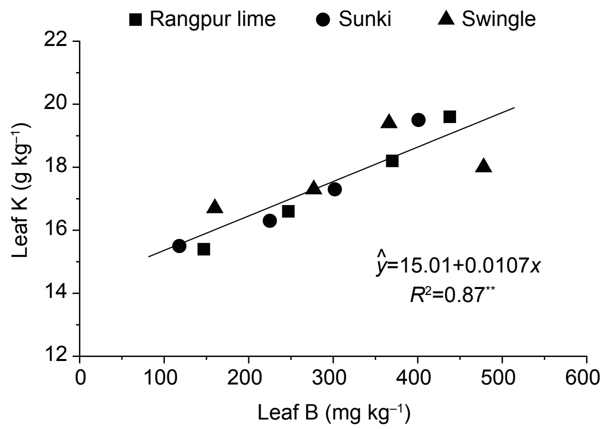

Fig. 4 The relationship between the levels of boron and potassium (K) in the leaves of the Natal sweet orange grafted onto different rootstocks and the application of different sources and doses of B via soil. Mean values for two years of evaluation (n=64). **p<0.01.

4. Discussion

Regardless of the fertilizer source, the application of B produced a linear increase in the level of the micronutrient available in the soil profile (Fig. 1). The mobility of B in the deeper soil layers was not limited by the adsorption of the

Table 1 Fruit quality of the Natal sweet orange grafted onto different rootstock varieties after the application of different sources and doses of boron (B) via soil over two years

	Weight (g fruit^{-1})	Height (cm)	Width (cm)	Juice (%)	Acidity (mg 100 mL^{-1})	SS (°Brix)[1)]	Ratio	SS/box (kg)[2)]
Period								
Year 1	208	7.5	7.3	51.4	0.757	11.6	15.5	2.44
Year 2	182	6.7	6.6	53.1	0.900	10.1	11.5	2.19
Rootstock								
Rangpur lime	191	7.1	6.9	52.3	0.755	10.8	14.9	2.30
Sunki	196	7.1	6.9	53.0	0.809	10.8	13.6	2.34
Swingle	197	7.1	7.0	51.4	0.922	10.9	12.1	2.29
Source								
Boric acid	195	7.1	7.0	52.1	0.826	10.8	13.6	2.30
Ulexite	194	7.1	6.9	52.3	0.830	10.9	13.4	2.32
Doses (kg ha^{-1} yr^{-1} of B)								
Control without B	196	7.1	6.9	52.5	0.851	10.9	13.3	2.34
2	195	7.1	7.0	52.5	0.834	10.9	13.5	2.32
4	194	7.1	6.9	52.6	0.821	10.7	13.5	2.30
6	194	7.1	7.0	51.4	0.807	10.8	13.8	2.27
F test								
Period	*	*	*	ns	*	ns	ns	ns
Rootstock	ns	ns	ns	ns	ns	ns	ns	ns
Source	ns	ns	ns	ns	ns	ns	ns	ns
Dose	ns	ns	ns	ns	ns	ns	ns	ns

[1)] SS, soluble solids.
[2)] SS/box, yield of soluble solids per box (40.8 kg).
ns, *, nonsignificant and significant at 5% by F test, respectively.

nutrient by the soil matrix, which commonly occurred in highly weathered and more acid soils, typically found in tropical regions, due to the large quantities of iron, aluminum and manganese hydroxide minerals in the clay fraction (Goldberg and Suarez 2011; Sá and Ernani 2016). At the highest dose of B (6 kg ha^{-1} yr^{-1}), the nutrient levels in the 40–60 down to the 80–100 cm layers were constant (2.1±0.02 mg dm^{-3} of B; Fig. 2). The increase in the level of B in deeper layers of the soil also demonstrated that the nutrient was prone to leaching with application of ulexite (Figs. 1 and 2). Additionally, it should be taken into consideration that about 40% of the root system of citrus plants was localized in the sub-superficial layers (20–60 cm; Cruz *et al.* 2005) what contributes to minimize differences on the efficiency of nutrient supplied by B fertilizers with contrasting solubility, as evaluated in the present study.

The levels of B in the deeper layers were lower than those found in the superficial ones (2.6 mg dm^{-3} of B) since the availability of B is also directly related to the quantity of soil organic matter (SOM) (Goldberg and Suarez 2011). In this experiment, the levels of SOM encountered in the 0–20 and 20–40 cm layers were 21 and 18 mg dm^{-3}, respectively, whereas, in the deeper layers (40–100 cm), the level was 14 mg dm^{-3} (p<0.05). In tropical soils, B leaching increases with either natural or anthropogenic soil acidification (Sá and Ernani 2016) that occurs along the years after orchard plantation (Alva *et al.* 2006b). At the end of the experiment, the soil pH ($CaCl_2$) was 5.0 at the 0–20 cm depth layer, lower than the initial condition (pH 5.7).

Furthermore, increases in the level of B in the soil and in leaves for all rootstocks used were directly related (R^2>0.94; p<0.01; data not shown), independently of the source applied. B taken up by roots from more concentrated nutrient solution occurs mostly via passive diffusion, in which uptake efficiency of rootstock varieties depends on root anatomical and physiological traits (Wang *et al* 2015; Mesquita *et al.* 2016). After absorption by the roots, B is transported to the leaves for the subsequent flushes of growth, with only a small proportion of the nutrient being stored in the roots or stems (Papadakis *et al.* 2003, 2004; Zhou *et al.* 2014), in contrast to that observed for other micronutrients like copper (Zambrosi *et al.* 2013; Hippler *et al.* 2016) and zinc (Hippler *et al.* 2015). There were distinct responses in fruit yield to the B increase in leaves what still depended on the rootstocks. Trees grafted onto Rangpur lime and Swingle responded positively to B fertilization, with that being more important in the trees onto Swingle (Boaretto *et al.* 2008; Mattos *et al.* 2008). On the other hand, trees grafted onto Sunki did not show a significant response in fruit yield as a function of B fertilization (Fig. 3).

Furthermore, trees grafted on Sunki presented higher average fruit yield (Fig. 3) what was mostly attributed to greater canopy volume achieved by those compared to the other rootstocks in this study, which characteristic was largely regulated by the vigor induced to the canopy of citrus trees (Castle and Gmitter 1999). Additionally, the Sunki had a lower demand for B, as it did not respond to treatment fertilization, even in a soil condition with low availability of this micronutrient. On the other hand, the highest demand for B was observed in the orange trees grafted onto Swingle.

Boaretto *et al.* (2008) also verified a higher demand for B in sweet oranges grafted onto Swingle. Furthermore, in nursery tree production, Swingle presented greater growth than Rangpur lime did when cultivated under conditions of high B availability (Mattos *et al.* 2008). Research had demonstrated that B was fundamental for greater root growth of Swingle (Boaretto *et al.* 2008; Mesquita *et al.* 2016), which could explain gains in productivity under the conditions of this experiment, where more severe droughts occurred in the dry winter season, in the South hemisphere, between May and August. During such period, severe water deficits impair flower induction and cell differentiation of citrus trees what affects fruit yield (Chica and Albrigo 2013). Trees grafted onto Swingle respond positively to increased B availability in the root medium by combining higher B absorption and root growth as well as better organization of xylem what taken together improve water and B transport to the plant canopy (Mesquita *et al.* 2016). When the scions were grafted onto Rangpur lime or Swingle, the highest fruit yield occurred with levels of leaf B between 220 and 300 mg kg^{-1} (Fig. 3), which corresponded to 1.4–1.8 mg dm^{-3} of B in the 0–20 cm soil layer (Fig. 1); this concentration range was considered high for citrus (Quaggio *et al.* 2010). However, leaf B concentration close to 300 mg kg^{-1} (a dose 4 kg ha^{-1} yr^{-1}; Fig. 3) were similar to those observed in other studies in commercial plantations of sweet oranges (Quaggio *et al.* 2003; Boaretto *et al.* 2011).

In the first year of evaluation, about one month after the application of the fertilizer sources, the treatments that received the highest dose (6 kg ha^{-1} yr^{-1}) showed moderate symptoms of B toxicity. These were characterized by chlorosis at the edges of the older leaves, evolving to the apex and the rest of the leaf surface (Papadakis *et al.* 2004; Mattos *et al.* 2005). Independent of the rootstocks, these symptoms manifested quicker in orange trees treated with boric acid, but after a few weeks, the occurrence of these symptoms was similar for both sources. However, in the second year, no visual symptoms of B toxicity were observed, which suggested, in perennial cultures, the differences in B source solubility were not sufficient to affect the supply of the micronutrient to the plant. Symptoms of B toxicity manifested when leaf B levels were above 400 mg kg^{-1}. These same effects were observed in a more moderate form in sweet orange trees grown in the field when the leaf level of B was 358 mg kg^{-1} (Quaggio *et al.* 2003) and, in a more accentuated form, in the Navelina orange in nutrient solutions when the level of B was over 444 mg kg^{-1} (Papadakis *et al.* 2004).

In Brazil, from the 1990s onward, the first recommendations for B application via soil appeared based on the nutritional management of orchards in Florida and California (USA) (Obreza and Morgan 2008), where levels of B in the leaves were considered adequate when the range was from 36 to 100 mg kg^{-1} and in soil from 0.2–0.6 mg dm^{-3} (GPACC 1997). Based on the results of recent research on the application of B on citrus plants at different stages of growth (Quaggio *et al.* 2003; Boaretto *et al.* 2008; Mattos *et al.* 2008), the recommended levels as adequate for B were altered to 80–160 mg kg^{-1} for leaves and 0.6–1.0 mg dm^{-3} in soil due to the greatest responses to fertilization in orchards with high fruit productivity (Quaggio *et al.* 2010). The results obtained in the present study suggested that the levels recommended by Quaggio *et al.* (2010) might not be sufficient to attend the demand for B by some rootstocks, as was verified for scions grafted onto Swingle whose use had increased in commercial citrus orchards (Pompeu and Blumer 2011). However, caution must be exercised when revising these levels, since the largest yields with trees grafted onto Swingle and Rangpur lime were obtained with leaf B levels between 250 and 300 mg kg^{-1} (Fig. 3), which were relatively close to phytotoxic levels (>400 mg kg^{-1}). In this way, as the absorption of B by the roots is predominantly by mass flow (Wimmer and Eichert 2013), and even sources with lower water solubility are able to make this micronutrient available in soil solution, problems with B phytotoxicity could become common in situations where high doses of B are applied to the orchard.

The increase in the availability of B in the soil influences the absorption of K (Fig. 4). Similar responses were observed in Florida in experiments under controlled conditions (Smith and Reuther 1949), under fertigation in the field (Cooper *et al.* 1952) and in Brazil with the sweet orange under non-irrigated conditions (Quaggio *et al.* 2003). This response has been consistently demonstrated. Until now, there has been insufficient information to establish whether an interaction between B and K is due to the effects of the availability of these nutrients in the soil or the characteristics of their absorption by citrus. It has been proposed that B is an important activator of plasma membrane H^+-ATPase activity in root cells and under specific conditions of this nutrient. H^+ pumping promotes hyperpolarization of the plasmalemma and subsequent absorption of K^+ to maintain cellular electro-chemical equilibrium (Schon *et al.* 1990; Britto and Kronzucker 2008).

Under our experimental conditions, no effect of the treatments was observed on the parameters linked to fruit quality (Table 1). However, Quaggio *et al.* (2003) verified a lower industrial quality of sweet orange fruit with increasing doses of B, where reductions in the SS and the level of vitamin C in the juice were observed. These authors justified these differences in fruit quality as being the result of the concomitant increase in the level of K in the leaves, as was verified in this study (Alva *et al.* 2006a; Quaggio *et al.* 2006, 2011). Besides the differences in the scions used, the levels of K in the leaves were in a range below what was recommended (Quaggio *et al.* 2010): from 7 to 10 mg kg^{-1}. These values were lower than those verified in this study (15 to 20 mg kg^{-1}; Fig. 4). Differences in fruit quality (fruit weight, height, width and acidity) observed from the first to the second year (Table 1) were also related to the age of the trees, as it was common for young orchards to produce larger fruits, but with a lower industrial yield (Stuchi *et al.* 2002).

5. Conclusion

B fertilization via soil application supplied the nutritional requirements of orange trees, even though fertilizer sources varied in water solubility (boric acid and ulexite). Furthermore, fruit yield of trees depended on the rootstock variety. Trees grafted onto Swingle citrumelo had a higher B demand, followed by Rangpur lime, with Sunki mandarin being the least responsive to B supply and the most sensitive to nutrient toxicity, revealed by reduced fruit yield when higher B doses were applied to the soil. For Swingle citrumelo, we observed that adequate levels of B in the soil for maximum production were 1.0 to 1.5 mg dm^{-3} what corresponded to leaf concentration of 200 to 300 mg kg^{-1} in the leaves. Such leaf values are superior to those currently used in the diagnosis of the nutritional status of citrus plants.

References

Abat M, Degryse F, Baird R, Mclaughlin M J. 2015. Boron phosphate (BPO_4) as a seedling-safe boron fertilizer source. *Plant and Soil*, **391**, 153–160.

Abreu C A, Abreu M F, van Raij B, Bataglia O C, Andrade J C. 1994. Extraction of boron from soil by microwave heating for ICP-AES determination. *Communication in Soil Science and Plant Analyses*, **24**, 3321–3333.

Alva A K, Mattos Jr D, Paramasivam S, Patil B, Dou H, Sajwan K. 2006a. Potassium management for optimizing Citrus production and quality. *International Journal of Fruit Science*, **6**, 3–43.

Alva A K, Paramasivam S, Fares A, Delgado J A, Mattos Jr D, Sajwan K. 2006b. Nitrogen and irrigation management practices to improve nitrogen uptake efficiency and minimize leaching losses. *Journal of Crop Improvement*, **15**, 369–420.

Bassanezi R B, Bergamin Filho A, Amorim L, Gimenes-Fernandes N, Gottwald T R, Bové J M. 2003. Spatial and temporal analyses of citrus sudden death, as a tool to generated hypotheses concerning its etiology. *Phytopathology*, **93**, 502–512

Bataglia O C, Furlani A M C, Teixeira J P F, Furlani P R, Gallo J R. 1983. *Métodos de Análise Química de Plantas*. Campinas, IAC. p. 48. (in Portuguese) (Boletim Técnico 78)

Bell R W, Dell B. 2008. *Micronutrients for Sustainable Food, Feed, Fibre and Bioenergy Production*. International Fertilizer Industry Association (IFA), Paris.

Brennan R F, Bell R W, Frost K. 2015. Risks of boron toxicity in canola and lupin by forms of boron application in acid sands of south-western Australian. *Journal of Plant Nutrition*, **38**, 920–937.

Britto D V, Kronzucker H J. 2008. Cellular mechanism of potassium transport in plants. *Physiologia Plantarum*, **133**, 637–650.

Boaretto R M, Quaggio J A, Mattos Jr D, Murauka T, Boaretto A E. 2011. Boron uptake and distribution in field grown citrus trees. *Journal of Plant Nutrition*, **34**, 839–849.

Boaretto R M, Quaggio J A, Mourão Filho F A A, Giné M F, Boaretto A E. 2008. Absorption and mobility of boron in young citrus plants. *Communication in Soil Science and Plant Analyses*, **39**, 2501–2514.

Castle W S, Gmitter F. 1999. Rootstocks and scion selection. In: Timmer L W, Duncan L W, eds., *Citrus Health Management*. APS Press, Paul. pp. 21–34.

Chica E J, Albrigo L G. 2013. Cool temperature and water deficit interact during floral induction in citrus. *Proceedings of the Florida State Horticultural Society*, **126**, 45–50.

Cooper W C, Gorton B S, Olson E O. 1952. Ionic accumulation in citrus as influenced by rootstock and scion and concentration of salts and boron in the substrate. *Plant Physiology*, **27**, 191–203.

Cruz A C R, Libardi P L, Carvalho L A, Rocha G C. 2005. Balanço de água no volume de solo explorado pelo sistema radicular de uma planta de citros. *Revista Brasileira de Ciência do Solo*, **29**, 1–10. (in Portuguese)

Gimeno V, Simón I, Nieves M, Martínez V, Cámara-Zapata J M, García A L, García-Sanchez F. 2012. The physiological and nutritional responses to an excess of boron by Verna lemon trees that were grafted on four contrasting rootstocks. *Trees*, **26**, 1513–1526.

Goldberg S, Suarez D L. 2011. Influence of soil solution cation composition on boron adsorption by soils. *Soil Science*, **176**, 80–83.

GPACC (Grupo Paulista de Adubação e Calagem Para Citros). 1997. Frutíferas. In: Raij B van, Cantarella H, Quaggio J A, Furlani A M C, eds., *Recomendações de Adubação e Calagem para o Estado de São Paulo*. IAC, Campinas. pp. 121–134. (in Portuguese)(Boletim Técnico 100).

Hippler F W R, Boaretto R M, Quaggio J A, Boaretto A E, Abreu Jr C H, Mattos Jr D. 2015. Uptake and distribution of soil applied zinc by *Citrus* trees - addressing fertilizer use efficiency with ^{68}Zn labeling. *PLOS ONE*, doi:10.1371/journal.pone.0116903.

Hippler F W R, Cipriano D O, Boaretto R M, Quaggio J A, Gaziola S A, Azevedo R A, Mattos Jr D. 2016. *Citrus* rootstocks regulate the nutritional status and antioxidant system of

trees under copper stress. *Environmental and Experimental Botany*, doi:10.1016/j.envexpbot.2016.05.007.
Huang L, Ye Z, Bell R W, Dell B. 2005. Boron nutrition and chilling tolerance of warm climate crop species. *Annals of Botany*, **96**, 755–767.
Liu G, Dong X, Liu L, Wu L, Peng S, Jiang C. 2014. Boron deficiency is correlated with changes in cell wall structure that lead to growth defects in the leaves of navel orange plants. *Scientia Horticulturae*, **176**, 54–62.
Liu G D, Wang R D, Wu L S, Peng S A, Wang Y H, Jiang C C. 2012. Boron distribution and mobility in navel orange grafted on citrange and trifoliate orange. *Plant and Soil*, **360**, 123–133.
Mattos Jr. D, Bataglia O C, Quaggio J A. 2005. Nutrição dos citros. In: Mattos Jr D, De Negri J D, Pio R P, Pompeu Jr J, eds., *Citros*. IAC, Campinas. pp. 197–219.
Mattos Jr D, Boaretto R M, Corrêa E R L, Abreu M F, Carvalho S A. 2008. Disponibilidade de boro em substrato para produção de porta-enxertos de citros em fase de sementeira. *Bragantia*, **67**, 983–989.
Mertens J, van Laer L, Salaets P, Smolders E. 2011. Phytotoxic doses of boron in contrasting soils depend on soil water content. *Plant and Soil*, **342**, 73–82.
Mesquita G L, Zambrosi F C B, Tanaka F A O, Boaretto R M, Quaggio J A, Ribeiro R V, Mattos Jr D. 2016. Anatomical and physiological responses of Citrus trees to varying boron availability are dependent on rootstock. *Frontiers in Plant Science*, **7**, 224.
Obreza T A, Morgan K T. 2008. *Nutrition of Florida Citrus Trees*. 2nd ed. Lake Alfred, University of Florida, USA. p. 96.
Papadakis I E, Dimassi K N, Bosabalidis A M, Therios I N, Patakas A, Giannakoula A. 2004. Effects of B excess on some physiological and anatomical parameters of 'Navelina' orange plants grafted on two rootstocks. *Environmental and Experimental Botany*, **51**, 247–257.
Papadakis I E, Dimassi K N, Therios I N. 2003. Response of two citrus genotypes to six boron concentrations: concentration and distribution of nutrients, total absorption, and nutrient use efficiency. *Australian Journal of Agricultural Research*, **54**, 571–580.
Pompeu Jr J, Blumer S. 2011. Citrumelos como porta-enxertos para a laranjeira 'Valência'. *Pesquisa Agropecuária Brasileira*, **46**, 105–107. (in Portuguese)
Pompeu Jr J, Blumer S. 2008. Morte súbita dos citros: Suscetibilidade de seleções de limão-cravo e uso de interenxertos. *Revista Brasileira de Fruticultura*, **30**, 371–378. (in Portuguese)
Quaggio J A, Mattos Jr D, Boaretto R M. 2010. Citros. In: Prochnow L I, Casarin W, Stipp S R, eds., *Boas Práticas Para o uso Eficiente de Fertilizantes*, vol 3. International Plant Nutrition Institute, Piracicaba. pp. 371–409. (in Portuguese)
Quaggio J A, Mattos Jr D, Boaretto R M. 2011. Sources and rates of potassium for sweet orange production. *Scientia Agricola*, **68**, 369–375.
Quaggio J A, Mattos Jr D, Cantarella H. 2006. Fruit yield and quality of sweet oranges affected by nitrogen, phosphorus and potassium fertilization in tropical soils. *Fruits*, **61**, 293–302.
Quaggio J A, Mattos Jr D, Cantarella H, Tank Jr A. 2003. Fertilização com boro e zinco no solo em complementação à aplicação via foliar em laranjeira Pêra. *Pesquisa Agropecuária Brasileira*, **38**, 627–634. (in Portuguese)
Raij B van, Alcarde J C, Cantarella H, Quaggio J A. 2001. *Análise Química Para Avaliação da Fertilidade de Solos Tropicais*. IAC, Campinas. (in Portuguese)
Redd J B, Hendrix D L, Hendrix Jr C M. 1992. *Quality Control Manual for Citrus Processing Plants*. Safety Harbour: AGScience, USA. p. 290.
Sá A A, Ernani P R. 2016. Boron leaching decreases with increases on soil pH. *Revista Brasileira de Ciência do Solo*, **40**, e0150008. (in Portuguese)
Schon M K, Novacky A, Blevins D G. 1990. Boron induces hyperpolarization of sunflower root cell membranes and increases membrane permeability to K^+. *Plant Physiology*, **93**, 566–571.
Smith P, Reuther W. 1949. Observations on boron deficiency in citrus. *Proceedings of the Florida State Horticultural Society*, **62**, 21–37.
Stuchi E S, Donadio L C, Sempionato O R. 2002. Qualidade industrial e produção de frutos de laranjeira 'Valência' enxertadas em sete porta-enxertos. *Laranja*, **23**, 453–471. (in Portuguese)
Syvertsen J P, Garcia-Sanchez F. 2014. Multiple abiotic stresses occurring with salinity stress in citrus. *Environmental and Experimental Botany*, **103**, 128–137.
Vale F, Alcarde J C. 1999. Solubilidade e disponibilidade dos micronutrientes em fertilizantes. *Revista Brasileira de Ciência do Solo*, **23**, 441–451. (in Portuguese)
Wang N, Yang C, Pan Z, Liu Y, Peng S. 2015. Boron deficiency in woody plants: Various responses and tolerance mechanisms. *Frontiers in Plant Science*, **6**, 916.
Wimmer M A, Eichert T. 2013. Review: Mechanisms for boron deficiency-mediated changes in plant. *Plant Science*, **203–204**, 25–32.
Zambrosi F C B, Mesquita G L, Tanaka F A O, Quaggio J A, Mattos Jr D. 2013. Phosphorus availability and rootstock affectt copper-induced damage to the root ultra-structure of *Citrus*. *Environmental and Experimental Botany*, **95**, 25–33.
Zhou G F, Peng S A, Liu Y Z, Wei Q J, Han J, Islam M Z. 2014. The physiological and nutritional responses of seven different citrus rootstock seedlings to boron deficiency. *Trees*, **28**, 295–307.

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