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Micronutrient and Silicon Uptake and Removal by Upland Rice Cultivars with Different Plant Architecture

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ABSTRACT: Upland rice cultivars manifest different nutritional demands. A field study was conducted to quantify the extraction, distribution, and removal of micronutrients and silicon by the upland rice cultivars. The experiment was arranged in a randomized complete block-split plot design. Plots consisted of three cultivars (Caiapó – traditional, BRS Primavera – intermediate, and Maravilha – modern) of upland rice. Split-plots consisted of plant samplings, which occurred at 39, 46, 55, 67, 75, 83, 92, 102, 111, 118, and 125 days after emergence (DAE). Up to the end of tillering (46 DAE), all cultivars exhibited low demand for most micronutrients and Si, and took up less than 24 % of the total B, Cu, and Si, but around 31 % of the total Zn. The period of greatest uptake of micronutrients and Si occurred from 65 to 80 DAE in the Caiapó and BRS Primavera cultivars, and after 80 DAE in the Maravilha cultivar. The Caiapó and BRS Primavera cultivars took up their necessary demand of B, Mn, and Fe in the first 98 DAE and Cu, Zn, and Si up to 105 DAE, but the Maravilha cultivar took up these nutrients for two to three weeks longer. The quantities of micronutrients and Si taken up by cultivars Caiapó, BRS Primavera, and Maravilha did not exhibit large differences, and these cultivars took up between 98-135 g B, 103-110 g Cu, 1,157-1,460 g Fe, 1,278-1,424 g Mn, 240-285 g Zn, and 111-124 kg Si per hectare. The BRS Primavera cultivar showed greater removal of nutrients, with average amounts per hectare of 19.7 g B, 25.8 g Cu, 200 g Fe, 234.2 g Mn, 102.4 g Zn, and 32.6 kg Si, while the other cultivars removed smaller amounts per hectare (14.4 g B, 19.9 g Cu, 160.7 g Fe, 136.3 g Mn, 67 g Zn, and 21.9 kg Si). The BRS Primavera showed a greater removal of nutrients because it has a higher yield and allocates a greater quantity of nutrients to the panicles.

Keywords: *Oryza sativa*, nutrient accumulation, uptake rates, nutritional requirement.

INTRODUCTION

The development of modern type of rice cultivar, adapted to dryland or irrigated production systems, has been an excellent strategy for maximizing Brazilian production of this cereal crop. Nevertheless, the rice cultivars used in this production system may have variable grain yields as a result of differences in the redistribution of assimilates among the plant organs throughout the period of development (Alvarez et al., 2012). Traditional rice cultivars, such as Caiapó, are notable for their height, long decumbent leaves, and long and vitreous grains (Alvarez et al., 2012). In contrast, modern cultivars like Maravilha are short plants with long thin grains, short upright leaves, strong stems and high tillering (Alvarez et al., 2012). Intermediate cultivars like BRS Primavera are the result of crosses between traditional and modern cultivars, and their main characteristics are a shorter plant and better grain quality (Santos et al., 2006). These modern cultivars represent an excellent alternative in composing crop rotation programs in *Cerrado* (Brazilian tropical savanna) areas under no-tillage systems where intensive cropping of soybean, maize, and cotton prevails (Moraes, 1990; Guimarães and Yokoyama, 1998; Guimarães and Stone, 2004).

The Brazilian Cerrado region has great agricultural potential for growing upland rice, especially for growing modern cultivars. Nevertheless, the low natural fertility of these soils, the increase in the yield levels of maize and soybeans grown in the region, and the intensive use of soil acidity amendments and concentrated NPK fertilizers have generated micronutrient deficiency problems in large areas of the *Cerrado* (Bernardi et al., 2003). Although micronutrients are taken up in small quantities by plants, they are fundamental for crop growth and development (Kirkby and Römheld, 2007) and the lack of any one of them causes significant yield losses. Thus, to avoid limitations on rice grain yield, the ready availability of these nutrients at the times of greatest plant demand is necessary (Fidelis et al., 2012), otherwise there may be nutritional deficiency.

In the rice crop, deficiency of zinc (Zn), manganese (Mn), and iron (Fe) results in chlorosis on the leaf blades and reduces plant development (Moraes, 1990; Fageria, 2006), while B deficiency substantially reduces the synthesis of dry matter (DM) of the shoots and roots (Fageria, 2000). Rice plants that are deficient in copper (Cu) exhibit chlorotic leaves with less tillering and lower viability of pollen grains (Das, 2014). Silicon (Si), although not considered essential (Epstein, 1994), is one of the nutrients that is most taken up by the rice plant (Tokura et al., 2011), such that when plants are grown in the absence of Si, DM accumulation in the grain is cut in half (Ma et al., 1989).

There are many older studies available in the literature on the nutritional demands of rice for micronutrients and Si (Gilmour, 1977; Malavolta et al., 1981a,b, 1982; Ma et al., 1989), as well as more recent studies by Fageria (2004) and Mauad et al. (2013). However, in most of these studies, rice was grown in greenhouse or the studies used traditional cultivars, whereas some cultivars were recommended only for flooded growing conditions. However, since modern rice cultivars in current use have genotypic characteristics different from those studied in the past, and considering that the uptake and use of nutrients by rice plants also depends on physiological processes inherent to the cultivars used (Fageria et al., 1995), the nutritional demands of these current cultivars may be different. There are studies showing that an increase in rice grain yield results in greater nutrient removal from the growing area (Crusciol et al., 2003a,b; 2007). Recent studies on these rice cultivars in current use that have different plant architectures have indicated the presence of significant differences in biomass production and grain yield (Guimarães et al., 2008; Alvarez et al., 2012). Thus, we hypothesized that the periods of greatest demand and the total amounts of micronutrients and Si taken up by these modern cultivars is greater than that of the cultivars used in the past, since the current cultivars have higher yields.

The aim of this study was to evaluate the extraction, distribution, and removal of micronutrients and Si by the upland rice cultivars Caiapó, BRS Primavera, and Maravilha.

MATERIALS AND METHODS

Site description, experimental design, upland rice cultivar characteristics, and crop management are briefly presented here. The full details of these topics were presented by Crusciol et al. (2016).

The field experiment was performed in Botucatu, State of São Paulo, in southeast Brazil (48° 23' W, 22° 51' S; 765 m above sea level), in the 2005/2006 growing season in a *Nitossolo Vermelho Distroférrico* (Santos et al., 2013) or Typic Rhodudalf (Soil Survey Staff, 2006). Prior to the experiment, soil chemical properties was determined at 0.00-0.20 m depth according methods proposed by Raij et al. (2001) and Korndörfer et al. (2004). The soil properties were: pH($CaCl_2$) 5.0, organic matter 21 g dm^{-3}, P (resin) 35 mg dm^{-3}, K^+ 2.5 $mmol_c$ dm^{-3}, Ca^{2+} 38 $mmol_c$ dm^{-3}, Mg^{2+} 17 $mmol_c$ dm^{-3}, H+Al 43 $mmol_c$ dm^{-3}, CEC 100.5 $mmol_c$ dm^{-3}, base saturation 57 %, S-SO_4 20 mg dm^{-3}; B 0.27 mg dm^{-3}; Cu 6.5 mg dm^{-3}; Fe 38 mg dm^{-3}; Mn 6.2 mg dm^{-3}; Zn 1.2 mg dm^{-3}, and Si 8 mg dm^{-3}.

The experiment was arranged in a randomized complete block design with split-plots and seven replications. The treatments consisted of cultivars of upland rice with different plant architecture (Caiapó – traditional group; BRS Primavera – intermediate group; and Maravilha – modern group) and eleven (11) plant sampling (assessment) times (39, 46, 55, 67, 75, 83, 92, 102, 111, 118, and 125 days after emergence – DAE). The information about the size, shape and useful area of plots and split-plots, and details about the upland rice cultivars was presented by Crusciol et al. (2016).

Rice sowing was performed mechanically on November 17th, at a row spacing of 0.30 m with 240 viable seeds m^{-2}. Mineral fertilization in sowing was applied in a rate of 20 kg ha^{-1} N, 120 kg ha^{-1} P_2O_5, and 20 kg ha^{-1} K_2O. No micronutrients or Si were applied. Plant emergence occurred at 7 d after sowing, and at 30 and 60 DAE, 40 and 40 kg ha^{-1} N, respectively, was applied. The N, P and K were applied as the fertilizers urea, superphosphate and potassium chloride, respectively. The information about the management of irrigation, weeds, pests and diseases was provided in detail by Crusciol et al. (2016).

Plant measurements, micronutrient and silicon accumulation

A complete description of plant sampling and obtaining of dry matter (DM) data were presented in Crusciol et al. (2016). In the dry samples, the concentrations of B, Cu, Fe, Mn, and Zn were determined according to methodology proposed by Malavolta et al. (1997), while Si concentration was determined according to the method proposed by Korndörfer et al. (2004). Based on micronutrient and Si concentrations and on the amounts of DM accumulated by Crusciol et al. (2016), the amounts of micronutrients and Si accumulated in each plant part were calculated. Accumulation rates of micronutrients and Si in panicles and shoot, and the extraction of these nutrients per Mg of grain were calculated as documented for the macronutrient accumulation in Crusciol et al. (2016).

Grain yield and nutrient removal

The details of upland rice cultivars harvest and calculation of grain yield were presented by Crusciol et al. (2016). A sample of grains from each plot was dried in a forced air oven (65 °C for 72 h) and ground to determine the micronutrient (B, Cu, Fe, Mn, and Zn) (Malavolta et al., 1997) and Si (Korndörfer et al., 2004) concentration in the grains. The micronutrient and Si removal, and relative removal of these nutrients, were calculated as documented for the macronutrient removal (Crusciol et al., 2016).

Statistical analyses

The data were subjected to ANOVA. The mean values of the cultivars at each sampling time were separated by the LSD test at 0.05 probability. The effects of plant samplings on the DM and nutrient accumulation variables were assessed by regression analysis using the software SigmaPlot 10.0.

RESULTS AND DISCUSSION

In the first 46 DAE, the accumulation of most micronutrients and Si in the stem + sheath did not differ between the cultivars, and represented approximately 10, 21, 46, 41, 24, and 22 % of the total amounts of B, Cu, Fe, Mn, Zn, and Si accumulated in this plant structure, respectively (Figures 1a, 2a, 3a, 4a, 5a, and 6a). The lower accumulation of these nutrients in this phase of the cycle is due to the slow initial growth of the crop (Guimarães et al., 2008) and the low accumulation of DM in this organ for all cultivars (Crusciol et al., 2016). This shows that in the initial stage of rice development, assimilation of micronutrients by the crop is low (Pavinato et al., 2009), except for the elements Fe and Mn. After 46 DAE, the quantities of micronutrients and Si accumulated in the stem + sheath increased up to nearly 90 to 100 DAE in the cultivars Caiapó and BRS Primavera, but in the cultivar Maravilha, there was an even greater increase in accumulation of these nutrients for 10 to 15 days longer (Figures 1a, 2a, 3a, 4a, 5a, and 6a). The Maravilha cultivar is characterized by a low rate of growth throughout its entire development cycle (Guimarães et al., 2008; Alvarez et al., 2012), which resulted in a slower accumulation of micronutrients and Si in this plant structure up to a later phase of the cycle. From 75 to 100 DAE, the Caiapó cultivar accumulated between 1.3-1.4-fold more Cu, Fe, and Si in the stem + sheath than the other cultivars, but after 100 DAE, the accumulation of all the nutrients in the stem + sheath of this cultivar did not differ from the Maravilha cultivar (Figures 1a, 2a, 3a, 4a, 5a, and 6a). In the BRS Primavera cultivar, the accumulation of B, Cu, Mn, and Fe in the stem + sheath was of 0.8-1.4-fold lower than that of the two other cultivars only after 75 DAE, although, in spite of the shorter cycle, the accumulation of Zn and Si in the stem + sheath of this cultivar did not differ from the others. In the final phase of the cycle, the quantities of micronutrients and Si accumulated in the stems + sheath of all the cultivars declined by 8-33 % depending on the cultivar (Figures 1a, 2a, 3a, 4a, 5a, and 6a). This result is due to a reduction in the amounts of DM accumulated in this organ of the plant (Crusciol et al., 2016).

At the beginning of vegetative development (39 DAE) there were no differences among cultivars in relation the amounts of micronutrients and Si accumulated in the leaf blades, which were only 10, 28, 26, 29, 33, and 10 % of the total amount of B, Cu, Fe, Mn, Zn, and Si accumulated in this structure, respectively (Figures 1b, 2b, 3b, 4b, 5b, and 6b). As of 39 DAE, the accumulations of these nutrients in the leaf blades of all the cultivars intensified until almost the end of the cycle. The maximum accumulation of micronutrients and Si in the leaf blades of the Caiapó cultivar occurred at 100 DAE. In the BRS Primavera cultivar, the maximum accumulations of these nutrients in the leaf blades were earlier and occurred from 84 to 90 DAE, but in the Maravilha cultivar, they occurred only after 100 DAE. In the leaf blades of the Caiapó cultivar, the accumulations of all the micronutrients and Si around of 100 DAE were greater than those of the other cultivars, with values per hectare of 90 g of B, 34 g of Cu, 773 g of Fe, 935 g of Mn, 79 g of Zn, and 53 kg of Si. However, after 100 DAE, the amounts of micronutrients and Si that accumulated in the leaf blades of the Caiapó cultivar became the same as those of the Maravilha cultivar. The high accumulation of nutrients in the leaf blades of the Caiapó cultivar is related to the greater leaf area index (Alvarez et al., 2012) and the biomass of the leaf blades of this cultivar is 34 % greater than that of other cultivars (Crusciol et al., 2016). The BRS Primavera cultivar has shown lower leaf blades biomass (Crusciol et al., 2016), and accumulated lower quantities of micronutrients and Si in this organ than the other cultivars, with values per hectare of 61 g B, 25 g Cu, 580 g Fe, 771 g Mn, 57 g Zn, and 44 kg Si (Figures 1b, 2b, 3b, 4b, 5b, and 6b). Since this cultivar is of the intermediate group, it also has smaller and more upright leaves than the Caiapó cultivar of the traditional group (Alvarez et al., 2012). In the final phase of the cycle, the quantities of micronutrients and

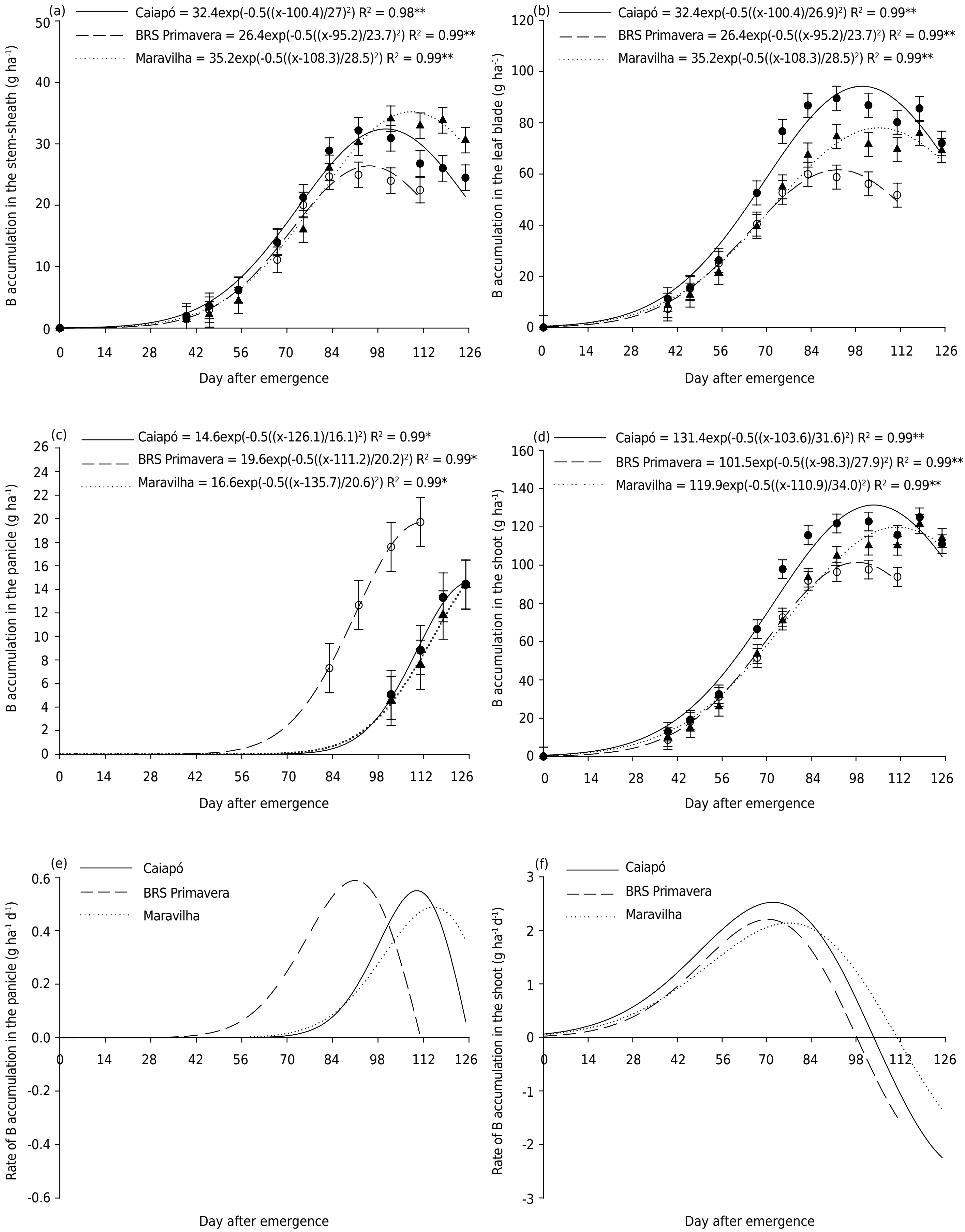

Figure 1. Boron (B) accumulation in the stems + sheath (a), leaf blades (b), panicles (c), shoots (d), and B accumulation rates in the panicles (e) and in the shoots (f) of rice cultivars throughout their cycle. ** and *: significant at 5 % and 1 % by the F test, respectively. Vertical bars indicate the value of LSD by the t test (LSD) at 5 %.

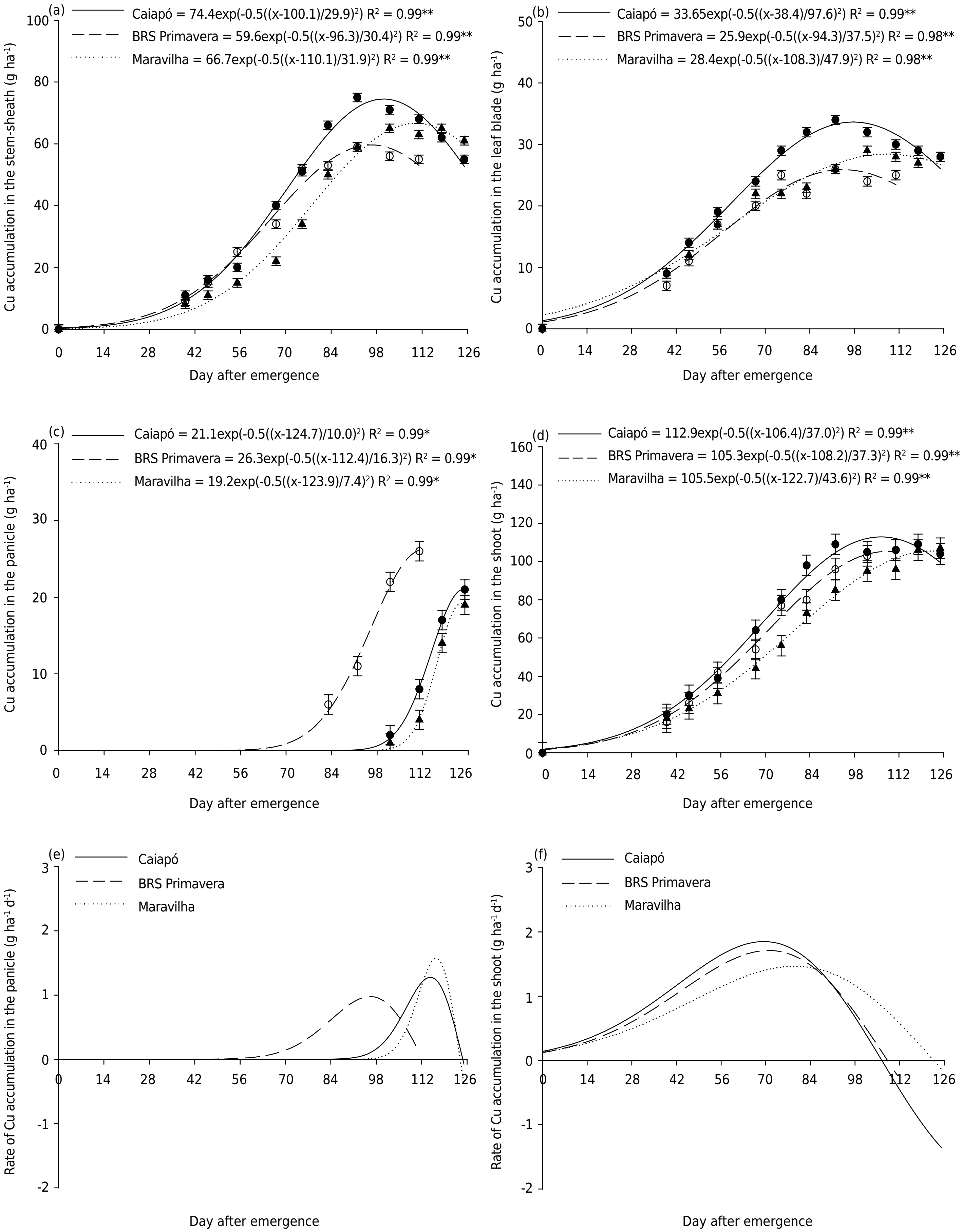

Figure 2. Copper (Cu) accumulation in the stems + sheath (a), leaf blades (b), panicles (c), shoots (d), and Cu accumulation rates in the panicles (e) and in the shoots (f) of rice cultivars throughout their cycle. ** and *: significant at 5 % and 1 % by the F test, respectively. Vertical bars indicate the value of LSD by the t test (LSD) at 5 %.

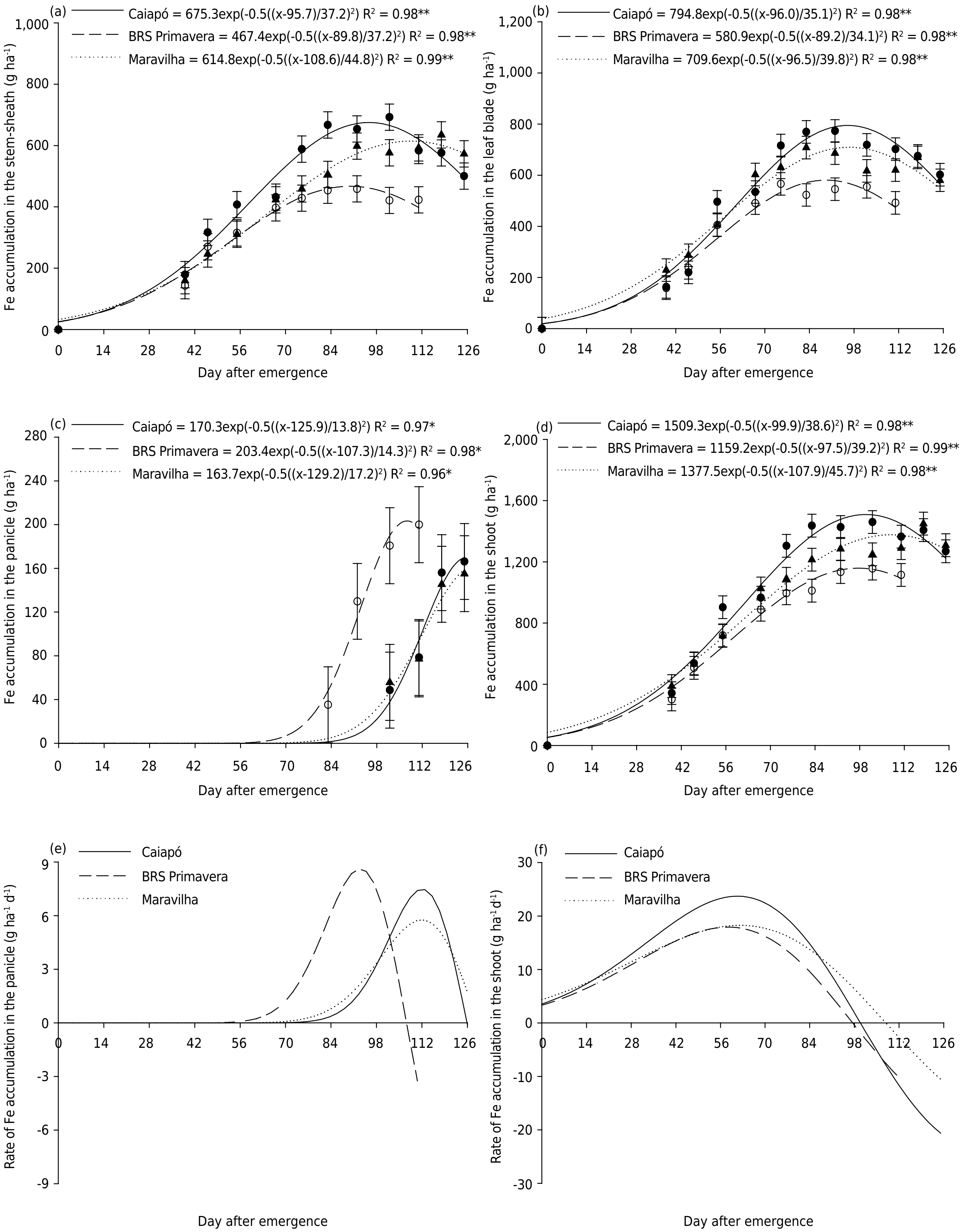

Figure 3. Iron (Fe) accumulation in the stems + sheath (a), leaf blades (b), panicles (c), shoots (d), and Fe accumulation rates in the panicles (e) and in the shoots (f) of rice cultivars throughout their cycle. ** and *: significant at 5 % and 1 % by the F test, respectively. Vertical bars indicate the value of LSD by the t test (LSD) at 5 %.

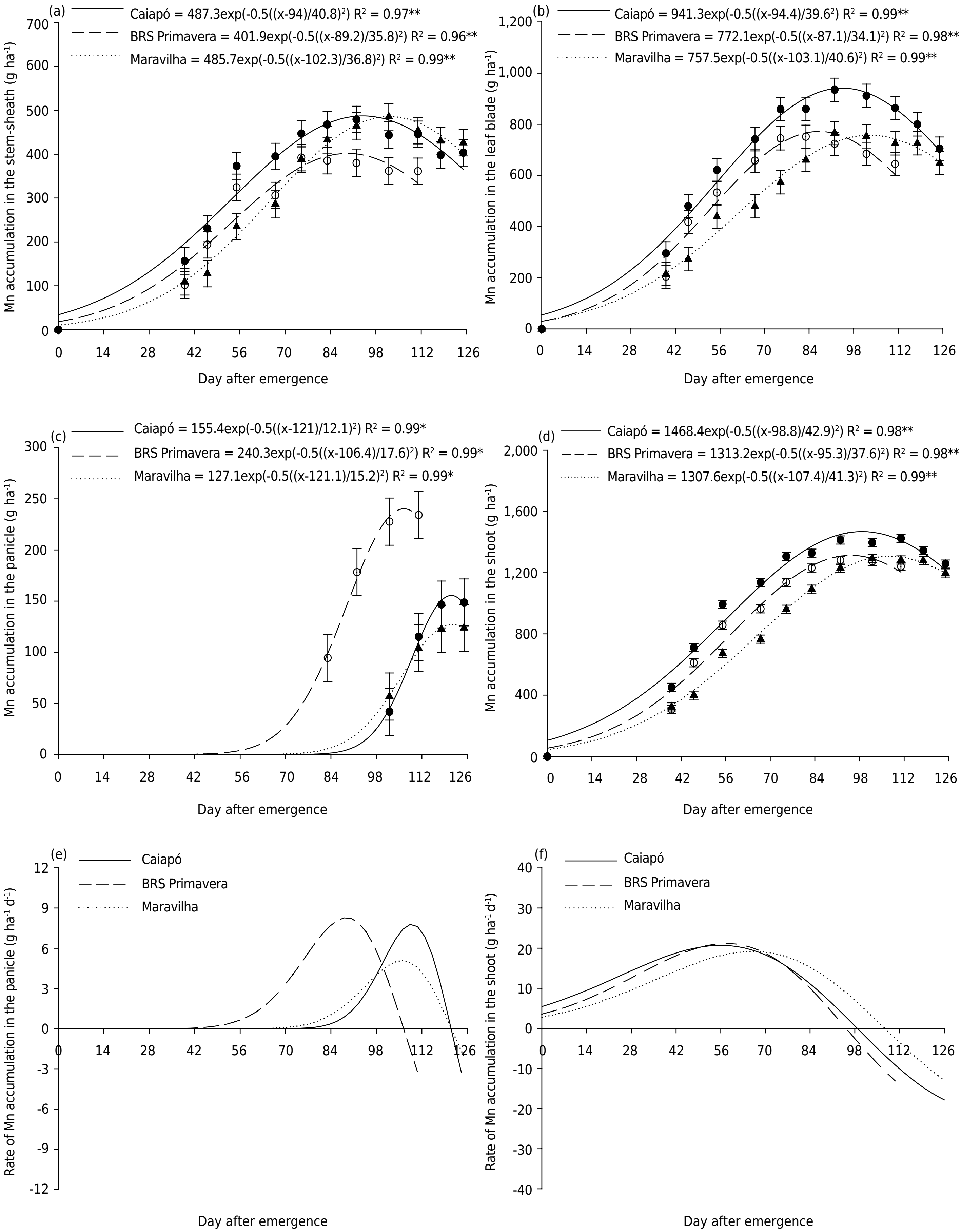

Figure 4. Manganese (Mn) accumulation in the stems + sheath (a), leaf blades (b), panicles (c), shoots (d), and Mn accumulation rates in the panicles (e) and in the shoots (f) of rice cultivars throughout their cycle. ** and *: significant at 5 % and 1 % by the F test, respectively. Vertical bars indicate the value of LSD by the t test (LSD) at 5 %.

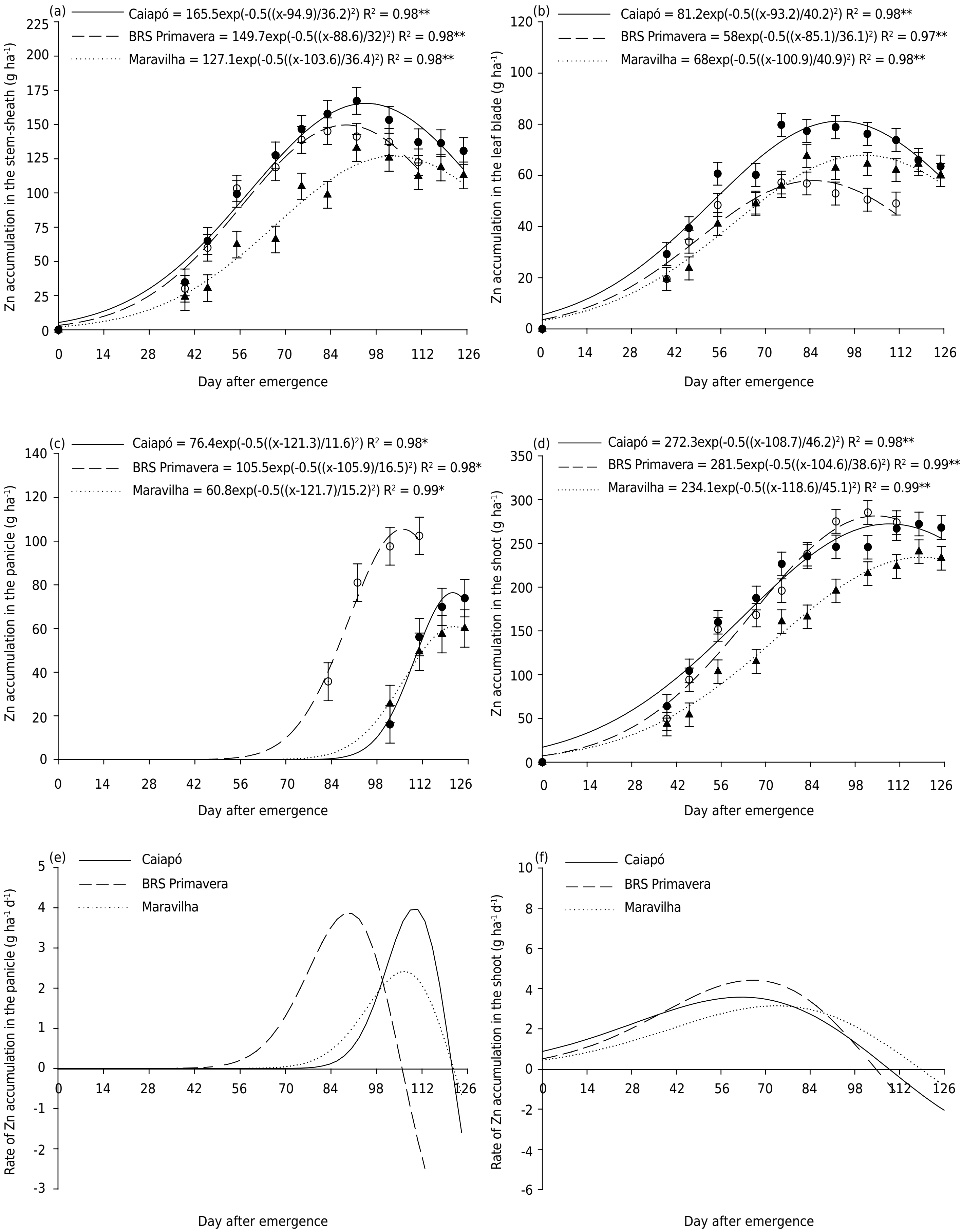

Figure 5. Zinc (Zn) accumulation in the stems + sheath (a), leaf blades (b), panicles (c), shoots (d), and Zn accumulation rates in the panicles (e) and in the shoots (f) of rice cultivars throughout their cycle. ** and *: significant at 5 % and 1 % by the F test, respectively. Vertical bars indicate the value of LSD by the t test (LSD) at 5 %.

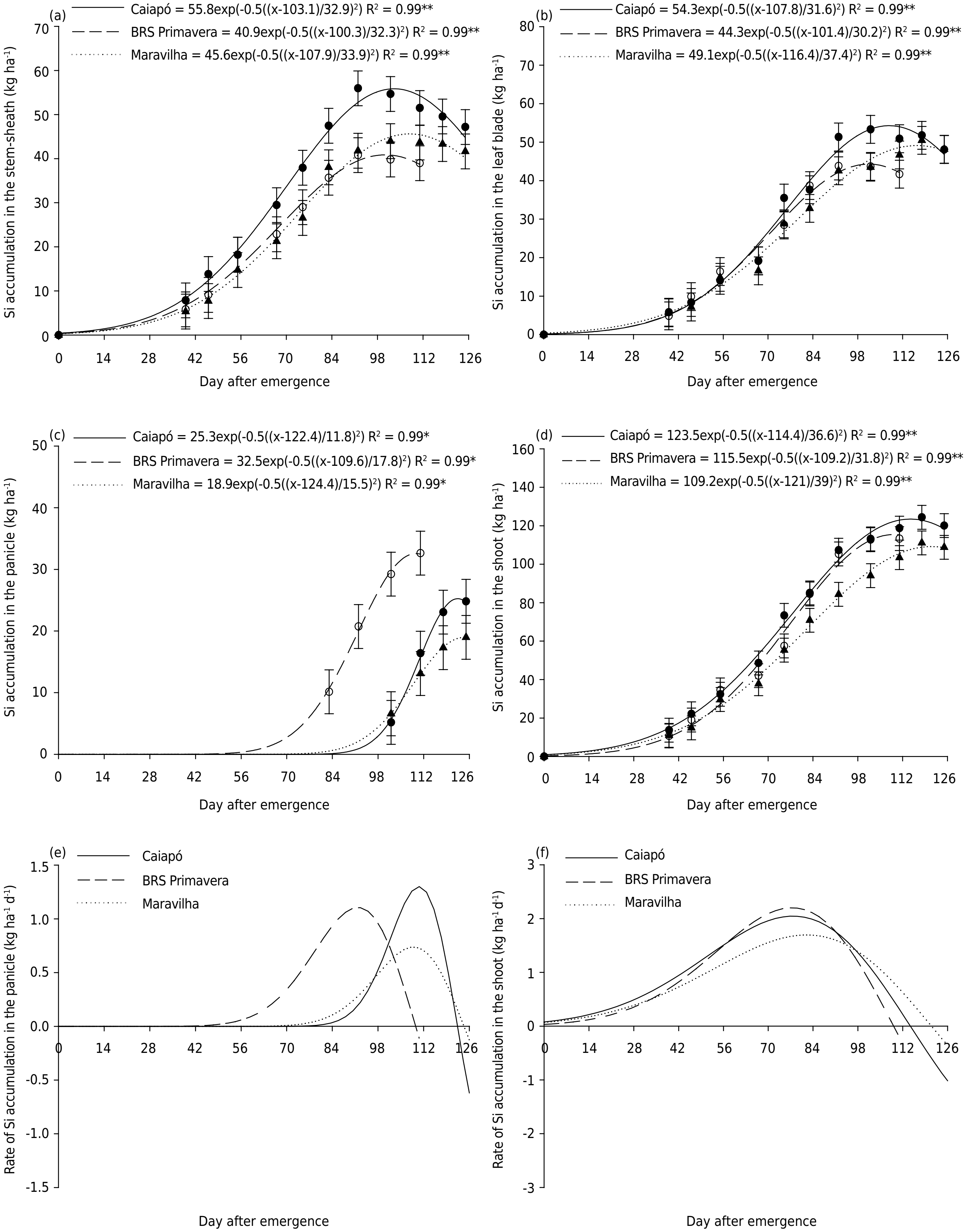

Figure 6. Silicon (Si) accumulation in the stems + sheath (a), leaf blades (b), panicles (c), shoots (d), and Si accumulation rates in the panicles (e) and in the shoots (f) of rice cultivars throughout their cycle. ** and *: significant at 5 % and 1 % by the F test, respectively. Vertical bars indicate the value of LSD by the t test (LSD) at 5 %.

Si accumulated in the leaf blades of all cultivars decreased (Figures 1b, 2b, 3b, 4b, 5b, and 6b) due to leaf senescence and a reduction in leaf blades DM (Crusciol et al., 2016).

In the panicles, the accumulation of micronutrients and Si increased with the flowering phase up to the end of the cycle (Figures 1c, 2c, 3c, 4c, 5c, and 6c). Throughout the entire reproductive and maturation phase, the accumulation of micronutrients and Si in the panicles of the BRS Primavera cultivar was, on average, 1.2-1.7-fold greater than in the other cultivars and occurred during an earlier phase of the cycle, when the accumulation rates of these nutrients in the panicles were already high (Figures 1c, 1e, 2c, 2e, 3c, 3e, 4c, 4e, 5c, 5e, 6c, and 6e). In the panicles of BRS Primavera, the accumulations per hectare were 19 g B, 26 g Cu, 199 g Fe, 234 g Mn, 102 g Zn, and 32 kg Si. In the panicles of the Caiapó and Maravilha cultivars, the accumulations of B, Cu, Fe, Mn, Zn, and Si were lower and not significantly different, with values per hectare of 14 g, 20 g, 160 g, 135 g, 67 g, and 21 kg, respectively. In these two cultivars, the accumulation rates of micronutrients and Si in the panicles remained high for a shorter period of time and occurred at an average of 20 days after the period of maximum accumulation of nutrients in the panicles of the BRS Primavera cultivar. The high accumulation of micronutrients and Si in the panicles of the BRS Primavera cultivar is the result of its high harvest index, which results in the greater development and accumulation of nutrients in the reproductive organ in relation to the vegetative organs of the plant (Figures 1, 2, 3, 4, 5, and 6).

During the beginning of the vegetative phase (46 DAE), the accumulation of micronutrients and Si in the shoots of all cultivars did not differ (Figures 1d, 2d, 3d, 4d, 5d, and 6d). However, after 46 DAE, the quantities of micronutrients and Si that had accumulated in the shoots increased intensely, and the cultivars reached maximum accumulations at different times in the cycle. This increase in the uptake of nutrients occurs due to the increase in shoot biomass with the advancement of plant age (Fageria and Santos, 2013), and demonstrates that the uptake of nutrients by rice cultivars varies with the growth and development stages of the plant (Fageria et al., 1997; Fageria, 2004). In the Caiapó and BRS Primavera cultivars, the maximum accumulation of B, Mn, and Fe occurred at 98 DAE, whereas the maximum accumulation of Cu, Zn, and Si was later and occurred after 105 DAE (Figures 1d, 2d, 3d, 4d, 5d, and 6d). In these cultivars, the period of greatest demand for nutrients occurred from tillering to grain formation, i.e., from 65 to 80 DAE, when the uptake rates reached maximum values (Figures 1f, 2f, 3f, 4f, 5f, and 6f). In other studies, the maximum micronutrient uptake rates by the rice plants occurred in this same crop phase (Gilmour, 1977; Malavolta et al., 1981a). In the Maravilha cultivar, the maximum accumulations of micronutrients and Si occurred on average two to three weeks after the period of maximum accumulation of these nutrients by the other cultivars, and the maximum uptake rates of the Maravilha cultivar always occurred after 80 DAE (Figures 1d, 1f, 2d, 2f, 3d, 3f, 4d, 4f, 5d, 5f, 6d, and 6f). Studying Zn uptake by rice, Jiang et al. (2008) also observed differences between the two cultivars studied in relation to the time periods of greatest uptake of this element.

Although the cultivars showed a greater demand for micronutrients and Si at different periods of the cycle, they did not differ in relation to the amounts of Cu and Si taken up, which ranged from 103 to 110 g ha^{-1} of Cu and from 111 to 124 kg ha^{-1} of Si (Figures 2d and 6d). Extraction of 77.1 g ha^{-1} of Cu in a flooded rice crop was observed by Fageria (2004). In spite of observing variations in the time of greatest demand for Si by the Caiapó and Maravilha cultivars, Mauad et al. (2013) also failed to observe large differences in the total amounts taken up by these cultivars. The BRS Primavera and Maravilha cultivars took up less Mn (1,278 g ha^{-1}) than the Caiapó cultivar (1,424 g ha^{-1}), and the largest proportion of the Mn taken up by the Caiapó cultivar was allocated to the leaf blades (Figure 4). The Maravilha cultivar took up a maximum of 240 g ha^{-1} of Zn, while the Caiapó and BRS Primavera cultivars took up an average of 278 g ha^{-1} of this nutrient and allocated most of this Zn taken up to the stems + sheath (Figure 5). The uptake of B and Fe was different among the cultivars, with the Caiapó cultivar taking up 135 g of B and 1,460 g of Fe per hectare; the Maravilha cultivar taking up 120 g of B and 1,290 g of Fe; and the BRS

Primavera cultivar taking up the lowest quantity of these nutrients, namely, 98 g of B and 1,157 g of Fe (Figures 1d and 3d). In the Caiapó and Maravilha cultivars, of the traditional and modern groups, the order of greatest uptake was Si>Fe>Mn>Zn>B>Cu, but in the BRS Primavera cultivar, from the intermediate group, Mn was taken up more than Fe, and Cu was taken up more than B (Figures 1d, 2d, 3d, 4d, 5d, and 6d). In a study carried out in pots, the cultivars BRSGO Guara and Talento had the same order of micronutrient uptake presented by the cultivars Caiapó and Maravilha (Fageria and Santos, 2013; Fageria and Knupp, 2013). However, other authors also observed a greater uptake of Mn than Fe by some rice cultivars (Fageria, 2004; Parry et al., 2005).

The BRS Primavera cultivar was the highest yielding and the one which extracted the lowest quantities of micronutrients and Si per Mg of grain produced (Table 1). This indicates greater nutritional efficiency, since the demand for micronutrients and Si of this cultivar was not greater than that of the other cultivars. These results show that the cultivars of the modern group (Maravilha) are not more demanding of nutrients than cultivars of the traditional group (Caiapó) because both the Caiapó (traditional group) and Maravilha (modern group) cultivars obtained very similar values of nutrient extraction per Mg of grain produced. For each ton of grain, the cultivars took up an average of 25 g of B, 23 g of Cu, 299 g of Fe, 291 g of Mn, 57 g of Zn, and 25 kg of Si (Table 1). Fageria (2004), in a study with a rice cultivar irrigated by flooding, observed lower values for the uptake of B (12 g) and Cu (15 g) and greater values of uptake of Fe (412 g), Mn (749 g), and Zn (91 g) per Mg of grain produced.

Table 1. Grain yield, micronutrient and Si extraction per Mg of grain, micronutrient and Si concentration in the grain, micronutrient and Si removal per area and per Mg of grain, and relative removal of micronutrient and Si by rice cultivars

Cultivar	Grain yield	B	Cu	Fe	Mn	Zn	Si
	kg ha^{-1}	Micronutrient and Si extraction (g Mg^{-1} of grain produced)(1)					kg Mg^{-1}
Caiapó	4,157 b	30.1 a	26.3 a	351.2 a	342.5 a	65.5 a	29.9 a
BRS Primavera	6,010 a	16.3 b	17.6 b	192.4 b	213.3 b	47.5 c	18.9 b
Maravilha	4,094 b	29.7 a	26.2 a	354.2 a	316.3 a	58.8 b	27.1 a
CV (%)	26.5	21.8	24.0	18.6	13.2	7.9	22.2
		Micronutrient and Si concentration in the grain (mg kg^{-1})					g kg^{-1}
Caiapó	-	4.0 a	5.9 a	46.0 a	41.1 a	20.4 a	6.9 a
BRS Primavera	-	3.8 a	4.9 b	38.2 a	44.8 a	19.6 ab	6.2 ab
Maravilha	-	4.0 a	5.2 ab	43.6 a	34.7 b	16.9 b	5.3 b
CV (%)	-	13.5	12.5	15.9	12.9	13.9	14.2
		Micronutrient and Si removal per area (g ha^{-1})					kg ha^{-1}
Caiapó	-	14.4 b	21.2 b	166.3 b	148.7 b	73.9 b	24.8 b
BRS Primavera	-	19.7 a	25.8 a	199.9 a	234.2 a	102.4 a	32.6 a
Maravilha	-	14.4 b	18.6 b	155.1 b	123.8 b	60.0 b	19.0 c
CV (%)	-	14.8	13.1	16.0	13.5	15.7	15.0
		Micronutrient and Si removal (g Mg^{-1} of grain produced)					kg Mg^{-1}
Caiapó	-	3.5 a	5.1 a	40.0 a	35.8 a	17.8 a	6.0 a
BRS Primavera	-	3.5 a	4.3 b	33.3 a	38.9 a	17.0 ab	5.4 ab
Maravilha	-	3.3 a	4.6 ab	37.9 a	30.2 b	14.7 b	4.6 b
CV (%)	-	13.5	12.5	15.9	12.9	13.9	14.2
		Relative removal of micronutrient and Si(2) (%)					
Caiapó	-	14	24	12	11	27	22
BRS Primavera	-	21	30	19	20	41	31
Maravilha	-	16	22	13	10	29	20
Mean	-	17	25	15	14	32	24

Values followed by the same letter in the column are not significantly different at p≤0.05 according to the LSD test. (1) Data based on grain yield and on the values of maximum micronutrients and Si accumulated in the shoot, obtained from figures 1, 2, 3, 4, 5, and 6. (2) Proportional micronutrient and Si removal in relation to the maximum quantities of these nutrients taken up by rice crop, obtained from figures 1, 2, 3, 4, 5, and 6.

There was no significant difference between the B and Fe concentrations in the grain of the cultivars studied (Table 1). Nevertheless, the grain of the Caiapó cultivar exhibited a Cu concentration that was 20.4 % greater than the BRS Primavera cultivar, and Zn and Si concentrations between 20.7 and 30 % greater than the Maravilha cultivar. However, in the grain of the Maravilha cultivar, the Mn concentration was 23.6 % lower than those of the other cultivars, but did not differ between themselves. With the exception of B, the concentrations of other micronutrients in the grain were lower than those obtained by Fageria (2004) in a flooded rice cultivar.

The removal of micronutrients and Si by the BRS Primavera cultivar per area was greater than that of the other cultivars, showing values per hectare of 19.7 g B, 25.8 g Cu, 200 g Fe, 234.2 g Mn, 102.4 g Zn, and 32.6 kg Si (Table 1). The greater removal by the BRS Primavera cultivar is the result of its high grain yield since the removal of micronutrients and Si per ton of grain produced showed little variation between the cultivars. The rice cultivar with the greatest yield removed the greatest quantities of micronutrients was also observed by Malavolta et al. (1982). Thus, fertilizer management with micronutrients and Si in upland rice cultivars should be carried out, especially considering the expected yield, since the quantities of nutrients taken up by the plants varied less than the quantities removed with the grain from the cropped area; the greater the yield, the greater the nutrient removal will be.

With regard to the relative removal of micronutrients and Si, it may be observed that of the total of micronutrients and Si taken up by the rice cultivars, the BRS Primavera cultivar removed from 5 to 12 % more nutrients along with the grain compared to other cultivars (Table 1). This occurred because the cultivar is higher yielding and accumulated greater quantities of micronutrients and Si in the panicles, thus removing relatively greater proportions of these nutrients.

The micronutrient with greatest relative removal was Zn, i.e., of the total taken up by the rice plant, around 32 % was removed along with the grain (Table 1). Zinc was the micronutrient removed in greatest proportions by the grain in a study carried out in a nutrient solution (Malavolta et al., 1982). The amounts of Cu and Si removed represented between 24 and 25 % of the total taken up by the plants throughout the cycle; however, for the micronutrients B, Fe, and Mn, these values were less than 17 %, which shows that a greater proportion of these micronutrients taken up remains in the vegetative organs (Furlani et al., 1977). Lower proportions of micronutrient removal in a flooded rice cultivar were obtained by Fageria (2004), the values of which were 7, 18, 3, 1, and 6 % for B, Cu, Fe, Mn, and Zn, respectively. In the case of Si, the relative removal values obtained were from 17 to 22 %, as observed by Ma et al. (1989). Zinc has been the most limiting micronutrient for growing rice in Cerrado soils, possibly because of the low availability in these soils (Vendrame et al., 2007) and because it is the micronutrient removed in the greatest proportions by the rice crop (Table 1).

CONCLUSIONS

Until the end of tillering (46 DAE), all cultivars exhibited low demand for most of the micronutrients and Si, and took up less than 24 % of the total of B, Cu, and Si, but around 31 % of the total Zn. The period of greatest uptake of micronutrients and Si occurred from 65 to 80 DAE in the Caiapó and BRS Primavera cultivars and after 80 DAE in the Maravilha cultivar. The Caiapó and BRS Primavera cultivars took up their needs of B, Mn, and Fe in the first 98 DAE and of Cu, Zn, and Si up to 105 DAE, but the Maravilha cultivar took up these nutrients for two to three weeks longer.

The quantities of micronutrients and Si taken up by cultivars Caiapó, BRS Primavera, and Maravilha of the traditional, intermediate, and modern groups did not exhibit big differences, and these cultivars took up the following levels per hectare: 98-135 g B, 103-110 g Cu, 1,157-1,460 g Fe, 1,278-1,424 g Mn, 240-285 g Zn, and 111-124 kg Si. The BRS Primavera cultivar showed greater removal of nutrients, with average amounts per hectare of 19.7 g B, 25.8 g Cu, 200 g Fe, 234.2 g Mn, 102.4 g Zn, and 32.6 kg Si, while the other cultivars removed smaller amounts per hectare (14.4 g B, 19.9 g Cu, 160.7 g Fe, 136.3 g Mn, 67 g Zn, and 21.9 kg Si). The BRS Primavera showed a greater removal of nutrients because it has a higher yield and allocates a greater quantity of nutrients to the panicles.

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REFERENCES

Alvarez RCF, Crusciol CAC, Nascente AS. Análise de crescimento e produtividade de cultivares de arroz de terras altas dos tipos tradicional, intermediário e moderno. Pesq Agropec Trop. 2012;42:397-406. doi:10.1590/S1983-40632012000400008

Bernardi ACC, Machado PLOA, Freitas PL, Coelho MR, Leandro WM, Oliveira Junior JP, Oliveira RP, Santos HG, Madari BE, Carvalho MCS, organizadores. Correção do solo e adubação no sistema de plantio direto nos cerrados. Rio de Janeiro: Embrapa Solos; 2003. (Documentos, 46).

Crusciol CAC, Fernandes AM, Carmeis Filho ACA, Alvarez RCF. Macronutrient uptake and removal by upland rice cultivars with different plant architecture. Rev Bras Cienc Solo. 2016;v40:e0150115. doi:10.1590/18069657rbcs20150115

Crusciol CAC, Soratto RP, Arf O. Produtividade de grãos e exportação de nutrientes de cultivares de arroz irrigadas por aspersão em consequência da época de semeadura. Bragantia. 2007;66:247-57. doi:10.1590/S0006-87052007000200008

Crusciol CAC, Arf O, Soratto RP, Machado JR. Extração de macronutrientes pelo arroz de terras altas sob diferentes níveis de irrigação por aspersão e de adubação. Rev Bras Agroci. 2003a;9:145-50. doi:10.18539/cast.v9i2.521

Crusciol CAC, Arf O, Soratto RP, Machado JR. Influência de lâminas de água e adubação mineral na nutrição e produtividade de arroz de terras altas. Rev Bras Cienc Solo. 2003b;27:647-54. doi:10.1590/S0100-06832003000400009

Das SK. Role of micronutrient in rice cultivation and management strategy in organic agriculture – A reappraisal. Agric Sci. 2014;5:765-9. doi:10.4236/as.2014.59080

Epstein E. Silicon. Ann Rev Plant Physiol Plant Molec Biol. 1994;50:641-64.

Fageria NK, Baligar VC, Jones CA. Growth and mineral nutrition of field crops. 2nd. ed. New York: Marcel Dekker; 1997.

Fageria NK, Knupp AM. Upland rice phenology and nutrient uptake in tropical climate. J Plant Nutr. 2013; 6:1-14. doi:10.1080/01904167.2012.724136

Fageria NK, Sant'ana EP, Moraes OP. Resposta de genótipos de arroz de sequeiro favorecido à fertilidade do solo. Pesq Agropec Bras. 1995;30:1155-61.

Fageria NK, Santos AB. Lowland rice growth and development and nutrient uptake during growth cycle. J Plant Nutr. 2013;36:1841-52. doi:10.1080/01904167.2013.816727

Fageria NK. Dry matter yield and nutrient uptake by lowland rice at different growth stages. J Plant Nutr. 2004;27:947-58. doi:10.1081/PLN-120037529

Fageria NK. Níveis adequados e tóxicos de zinco na produção de arroz, feijão, milho, soja e trigo em solo de cerrado. Rev Bras Eng Agríc Amb. 2000;4:390-5. doi:10.1590/S1415-43662000000300014

Fageria NK. Nutrição mineral. In: Santos AB, Stone LF, Vieira NRA, editores. A cultura do arroz no Brasil. 2ª. ed. rev. Santo Antônio de Goiás: Embrapa Arroz e Feijão; 2006.

Fidelis RR, Rodrigues AM, Silva GF, Barros HB, Pinto LC, Aguiar RWS. Eficiência do uso de nitrogênio em genótipos de arroz de terras altas. Pesq Agropec Trop. 2012;42:124-8. doi:10.1590/S1983-40632012000100018

Furlani PR, Bataglia OC, Furlani AMC, Azzini LE, Schmidt NC. Composição química inorgânica de três cultivares de arroz. Bragantia. 1977;36:109-15.

Gilmour JT. Micronutrient status of the rice plant. Micronutrient uptake rate as a function of time. Plant Soil. 1977;46:559-64.

Guimarães CM, Yokoyama LP. O Arroz em rotação com soja. In: Breseghello F, Stone LF, editores. Tecnologias para o arroz de terras altas. Santo Antônio de Goiás: Embrapa Arroz e Feijão; 1998. p.19-24.

Guimarães CM, Stone LF. Arroz de terras altas em rotação com soja. Pesq Agropec Trop. 2004;34:127-32. doi:10.5216/pat.v34i3.2305

Guimarães CM, Stone LF, Neves CF. Eficiência produtiva de cultivares de arroz com divergência fenotípica. Rev Bras Eng Agríc. 2008;12:465-470. doi:10.1590/S1415-43662008000500004

Jiang W, Struik PC, van Keulen H, Zhao M, Jin LN, Stomph TJ. Does increased zinc uptake enhance grain zinc mass concentration in rice? Ann Appl Biol. 2008;153:135-47. doi:10.1111/j.1744-7348.2008.00243.x

Kirkby EA, Römheld V. Micronutrientes na fisiologia de plantas: funções, absorção e mobilidade. Piracicaba: IPNI; 2007. (Informações agronômicas, 118).

Korndörfer GH, Pereira HS, Nola A. Análise de silício: solo, planta e fertilizante. Uberlândia: GPSi-ICIAG-UFU; 2004. (Boletim técnico, 2).

Ma J, Nishimura K, Takahashi E. Effect of silicon on the growth of rice plant at different growth stages. Soil Sci Plant Nutr. 1989;35:347-56. doi:10.1080/00380768.1989.10434768

Malavolta E, Vitti GC, Oliveira SA. Avaliação do estado nutricional das plantas: princípios e aplicações. 2ª. ed. Piracicaba: Associação Brasileira para Pesquisa da Potassa e do Fosfato; 1997.

Malavolta E, Florio A, Orellana AP, Cruz AP, Frenhani AA, Silva AT, Rodrigues BN, Nóbrega C, Azeredo DF, Paulo EM, Oliveira FA, Pereira HHG, Cabral CP, Pavan LHS, Dario LA, Antoniolli FC. Estudos sobre a nutrição mineral do arroz. X – Marcha de absorção de micronutrientes pela variedade IAC-25. Anais ESALQ. 1981a;38:551-9.

Malavolta E, Gomes IA, Guerrini IA, Carneiro IF, Mazza JA, Silva JCA, Sabino JC, Ramos JV, Chaves JCD, Daniel LA, Corrêa LS, Schiavuzzo MA, Costa MP, Cabral CP, Pavan LHS, Dario LA, Antoniolli FC. Estudos sobre a nutrição mineral do arroz. XI – Marcha de absorção de micronutrientes pela variedade IAC-47. Anais ESALQ. 1981b;38:561-7.

Malavolta E, Pauletto EA, Freitas JR, Cavalcanti LF, Liva ML, Fiore MF, Primavesi O, Fonseca SM, Cabral CP. Estudos sobre a nutrição mineral do arroz. XVII – Exigências nutricionais das variedades IAC-164 e IAC-165. Anais ESALQ. 1982;39:411-24.

Mauad M, Crusciol CAC, Nascente AS, Grassi Filho H, Corrêa JC. Acúmulo de silício na parte aérea de cultivares de arroz de terras altas afetado pela aplicação de silicato e carbonato no solo. Semina: Cienc Agrár. 2013;34:2049-60. doi:10.5433/1679-0359.2013v34n5p2049

Moraes JFV. Manejo dos solos dos cerrados. I. Produção de feijão, trigo e arroz em cultivos sucessivos em Latossolo Vermelho-Escuro. Pesq Agropec Bras. 1990;25:633-40.

Parry MM, Carvalho JG, Kato MSA, Vielhauer K. Estado nutricional do arroz cultivado em diferentes épocas e adubações sob cobertura morta. Rev Bras Eng Agríc Amb. 2005;9:57-65. doi:10.1590/S1415-43662005000100009

Pavinato PS, Aguiar A, Castro GSA, Crusciol CAC. Boro em arroz de terras altas cultivado em solução nutritiva. Bragantia. 2009;68:743-51. doi:10.1590/S0006-87052009000300022

Raij Bvan, Andrade JC, Cantarella H, Quaggio JA. Análise química para avaliação da fertilidade de solos tropicais. Campinas: Instituto Agronômico de Campinas; 2001.

Santos AB, Stone LF, Vieira NRA. A cultura do arroz no Brasil. 2ª. ed. Santo Antônio de Goiás: Embrapa Arroz e Feijão; 2006.

Santos HG, Jacomine PKT, Anjos LHC, Oliveira VA, Oliveira JB, Coelho MR, Lumbreras JF, Cunha TJF. Sistema brasileiro de classificação de solos. 3ª. ed. Rio de Janeiro: Embrapa Solos; 2013.

Soil Survey Staff. Keys to soil taxonomy. 10th.ed. Washington, DC: USDA-SCS; 2006.

Tokura AM, Furtini Neto AE, Carneiro LF, Curi N, Santos JZL, Alovisi AA. Dinâmica das formas de fósforo em solos de textura e mineralogia contrastantes cultivados com arroz. Acta Sci Agron. 2011;33:171-9. doi:10.4025/actasciagron.v33i1.1435

Vendrame PRS, Brito OR, Quantin C, Becquer T. Disponibilidade de cobre, ferro, manganês e zinco em solos sob pastagens na Região do Cerrado. Pesq Agropec Bras. 2007;42:859-64. doi:10.1590/S0100-204X2007000600013