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INFLUENCE OF POTASSIUM LEVELS ON ROOT GROWTH AND NUTRIENT UPTAKE OF UPLAND RICE CULTIVARS[1]

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ABSTRACT – Potassium (K) is an essential nutrient for upland rice growth, but little information on the effects of K on root growth and nutrient uptake capacity of upland rice is found. Therefore, an experiment was conducted under greenhouse conditions to evaluate the influence of soil K levels on root growth and nutrient uptake of four upland rice cultivars. A completely randomized experimental design, in a 4x4 factorial scheme (4 levels of K: 20, 40, 80, and 160 mg dm^{-3}; 4 cultivars: *Caiapó*, *BRS-Primavera*, *IAC-202*, and *Maravilha*) was used, with four replications. Based on regression equations, the highest values of root length density would be found with 136 mg dm^{-3} of K. The root diameter and dry matter, shoot dry matter and shoot K concentration increased linearly with the increasing K rates. The shoot K concentration of the upland rice cultivars did not differ. The increased level of K in the soil reduced the shoot Ca concentration of intermediate and modern cultivars, and the shoot Mg concentration of all cultivars. The potassium fertilization increased the plant growth, but the magnitude of this effect varied according to the cultivar.

Key words: *Oryza sativa* L.. Root length. Plant nutrition.

INFLUÊNCIA DE NÍVEIS DE POTÁSSIO NO CRESCIMENTO RADICULAR E NA ABSORÇÃO DE NUTRIENTES EM CULTIVARES DE ARROZ DE TERRAS ALTAS

RESUMO – O potássio (K) é um nutriente essencial para o crescimento do arroz, no entanto existem poucas informações sobre os efeitos do K no crescimento radicular e na capacidade de absorção de nutrientes por diferentes cultivares de arroz de terras altas. Um experimento foi conduzido em casa de vegetação para avaliar a influência de diferentes níveis de K no solo no crescimento radicular e absorção de nutrientes de quatro cultivares de arroz de terras altas. O delineamento experimental foi inteiramente casualizado, em esquema fatorial 4x4, (4 níveis de K: 20, 40, 80 e 160 mg dm^{-3}; 4 cultivares: *Caiapó*, *BRS-Primavera*, *IAC-202* e *Maravilha*), com quatro repetições. Com base nas equações de regressão, o maior valor para comprimento radicular seria obtido com aplicação de 136 mg dm^{-3} de K. O diâmetro e a matéria seca radicular, a concentração de K e a biomassa da parte aérea aumentaram linearmente com o aumento das doses de K, porém a concentração de K na parte aérea não diferiu entre as cultivares de arroz. O aumento do nível de K no solo reduziu a concentração Ca na parte aérea das cultivares dos grupos intermediário e moderno, mas a concentração de Mg reduziu em todas as cultivares. A adubação potássica aumentou o desenvolvimento das plantas, variando de acordo com o genótipo.

Palavras chave: *Oryza sativa* L.. Comprimento Radicular. Nutrição mineral.

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INTRODUCTION

Rice (*Oryza sativa* L.) is grown in Brazil using two different cropping systems, upland and lowland (SANTOS; STONE; VIEIRA, 2006). The plant yield capacity is reduced under upland conditions, mainly due to water stress, however, inadequate application of nutrients has also been reported as an important limiting factor of plant growth (CLOVER; MALLARINO, 2013; LOPES et al., 2013).

Potassium (K) is extracted from the soil in large amounts by upland rice plants (SLATON et al., 2009; FAGERIA; MOREIRA; COELHO, 2011b). The accumulation of K in rice shoots can reach 245 kg ha^{-1}, exhibiting greater rates than nitrogen, according to the cultivar and environmental condition (CRUSCIOL et al., 2016). The main role of K in plants is the osmoregulation of cells and tissues (FAGERIA; BALIGAR; JONES, 2011a), therefore, the increase in rice grain yield due to K fertilization is not as significant as the increases due to nitrogen and phosphorus fertilization, even considering the variations among cultivars (FARINELLI et al., 2004).

The characteristics of the upland rice root system may be an important factor to increase the K fertilization effect on grain yield, but little is known about their mechanisms. Root systems can develop significantly to uptake water and nutrients, even under low K availability (FAGERIA; BALIGAR; LI, 2008; GUIMARÃES et al., 2011). Although the pattern of root growth is controlled genetically, the soil chemical properties can modify the root architecture (SAINJU et al., 2005). Zobel (2003) confirmed that the root length density is usually affected by both factors (genotype and soil conditions), but the root diameter is more influenced by soil conditions.

Fageria and Moreira (2011) reported that the upland rice root system comprises 22% of the total plant dry matter, and that 70% of the root system is concentrated in the first 20 cm, and 90% in the first 40 cm of the soil, however, these characteristics can be modified according to soil chemical condition. A more vigorous root system allows better plant adaptation to water stress, maintaining the plant's ability to uptake water and nutrients, resulting in greater yield, particularly in non-irrigated crop systems.

Some authors have studied the effects of K fertilization on plant root growth (COSTA et al., 2009), however, little information is available on upland rice. In addition, previous studies were conducted, in general, evaluating the effect of K fertilization on yield components, grain production and quality parameters of upland rice cultivars (FARINELLI et al., 2004; ZARATIN et al., 2004), and the effect of K levels on root growth are little investigated. This information is important to adjust the recommendations of K rates for upland rice, especially in areas without irrigation and with frequent dry spells during rainfall season. Therefore, the objective of this study was to evaluate the influence of soil K levels on root growth and nutrient uptake of upland rice cultivars.

MATERIAL AND METHODS

The experiment was conducted under greenhouse conditions, in Botucatu SP, Brazil. Samples from the layer 0-20 cm of a Hapludox soil were collected, which had 690 g kg^{-1} of sand, 160 g kg^{-1} of clay and 150 g kg^{-1} of silt per sample. Soil chemical attributes were determined (0–20 cm) according to Raij et al. (2001), before the experiment was implemented (Table 1). The field capacity of the unstructured soil portion (sieved) in free drainage was determined at −0.03 MPa in a Richards extractor device, which resulted in 180 g kg^{-1}.

Table 1. Soil chemical properties prior to experiment initiation.

Layer	pH ($CaCl_2$)	P (resin)	H+Al	Ca^{2+}	Mg^{2+}	K^+	CEC	BS[1]
cm		mg dm^{-3}	--------------------	------ mmol$_c$ dm^{-3}	--------------------			%
0-20	3.8	2.0	52	5.0	1.0	0.2	58.2	10.6

[1]BS: base saturation.

The experiment was conducted in a completely randomized experimental design, in a 4x4 factorial scheme, with four replications. The treatments consisted of four K levels (20, 40, 80 and 160 mg dm^{-3}) and four cultivars of upland rice (*Caiapó* - traditional type, *IAC-202* and *BRS-Primavera* - intermediate type and *Maravilha* - modern type). Each experimental unit (plot) consisted of a 12 dm^{-3} polyethylene pot.

The characteristics of the four cultivars, which are used for rice production in upland systems, are described below according to the methods of Santos, Stone, and Vieira (2006).

Caiapó (released in 1992) is from the traditional type group. It produces tall plants with long and decumbent leaves and a low tillering capacity, and has the disadvantage of plant lodging in fertile soils or when fertilized with high rates of nitrogen.

Maravilha (released in 1996) is from the modern group. It produces short plants, short and erect leaves, strong stems, has high tillering and respond to fertilization without lodging, improving soil fertility and nitrogen fertilization.

IAC-202 (released in 1998) and *BRS-Primavera* (released in 1997) are from the intermediate group. They produce plants that have intermediate characteristics between the traditional and modern groups.

Lime (CaO 24%; MgO 18%) was applied to the sieved soil to increase its base saturation up to 60%. Subsequently, 10 kg of soil samples were packed in plastic bags with a water content of approximately 180 g kg^{-1} (field capacity) and incubated for 30 days. After this period, 120 mg dm^{-3} of nitrogen fertilizer (urea 44% N) was applied (60 mg dm^{-3} at sowing and 60 mg dm^{-3} top-dressed at early tillering), as well as 100 mg dm^{-3} of P (triple superphosphate), the K levels (potassium chloride), 2 mg dm^{-3} of boron (boric acid) and 5 mg^{-3} of Zn (oxide zinc), in each pot.

Ten seeds were sown per pot, and the plantlets were thinned to 4 specimens per pot. Soil moisture was monitored daily during the experiment by weighing the pots and applying water when transpiration reached 85% of the soil water field capacity. The upland rice plants were collected when they reached the full flowering stage (GUIMARÃES et al., 2011). After the crop harvest, soil samples were collected to determine the exchangeable K content in the soil, following the methods proposed by Raij et al. (2001). The plants were sectioned, separating shoots and roots. The soil in the roots was cleaned by washing them in running water over a 0.5 mm-mesh sieve. The root length and mean diameter were measured through image scanning using an HP Scanjet 4c/T and the Reg WinRhizo 3.8b software (Regent Instruments Inc.), following the method proposed by Tennant (1975). The roots were dried at 65°C for 72 h and weighed to determine their biomass (g plant^{-1}).

The shoots were washed in running water, dried in a forced air circulation oven at 65°C, and then weighed to determine their dry matter. Based on the sum of the dry matter of roots and shoots, the total dry matter, as well as the relationship between these parameters were calculated. Sub-samples of shoots were collected to determine the concentrations of N, P, K, Ca, Mg, S and Zn following the methods of Malavolta, Vitti and Oliveira (1997).

The uptake of N, P, K, Ca, Mg, S and Zn was determined using the data on the shoot dry matter, nutrient concentrations and nutrient content in the shoots. The nutrient uptake in relation to the root length was determined by dividing the nutrient levels in the plant by root length (ROSOLEM et al., 1993; SANTOS; STONE; VIEIRA, 2006). Nutrient use efficiency was calculated by dividing the shoot dry matter by the nutrient shoot content (CRUSCIOL et al., 2013).

The data on the roots (length density, diameter, and dry matter) as well as the shoot and total dry matter, nutrient concentration, nutrient content, nutrient uptake per root length and nutrient use efficiency, were analyzed through two-way ANOVA with the Statistical Software Package SAS (SAS INSTITUTE, 1999). The different upland rice cultivars and K levels were considered fixed effects (independent factors). Data was analyzed using the LSD test ($P \leq 0.05$). Regression analysis was employed for the K levels.

RESULTS AND DISCUSSION

The exchangeable K content in the soil increased after the harvest, depending on the amount of K applied, exhibiting a quadratic effect (Figure 1). Based on the regression equation, the excess of K in the soil treated with 160 mg dm^{-3} of K probably increased the ion acquisition by root cells, inducing a high accumulation of K by the plants. Due to specific K transporter mechanisms in the root membrane cells, K uptake in some species, such as rice, is very high (CRUSCIOL et al., 2016), and the availability of this nutrient in the soil plays a fundamental role in the K accumulation in these plants (KAMINSKI et al., 2007). The leaching effect must not be considered, because the irrigation was monitored to avoid water excess.

The modern-type cultivar *Maravilha* has high yield potential and photosynthetic efficiency (SANTOS; STONE; VIEIRA, 2006), but this genotype showed a lower root length density compared to cultivars from the intermediate group (*IAC-202* and *BRS-Primavera*) (Table 2). *Maravilha* presented the shortest root length, probably because this cultivar was intended for cultivation under irrigation or in areas with adequate rainfall conditions, thus, requiring smaller root system for water and nutrient uptake (SANTOS; STONE; VIEIRA, 2006; GUIMARÃES et al., 2011). According to Hsiao et al. (2009) and Fageria and Moreira (2011), the root length density is a characteristic that is genetically controlled, leading to differences among cultivars, as observed in the present experiment. Potassium deficiency has variable influence on physiological mechanisms of different rice genotypes (YANG et al. 2005). In addition to the genetic factors, the availability of K in the soil can influence the root growth. Based on the regression equation, the highest root length density would be reached with 136 mg dm^{-3} of K (Figure 2a), confirming the effect of K availability in root morphology. Similar results were observed by Hallmark and Barber (1981) for a soybean species. Therefore, potassium deficiency can affect root morphology and reduce root growth.

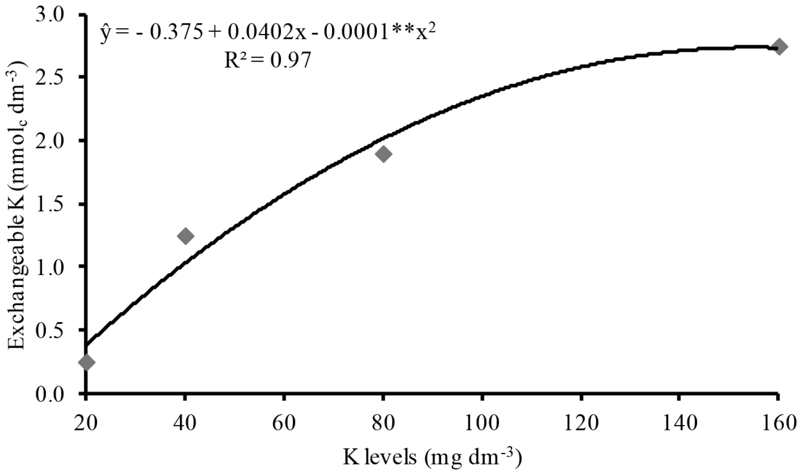

Figure 1. Exchangeable K contents in the soil as affected by increasing K levels. **significantly different at $p \leq 0.01$.

Table 2. Length, diameter, and dry matter of the root system, shoot dry matter, total dry matter, and root/shoot dry matter ratio of upland rice as affected by cultivar and increasing K levels.

Treatments	Root lenght	Root diameter	Root dry matter	Shoot dry matter	Total dry matter	Root/Shoot ratio
Cultivars	m plant^{-1}	mm	g plant^{-1}	g plant^{-1}	g plant^{-1}	
Maravilha	64.1 b[1]	0.14 a	7.4 a	5.0 a	12.4 a	1.4 a
Caiapó	72.3 ab	0.13 a	6.9 a	5.2 a	12.1 a	1.3 a
IAC 202	81.7 a	0.18 a	7.5 a	4.9 a	12.4 a	1.5 a
BRS Primavera	83.8 a	0.16 a	8.3 a	5.4 a	13.7 a	1.5 a
ANOVA (F probability)						
Cultivar (C)	0.0071	0.2937	0.5000	0.3157	0.4595	0.4484
K level (L)	<0.0001	0.0033	<0.0001	<0.0001	<0.0001	0.0079
C x L	0.1724	0.8050	0.9811	0.3246	0.9529	0.8819
CV (%)	21.60	31.58	35.72	14.10	24.11	28.69

[1] Values followed by the same letter vertically are not significantly different at $p<0.05$ according to a LSD test.

According to Yang et al. (2005), rice roots cause changes in the K fractionation and mobility in the rhizosphere, which may influence the uptake of K, root growth and crop yields. The potassium fertilization generated significant changes in root diameter (Table 2), which increased linearly with the increase of K rates (Figure 2b). The plants under low level of K, exhibited more favorable architecture for nutrient uptake, with thin roots. The main mode of nutrient transport from the soil solution to the plant is diffusion (FAGERIA; BALIGAR; JONES, 2011a), thus, the small root diameter found with the lowest K rates may benefit the plant adaptation, enabling the roots more efficiently to reach the nutrients in the soil (FAGERIA; BALIGAR; JONES, 2011a). For example, under low levels of K in the soil, the plant may have low root dry matter production as a result of reduced growth, while a proportional increase in the number of thin roots may increase the plant nutrient uptake ability (HALLMARK; BARBER, 1981). Similar results have been reported by Crusciol et al. (2005) for P fertilization. Roots with a small diameter are extremely important for plant development, since 90 –95% of the root length consists of roots with diameter less than 0.6 mm (ZOBEL, 2003; FAGERIA; BALIGAR; JONES, 2011a).

Potassium deficiency can significantly affect the root morphology, linearly increasing the root dry matter, and also the shoot and total dry matter production to a quadratic behavior, with the addition of K rates in the soil (Figure 2c). According to the regression model, the maximum values of shoot and total dry matter would be achieved with 146 and 151 mg dm^{-3} of K, respectively (Figure 3a and 3b). The increase in shoot dry matter observed with the highest rate of K was 2.95-fold higher than that with the lowest rate of K, while in the root system, the increase was only 1.89-fold higher than that with the lowest rate of K. Thus, the distribution of photoassimilates in the shoots and roots was altered, and the relationship increased as a function of the K availability in the soil (Figure 2F). No interaction was observed between the cultivars and K rates, but the K added to the soil increased the root growth (Table 2).

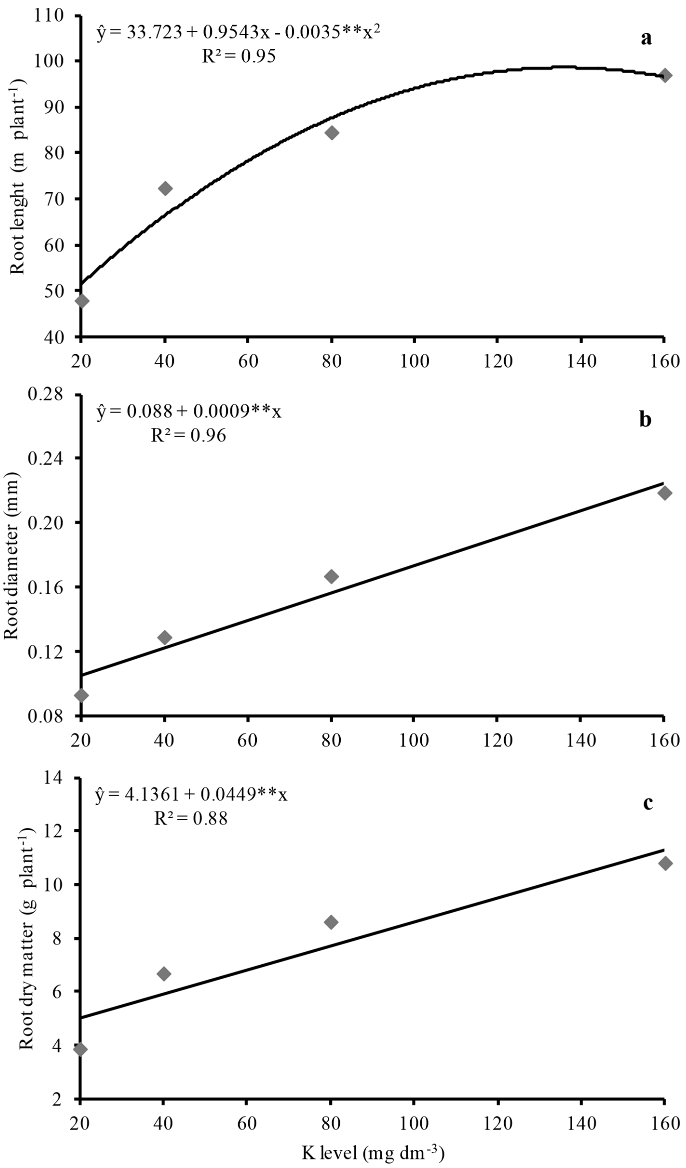

Figure 2. Length (a), diameter (b), and root dry matter (c) of upland rice as affected by increasing K levels. **significantly different at $p \leq 0.01$.

Despite the differences in root length density found among the upland rice cultivars (Table 2), no differences were found for N, P, and K concentration in the shoots (Table 3). Regarding N, this result may be due to the high mobility of nitrate in the soil, which allows contact between ions and roots (FAGERIA; BALIGAR; LI, 2008). Therefore, even in the treatments where shorter root lengths were found, N uptake was not reduced. Regarding P, this nutrient exhibits low mobility in the soil, however, rice plants require low P levels, showing a low uptake rate (SANTOS; STONE; VIEIRA, 2006; CRUSCIOL et al., 2016).

Potassium concentration in the shoots was similar among the cultivars (Table 3), however, differences in root length were found as a function of K fertilization and type of plant. Although genetic factors did not influence K concentration in the shoot, the higher availability of K in the soil improved the K uptake rate by plants (Figure 2a). Similar results were reported by Slaton et al. (2009), and Guimarães et al. (2011) in rice and Clover and Mallarino (2013) in corn and soybean. Therefore, the contact between ions and roots increases with the increase of K availability in the soil, contributing to greater K uptake by the roots.

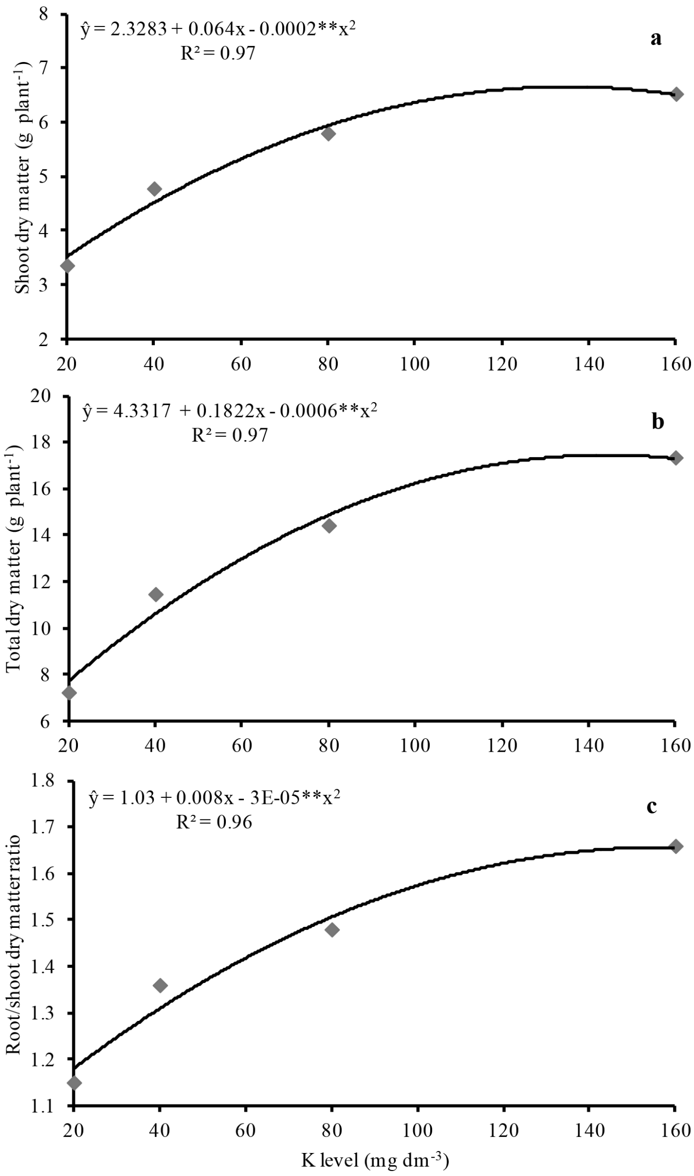

Figure 3. Shoot dry matter (a), total dry matter (b), and root/shoot dry matter ratio (c) for upland rice as affected by increasing K levels. **significantly different at $p \leq 0.01$.

Table 3. Nutrient concentration in the shoot of upland rice as affected by cultivar and increasing K levels.

Treatments	N	P	K	Ca	Mg	S	Zn
Cultivars	g kg^{-1}						mg kg^{-1}
Maravilha	45 a[1]	3.1 a	20 a	11.3 a	4.7 b	3.2 a	27 b
Caiapó	46 a	3.4 a	18 a	9.3 b	4.5 b	2.8 b	27 b
IAC 202	50 a	3.3 a	19 a	9.7 b	5.1 a	3.2 a	21 b
BRS Primavera	47 a	3.4 a	18 a	11.2 a	4.5 b	3.1 a	34 a
ANOVA (F probability)							
Cultivar (C)	0.3938	0.0411	0.6689	<0.0001	0.0039	0.0238	0.0083
K level (L)	0.0771	0.1377	<0.0001	0.0003	<0.0001	<0.0001	0.9611
C x L	0.8568	0.1271	0.6781	0.1351	0.1121	0.3009	0.5663
CV(%)	11.26	10.40	9.84	7.86	10.35	12.97	8.93

[1] Values followed by the same letter vertically are not significantly different at $p<0.05$ according to a LSD test.

Differences among the cultivars regarding the Ca, Mg, S and Zn concentrations in the shoot were found (Table 3). The modern and intermediate cultivars (*Maravilha* and *BRS-Primavera*) presented more efficient uptake and Ca transport, and the *BRS-Primavera* presented greater shoot Zn concentration. The highest Mg concentration was found in the cultivar *IAC-202*, probably because of the presence of a more specific carrier of Mg in the root system, resulting in higher levels of Mg uptake compared to those by the other cultivars, however, this specific carrier was not measured to confirm this hypothesis. According to Tanoi et al. (2011), the genetic characteristics can implicate in biosynthesis of specific proteins, with action on Mg transport. The cultivar *Caiapó* (traditional group) had lower values for Ca, S and Zn concentration in the shoot compared to the *BRS-Primavera* (intermediate group). According to Fageria, Baligar and Li (2008), these results are due to genetic characteristics that control the versatility of specific carriers involved in ion uptake through the plasmatic membrane of the root cells. The specificity and selectivity of these protein carriers are directly related to the use efficiency of mineral fertilizers (FAGERIA; BALIGAR; JONES, 2011a).

The shoot K concentrations increased linearly with the increasing K rates (Figure 4a). In contrast, the concentrations of Ca, Mg and S in the shoot decreased with the increasing K rates (Figures 4b, 4c and 4d). This result indicates interaction effects between K and other cations such as Ca and Mg (DALIPARTHYA; BARKER; MODAL, 1994). Rosolem et al. (1993) found in a three-year experiment that an annual K fertilization of 120 or 180 kg ha^{-1} of K_2O decreases Ca and Mg concentrations in soybean plants. A negative effect of K fertilizer was also observed on S uptake, probably due to an antagonistic effect between the Cl from KCl and SO_4 (ORTEGA; MALAVOLTA, 2012). In addition, the results found in the present work regarding nutrient concentrations may be related to differences in nutrient uptake efficiency among cultivars (FAGERIA; MOREIRA, 2011).

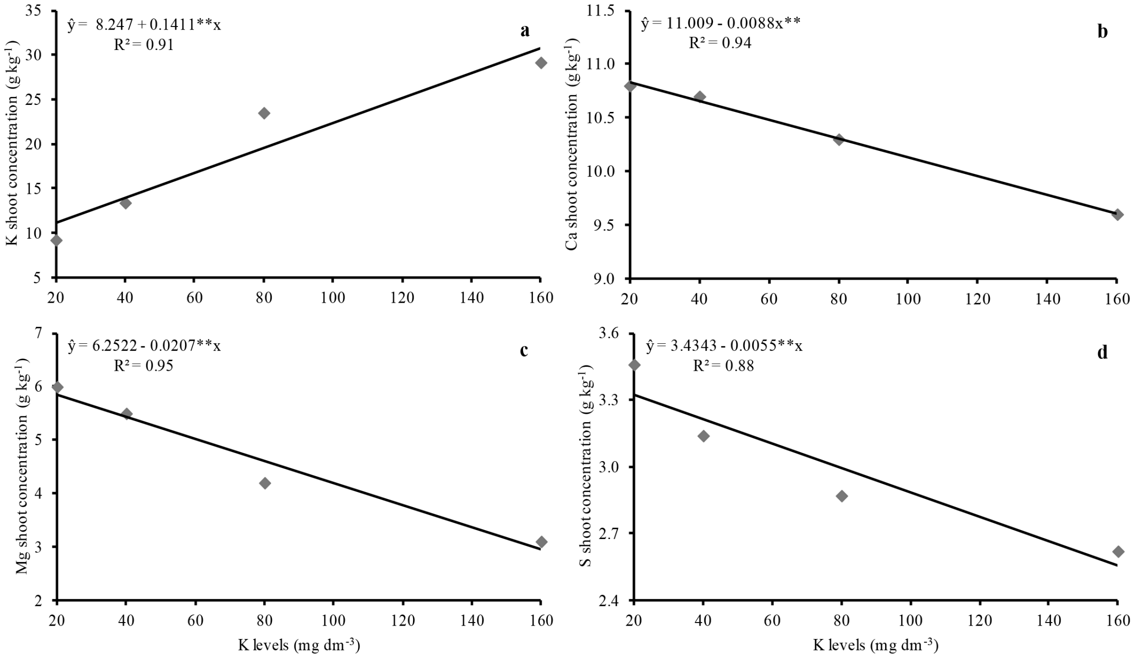

Figure 4. Potassium (a), calcium (b), magnesium (c), and sulfur (d) concentration in the shoot of upland rice as affected by increasing K levels. **significantly different at $p \leq 0.01$.

Cultivars Maravilha and BRS-Primavera cultivars showed greater Ca shoot contents (Table 4), probably because these cultivars had higher shoot Ca concentration than the other cultivars. Similarly, *BRS -Primavera* had higher values of Zn concentration and content in the shoot. The use of genotypes with greater uptake efficiency is important when the aim is to optimize mineral fertilization in cropping systems (CRUSCIOL et al., 2005).

Table 4. Nutrient content in the shoot of upland rice as affected by cultivar and increasing K levels.

Treatments	N	P	K	Ca	Mg	S	Zn
Cultivars			g plant^{-1}				mg plant^{-1}
Maravilha	0.222 a[1]	0.016 a	0.107 a	0.056 a	0.022 a	0.016 a	0.135 b
Caiapó	0.234 a	0.016 a	0.103 a	0.048 b	0.023 a	0.014 a	0.133 b
IAC 202	0.240 a	0.017 a	0.102 a	0.047 b	0.024 a	0.015 a	0.103 b
BRS Primavera	0.246 a	0.018 a	0.107 a	0.060 a	0.023 a	0.016 a	0.183 a
ANOVA (F probability)							
Cultivar (C)	0.5195	0.1073	0.9455	0.0002	0.6885	0.2055	0.0128
K level (L)	<0.0001	<0.0001	<0.0001	<0.0001	0.0923	<0.0001	0.0026
C x L	0.1813	0.5955	0.9462	0.1439	0.1091	0.4811	0.6265
CV(%)	12.87	15.18	17.82	17.01	18.20	19.17	22.72

[1] Values followed by the same letter vertically are not significantly different at $p<0.05$ according to a LSD test.

Potassium levels increased the shoot contents of N, P, K, Ca, S and Zn in the upland rice plants (Figures 5a, 5b, 5c, 6a, 6b and 6c). These increases may be due to its stimulation of root and shoot growth. Medeiros, Soares and Guimarães (2005) reported that plants with well-developed root systems have the ability to exploit a greater soil volume, which is fundamental for increasing the contact between roots and nutrients, resulting in an improvement in nutrient uptake.

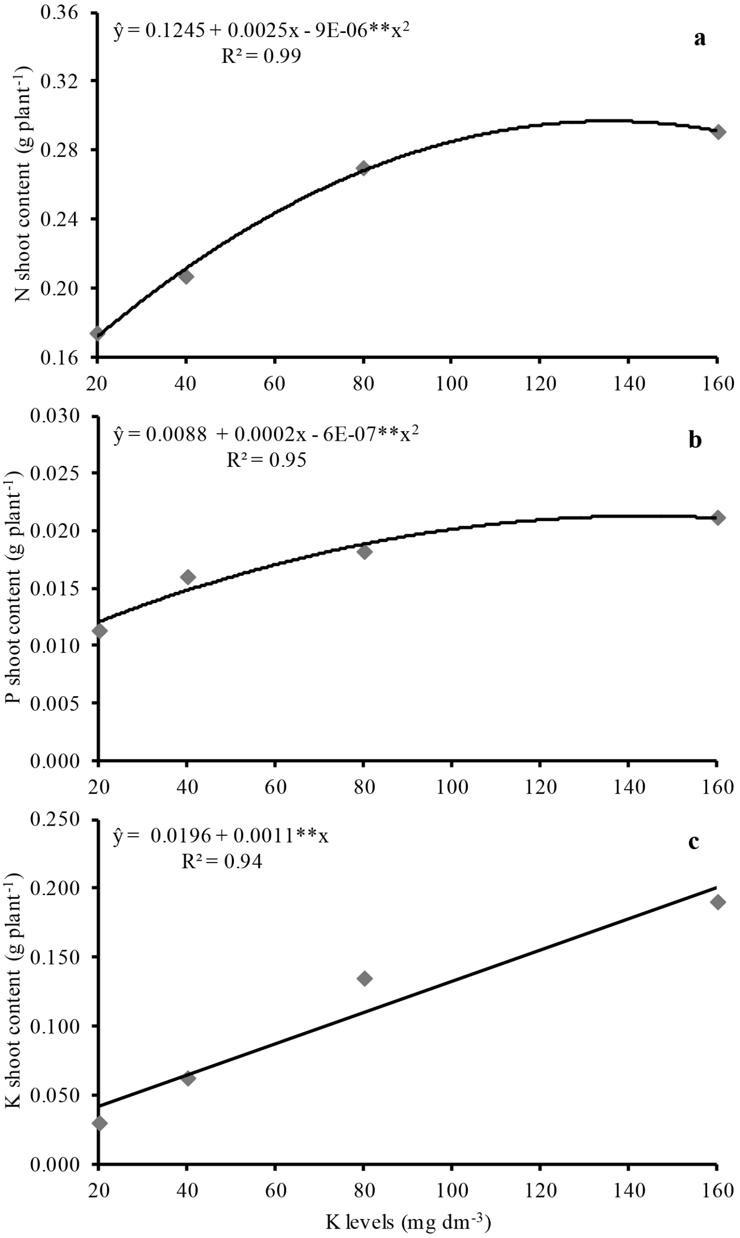

Figure 5. Nitrogen (a), phosphorus (b), and potassium (c) content in the shoot of upland rice as affected by increasing K levels. **significantly different at $p \leq 0.01$.

Phosphorus, K, Ca, S and Zn uptake per root length was affected by the genetic factor (Table 5). According to Horn et al. (2006), differences in the kinetic parameters of nutrient uptake is a result of the expression of genetic characteristics, especially on membrane protein transporters in root cells. This result denotes the importance of breeding programs for developing rice cultivars with high capacity of nutrient uptake.

The application of K promoted greater availability of K in the soil, increasing the K diffusion rate in the soil, and consequently, the contact between K and the rice roots (Figure 7a). Similar results were found by Oliveira, Rosolem and Trigueiro (2004) in cotton (*Gossypium hirsutum*). Conversely, the Mg and S uptake per unit of root length was reduced with the increasing K rates (Figures 7b and 7c).

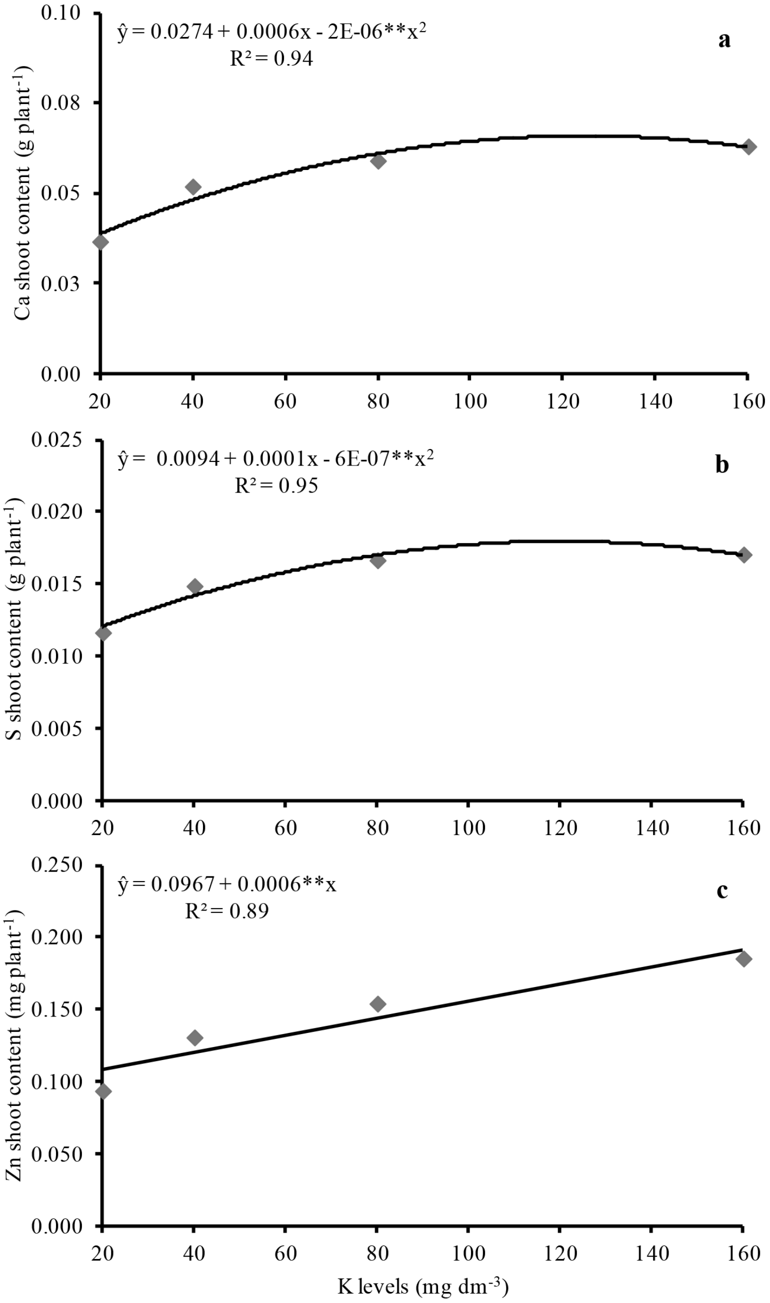

Figure 6. Calcium (a), sulfur (b) and zinc (c) content in the shoot of upland rice as affected by increasing K levels. **significantly different at $p \leq 0.01$.

Table 5. Nutrients uptake per unit root length of upland rice as affected by cultivar and increasing K levels.

Treatments	N	P	K	Ca	Mg	S	Zn
Cultivars				g m^{-1}			mg m^{-1}
Maravilha	0.004 a[1]	0.0003 a	0.0016 a	0.0009 a	0.0004 a	0.0003 a	0.002 a
Caiapó	0.003 a	0.0003 a	0.0015 ab	0.0008 b	0.0004 a	0.0002 b	0.002 a
IAC 202	0.003 a	0.0002 b	0.0012 b	0.0006 c	0.0003 a	0.0002 b	0.001 b
BRS Primavera	0.003 a	0.0003 a	0.0013 ab	0.0008 b	0.0003 a	0.0002 b	0.002 a
ANOVA (F probability)							
Cultivar (C)	0.4756	0.5845	0.1428	<0.0001	0.2521	0.0208	0.0034
K level (L)	0.1281	0.6159	<0.0001	0.1558	<0.0001	0.0081	0.9838
C x L	0.2761	0.0899	0.2347	0.0911	0.0772	0.0644	0.1717
CV(%)	22.98	18.75	17.92	20.64	23.78	21.26	24.67

[1] Values followed by the same letter vertically are not significantly different at $p<0.05$ according to a LSD test.

The competition between Mg^{2+} and K^+ ions for the same binding sites on the carrier during the ion acquisition process is most likely reflected in negative effects on Mg uptake (MORTVEDT; KHASAWNEH, 1986). A marked imbalance of these two macronutrients can result in nutritional deficiencies and may severely impact the grain yield. The decrease in the S uptake may be related to the competition between Cl^- and SO_4^{-2}, however, the K levels effect on root length density, enhancing plant exploration, may have leaded the rice plants to a lower requirement of S per unit of root length. Although, this result comes from a greenhouse experiment, where plants were grown in pots with a restrict soil volume, in a field condition the results could be more expressive, since root system can explore a greater volume of soil.

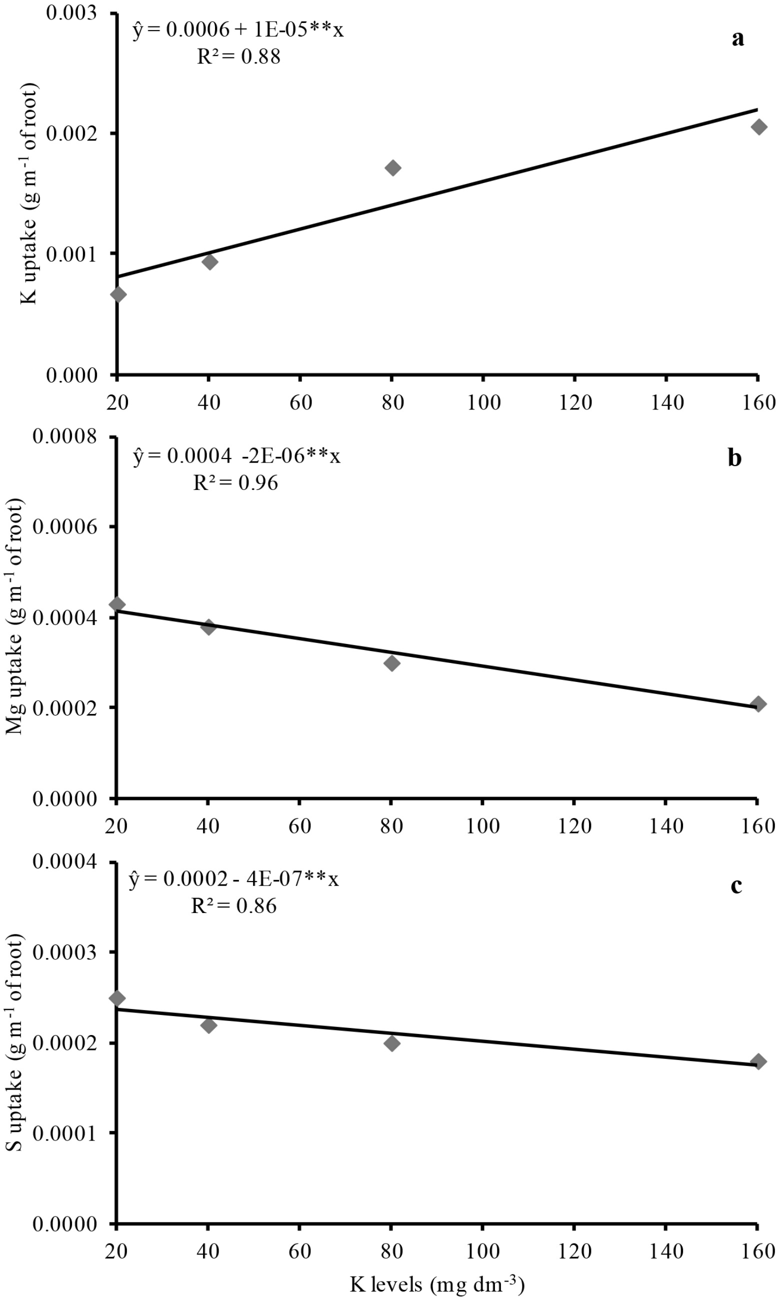

Figure 7. Potassium (a), magnesium (b) and sulfur (c) uptake per unit root length of upland rice as affected by increasing K levels. **significantly different at $p \leq 0.01$.

The cultivar *Caiapó* is from the traditional group, however, it had nutrient use efficiency similar to the modern cultivars (Table 6). Only the P use efficiency of *Caiapó* was lower than that of the modern cultivar (*Maravilha*). According to Santos, Stone, and Vieira (2006), *Caiapó* is highly efficient in nutrient uptake and requires lower amounts of photosynthetic compounds for the formation of vegetative structures.

Table 6. Nutrient use efficiency of upland rice as affected by cultivar and increasing K levels.

Treatments	N	P	K	Ca	Mg	S	Zn
Cultivars			g SDM g SNC^{-1}				mg g^{-1}
Maravilha	21 a[1]	330 a	66 a	89 b	237 ab	318 b	37.5 b
Caiapó	22 a	301 b	65 a	109 a	227 ab	372 a	45.3 a
IAC 202	21 a	308 b	66 a	104 a	219 b	322 b	49.3 a
BRS Primavera	22 a	299 b	71 a	90 b	241 a	350 ab	31.5 b
ANOVA (F probability)							
Cultivar (C)	0.1341	0.0646	0.4653	<0.0001	0.0919	0.0072	0.0002
K level (L)	0.0638	0.1677	<0.0001	0.0032	<0.0001	<0.0001	0.7214
C x L	0.3142	0.2206	0.1034	0.1315	0.2175	0.2476	0.1033
CV(%)	12.52	11.30	15.59	8.63	11.31	10.39	16.68

[1] Values followed by the same letter vertically are not significantly different at P<0.05 according to a LSD test. SDM: shoot dry matter; SNC: shoot nutrient content.

The low Ca and Zn use efficiency by the modern and intermediate cultivar groups (*Maravilha* and *BRS-Primavera*) is related to the higher accumulation of these nutrients and shoot dry matter production (Table 4). Despite the small variations observed, these results showed that the cultivars exhibit similar characteristics regarding the conversion rate of nutrients into dry matter. In addition to genetic factors, the physiological changes caused by environmental conditions during the cultivation period caused changes in the efficiency of nutrient absorption (FAGERIA; MOREIRA, 2011).

The highest K use efficiency was observed with application of 20 mg dm^{-3} of K (Figure 8a). Although higher K levels increase nutrient content in plant structures (Figure 5a, 5b, 5c, 6a, 6b, and 6c), the effect resulted in lower conversion of nutrients into dry matter. According to Rosolem et al. (1993), the K availability in the soil negatively affects the uptake of other cations, including Ca and Mg, which are directly related to the synthesis of plant dry matter (root and shoot). The influence of K availability on these cationic macronutrients can be observed in the present experiment by the Ca and Mg shoot concentration data (Figures 4b and 4c).

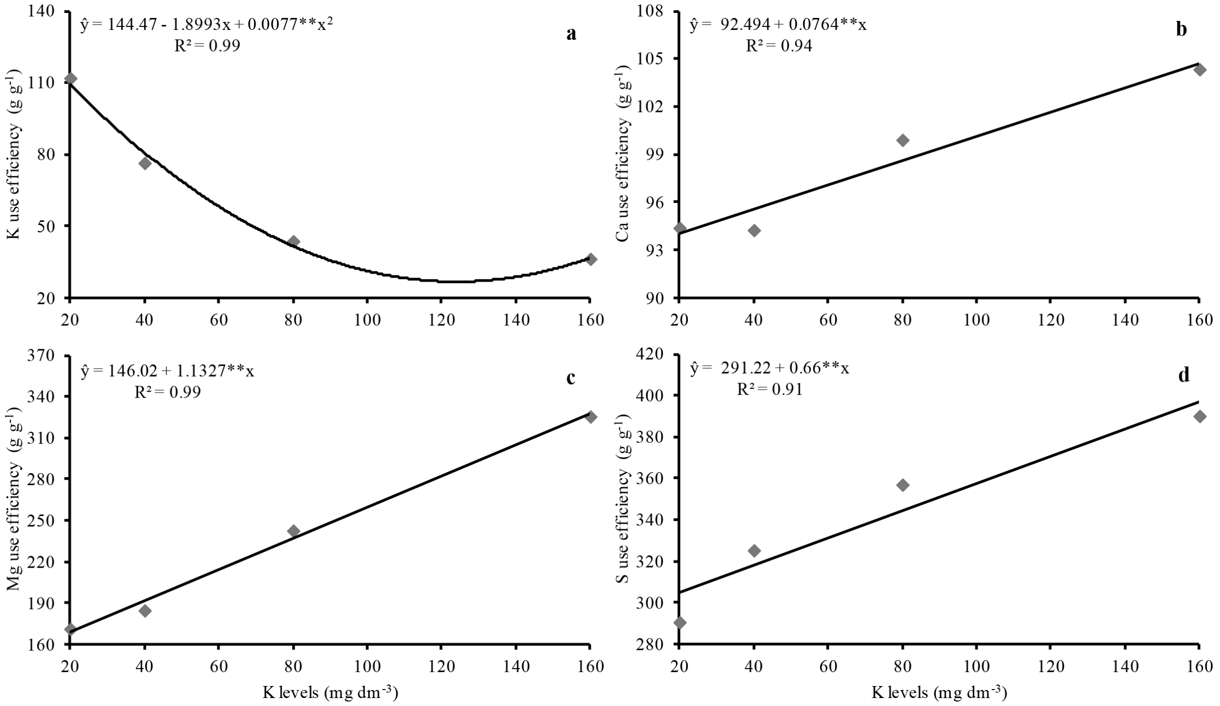

Figure 8. Potassium (a), calcium (b), magnesium (c) and sulfur (d) use efficiency of upland rice as affected by increasing K levels. **significantly different at p≤0.01.

The Ca, Mg and S use efficiency increased according to the increase of K fertilization in the soil (Figures 8b, 8c and 8d, respectively). These results can be explained by the low total dry matter production. The Ca, Mg and S use efficiency improved as the K availability increased root and shoot growth. According to Fageria, Baligar and Jones (2011a), the nutrient use efficiency may vary depending on the nutrient balance in the plant, and when an element shows lower availability in the soil, the accumulation of dry matter by the plant is limited, leading to a decline in the use efficiency of other nutrients.

CONCLUSIONS

The application of K in the soil increases plant biomass, length density and root diameter of upland rice cultivars. The K shoot concentration is similar for all cultivars evaluated. Increasing K levels in the soil reduces Ca, Mg, and S shoot concentration, but increases use efficiency of these nutrients by upland rice plants.

REFERENCES

CLOVER, M. W.; MALLARINO, A. P. Corn and soybean tissue potassium content responses to potassium fertilization and relationship with grain yield. **Soil Science Society of America Journal**, Madison, v. 77, n. 2, p. 630-642, 2013.

COSTA, S. E. V. G. A. et al. Distribuição de potássio e de raízes no solo e crescimento de milho em sistemas de manejo do solo e da adubação em longo prazo. **Revista Brasileira de Ciência do Solo**, Viçosa, v. 33, n. 5, p. 1291-1301, 2009.

CRUSCIOL, C. A. C. et al. Doses de fósforo e crescimento radicular de cultivares de arroz de terras altas. **Bragantia**, Campinas, v. 64, n. 4, p. 643-649, 2005.

CRUSCIOL, C. A. C. et al. Macronutrient uptake and removal by upland rice cultivars with different plant architecture. **Revista Brasileira de Ciência do Solo**, Viçosa, v. 40, 2016.

CRUSCIOL, C. A. C. et al. Upland Rice growth and mineral nutrition as affected by cultivars and sulfur availability. **Soil Science Society of America Journal**, Madison, v. 77, n. 1, p. 328-335. 2013.

DALIPARTHY, J.; BARKER, A. V.; MONDAL, S. S. Potassium fractions with other nutrients in crops. A review focusing on the tropics. **Journal of Plant Nutrition**, Philadelphia, v. 17, n. 1, p. 1859-1886, 1994.

FAGERIA, N. K.; BALIGAR, V. C.; JONES, C. A. **Growth and mineral nutrition of field crops**. 3. ed. Boca Raton: CRC Press, 2011a. 560 p.

FAGERIA, N. K.; BALIGAR, V. C.; LI, Y. C. The role of nutrient efficient plants in improving crop yields in the twenty first century. **Journal of plant nutrition**, Philadelphia, v. 31, n. 6, p. 1121–1157. 2008.

FAGERIA, N. K.; MOREIRA, A. The role of mineral nutrition on root growth of crop plants. **Advances in Agronomy**, New York, v. 110, n. 1, p. 251-331, 2011.

FAGERIA, N. K.; MOREIRA, A.; COELHO, A. M. Yield and yield components of upland rice as influenced by nitrogen sources. **Journal of plant nutrition**, Philadelphia, v. 34, n. 1, p. 361-370, 2011b.

FARINELLI, R. et al. Características agronômicas de arroz de terras altas sob plantio direto e adubação nitrogenada e potássica. **Revista Brasileira de Ciência do Solo**, Viçosa, v. 28, n. 3, p. 447-454, 2004.

GUIMARÃES, C. M. et al. Sistema radicular do arroz de terras altas sob deficiência hídrica. **Pesquisa Agropecuária Tropical**, Goiânia, v. 41, n. 1, p. 126-134, 2011.

HALLMARK, W. B.; BARBER, S. A. Root growth and morphology, nutrient uptake, and nutrient status of soybean as affected by soil K and bulk density. **Agronomy Journal**, Madison, v. 73, n. 5, p. 779-782, 1981.

HORN, D. et al. Parâmetros cinéticos e morfológicos da absorção de nutrientes em cultivares de milho com variabilidade genética contrastante. **Revista Brasileira de Ciência do Solo**, Viçosa, v. 30, n. 1, p. 77-85, 2006.

HSIAO, T. C. et al. AquaCrop – The FAO crop model to stimulate yield response to water: III. Parameterization and testing for maize. **Agronomy Journal**, Madison, v. 101, n. 3, p. 448–459, 2009.

KAMINSKI, J. et al. Depleção de formas de potássio do solo afetada por cultivos sucessivos. **Revista Brasileira de Ciência do Solo**, Viçosa, v. 31, n. 5, p. 1003-1010, 2007.

LOPES, R. A. et al. Doses, fontes e épocas de aplicação de nitrogênio em arroz de terras altas cultivado em sistema semeadura direta. **Revista Caatinga**, Mossoró, v. 26, n. 4, p. 79-87, 2013.

MALAVOLTA, E.; VITTI, G. C.; OLIVEIRA, S. A. **Avaliação do estado nutricional de plantas**: princípios e aplicações. 2. ed. Piracicaba, SP: Potafós, 1997. 309 p.

MEDEIROS, R. D.; SOARES, A. A.; GUIMARÃES, R. M. Compactação do solo e manejo da água. I: efeitos sobre a absorção de N, P, K, massa seca de raízes e parte aérea de plantas de arroz. **Ciência e Agrotecnologia**, Lavras, v. 29, n. 5, p. 940-947, 2005.

MORTVEDT, J. J.; KHASAWNEH, F. E. Effects of growth responses on cationic relationships in plants. **Soil Science**, Baltimore, v. 141, n. 3, p. 200-207, 1986.

OLIVEIRA, R. H.; ROSOLEM, C. A.; TRIGUEIRO, R. M. Importância do fluxo de massa e difusão no suprimento de potássio ao algodoeiro como variável de água e potássio no solo. **Revista Brasileira de Ciência do Solo**, Viçosa, v. 28, n. 3, p. 439-445, 2004.

ORTEGA, A. E.; MALAVOLTA, E. Los más recientes micronutrientes vegetales. **Informaciones Agronómicas de Hispanoamérica**, Georgia, v. 7, n. 1, p. 16-25, 2012.

RAIJ, B. VAN et al. **Análise química para avaliação da fertilidade de solos tropicais**. Campinas, SP: IAC, 2001. 284 p.

ROSOLEM, C. A. et al. Potassium fertilization, root morphology and potassium absorption by soybean. **Journal of Plant Nutrition**, Philadelphia, v. 16, n. 3, p. 479-492, 1993.

SAINJU, U. M.; SINGH, B. P.; WHITEHEAD, W. F. Tillage, cover crops, and nitrogen fertilization effects on cotton and sorghum root biomass, carbon, and nitrogen. **Agronomy Journal**, Madison, v. 97, n. 5, p. 1279–1290, 2005.

SANTOS, A. B.; STONE, L. F.; VIEIRA, N. R. A. **A cultura do arroz no Brasil**. 2. ed. Santo Antônio de Goiás, GO: Embrapa Arroz e Feijão, 2006. 1000 p.

SAS Institute. **Procedure guide for personal computers**. 5. version. Cary: Analytics, Business Intelligence and Data Management, 1999.

SLATON, N. A. et al. Correlation and calibration of soil potassium availability with rice yield and nutritional status. **Soil Science Society of America Journal**, Madison, v. 73, n. 4, p. 1192-1201, 2009.

TANOI, K. et al. The analysis of magnesium transport system from external solution to xylem in rice root. **Soil Science and Plant Nutrition**, Oxon, v. 57, n. 1, p. 265-271, 2011.

TENNANT, D. A. Test of a modified line intersect method of estimating root length. **Journal of Ecology**, Oxford, v. 63, n. 3, p. 995-1001, 1975.

YANG, X. E. et al. Room-induced changes of potassium in the rhizosphere of lowland rice. **Communication in Soil Science and Plant Analyses**, New York, v. 36, n. 13, p. 1947–1963, 2005.

ZARATIN, C. et al. Efeitos de quatro doses de potássio em seis cultivares de arroz de sequeiro irrigados por aspersão. I. Componentes de produção e produtividade. **Científica**, Jaboticabal, v. 32, n. 2, p. 115-120, 2004.

ZOBEL, R. W. Sensitivity analysis of computer based diameter measurement from digital images. **Crop Science**, Madison, v. 43, n. 2, p. 583–591, 2003.