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Production and accumulation of silicon (Si) in rice plants under silicate fertilization and soil water tensions

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Abstract

This study aimed to evaluate the effect of silicate fertilization and soil water tensions on the production and accumulation of silicon in upland rice plants in an Oxisol of the Cerrado, Brazil. The experiment was conducted in a greenhouse from June to October 2014. A 5×5 factorial scheme fractionated with five soil water tensions (0, 15, 30, 45 and 60 kPa) and five silicon doses (0, 120, 240, 480 and 960 mg dm^{-3}) was used and was distributed according to a randomized block design with four replications. The results were submitted to an analysis of variance (F test) and regression study with 5% probability ($p \leq 0.05$). The following components were evaluated: the leaf angle, chlorophyll content, mass of grains, dry mass of the shoot, dry mass of the root, and concentration and accumulation of silicon. Silicon doses of 775.8 and 751.7 mg dm^{-3} provided a lower leaf angle and higher chlorophyll content, respectively. The addition of soil water tensions caused a reduction of 46.4% grain mass, comparing the lowest soil water tension (0 kPa) with the highest tension (60 kPa). The soil water tensions of 45 kPa, 38 kPa, 47 kPa and 46.7 kPa provided the lowest values of dry mass of shoot, dry mass of root, concentration of silicon and silicon accumulation, respectively. The dose of 750 mg dm^{-3} silicon improved plant architecture and increased the chlorophyll content of upland rice plants.

Keywords: *Oryza sativa*; tensiometer; silicon; accumulation; leaf angle; chlorophyll content.

Abbreviations: ABA_abscisic acid; pH_hydrogen potential; P_phosphorus; Ca_calcium; Mg_magnesium; H_Hydrogen; Al_aluminum; CEC_cation exchange capacity; V_base saturation; OM_organic matter; PA_pure analytical-grade; B_Boron; Cu_copper; Mn_manganese; Zn_zinc; Mo_molybdenum; SAS_statistical analysis system; F-test_statistical test; RSREG_regression procedures; GLM_command general linear model procedure; PRNT_relative power of total neutralization; NADP_nicotinamide adenine dinucleotide phosphate; SPAD_soil plant analysis development; kPa_kilopascals.

Introduction

Rice (*Oryza sativa* L.) is among the most consumed cereals in the world. Being a basic component of the Brazilian population diet, rice provides 17.9% of the protein and 34.2% of the total calories ingested considering all socio-economic classes (Naves and Bassinello, 2006). Rice production in Brazil occurs in lowland ecosystems with flooded rice and in ecosystems of upland rice that are grown in rainfed systems or irrigated by sprinklers. The production system of upland rice is the most geographically widespread, with 65% of the cultivated area in the Cerrado region (IBGE, 2014). This region is characterized by a prevalence of soils with low fertility and the occurrence of dry spells, which cause water deficit to the culture (Bastos and Ferreira, 2010). This factor, along with the high evapotranspiration demand of the atmosphere, significantly decreases rice yields. Thus, the incorporation of cultivation techniques, which can increase the tolerance of plants to water stress periods and control soil moisture, are of fundamental importance to consolidate with high productivity the presence of the rice crop in grain production systems in the region of Cerrado. The control of soil moisture through tensiometry has demonstrated its practicability in the monitoring of irrigation in the conditions of the Cerrado Oxisols (Guerra et al., 1994). With the daily monitoring of moisture conditions in the area of plant roots, it is possible to properly manage irrigation by measuring the water tension in the soil and thus to provide water at the appropriate time and in sufficient quantity to meet the water needs of the plant. Tensiometry combined with fertilization with beneficial chemicalscreates a viable alternative to upland rice crops. Among these elements, silicon is notable; although it is not physiologically essential for plants, it provides several benefits, especially for monocots such as rice. The beneficial action of silicon in rice plants has been linked to several indirect effects that include increased utilization efficiency and use of solar energy and, consequently, an increased photosynthetic capacity; reduced perspiration; increased resistance to certain insects and diseases; increased absorption of other elements, such as phosphorus; and a more upright shape (Ávila et al., 2010; Ghareeb et al., 2011). In Brachiaria, Sousa and Santos (2010) observed a linear increase in the silicon content at shoot doses of up to 1600 kg ha^{-1} silicon available in the soil. Working with the foliar application of silicon on corn, Freitas et al. (2011) observed increased foliar until a dose of 217.9 g ha^{-1}. In sugar cane culture, Elawad et al. (1982) in the United States of America and Korndörfer et al. (2002) in Brazil, reported an increase of 14 t ha^{-1} in the production of sugar cane grown in Neossolo Quarzarênico with a dose of 4 t ha^{-1}

calcium metasilicate. Lima-Filho and Tsai (2007) found that silicon doses in growing wheat (cv. BR40) led to an increase in grain production of 100% with the higher dose (100 mg dm^{-3}) compared to the control. Hence, silicon in rice plants confers better morphological and physiological conditions to the plant, particularly when plants are under biotic or abiotic stress (Ma, 2004; Ma and Yamaji, 2006). Due to the economic and social importance of the upland rice crop in Brazil, studies are necessary to investigate rice hydric needs, climatical stress resistance and the effect of silicon applications as a stress reducer under the adverse conditions of the Brazilian Cerrado. Thus, the objective of this study was to evaluate the effect of silicate fertilization and soil water tension on the production and accumulation of silicon in upland rice plants in an Oxisol of the Cerrado.

Results and Discussion

Leaf angle of rice plants

There was not an interaction between the silicon fertilization and soil water tensions for all variables. However, there was an effect, in isolation, of the factors of silicon fertilization and soil water tensions on all of the analyzed variables.

According to the applied statistical model, an isolated effect was found on the leaf angle of rice plants (Fig. 1) with the evaluated doses of silicon. The effects were fit to a quadratic regression model. The smallest leaf angle (15.78°) was observed with a silicon dose of 785.8 mg dm^{-3}. The increase in silicon levels resulted in a smaller opening of the leaf angle of rice plants. This effect madeing the plants more erect and reduced the self-shading of lower leaves of the canopy (Deren et al., 1994), which made the plants more photosynthetically efficient and better able to exploit the space available to intercept solar radiation while also increasing their longevity and allowing increased tillering.

The greatest difference in leaf angle was 14.73°, between the plants that were fertilized with the silicon dose that provided the lowest leaf angle and the plants that were not fertilized with silicate. A similar result was found by Zanão Júnior et al. (2010), who, working with doses of silicon and manganese in rice, observed a change in the leaf angle of 19° between plants in the absence and presence of silicate fertilization. In this study, the visual symptoms of silicon deficiency were evident; the leaves with the absence of this element had lower stiffness and the hems bowed, causing self-shadowing and corroborating the observations made by Dobermann and Fairhust (2000) that no nutritional disorder other than silicon deficiency causes this type of symptom in rice plants. Freitas et al. (2013) observed a decrease in leaf angle when working with silicon doses of 0, 30, 60, 90 and 120 mg dm^{-3} and aluminum stress in rice cultivars (BRS Talento and Guarani). According to Ávila et al. (2010) and Gao et al. (2006), silicon confers upon rice plants resistance to lodging, making the plants more erect and resulting in improved photosynthetic efficiency due to the smaller opening of the leaf angle, which allows for a greater capture of light energy. In a study of rice plants, Ma and Yamaji (2006) observed that silicon provides better morphophysiological conditions for plants subjected to biotic and abiotic stress.

Chlorophyll content

Silicon fertilization influenced the chlorophyll content of the leaves of rice according to a quadratic regression model (Fig. 2).

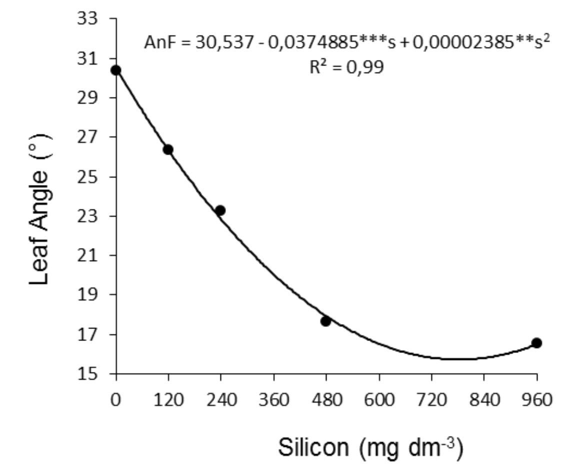

Fig 1. Leaf angle of rice plants under silicon doses in a Oxisol of the Cerrado. AnF = leaf angle, s = silicon. ***, significant at 0.01% probability.

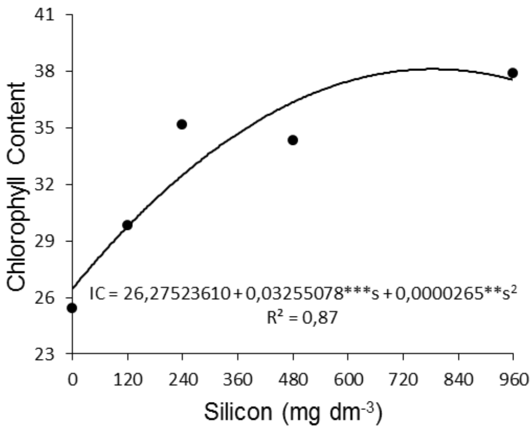

Fig 2. Chlorophyll content of rice plants under silicon doses in a red Oxisol of the Cerrado. CC = Chlorophyll content, s = silicon. ***,**, significant at 0.01% and 1% probability.

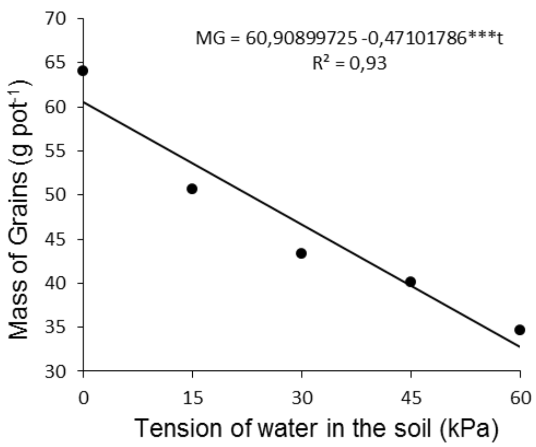

Fig 3. Mass of grains of rice plants subjected to soil water tensions in a Oxisol of the Cerrado. MG=mass of grains, T=tension of water in the soil. ***, significant at 0.01% probability.

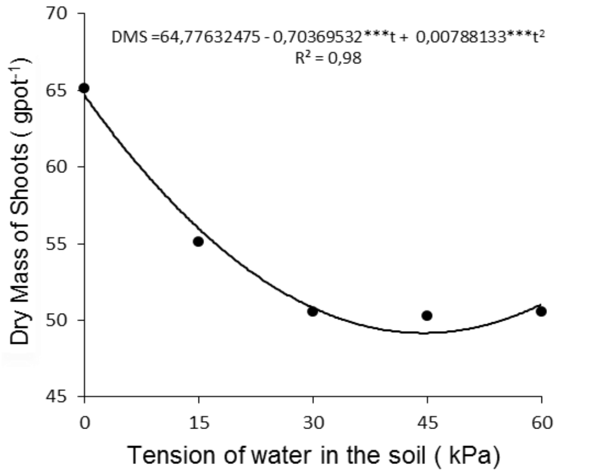

Fig 4. Dry mass of shoots of rice plants under the soil water tensions of a Cerrado Oxisol. DMS=dry mass of shoot, t=tension of water in the soil. ***, significant at 0.1% probability.

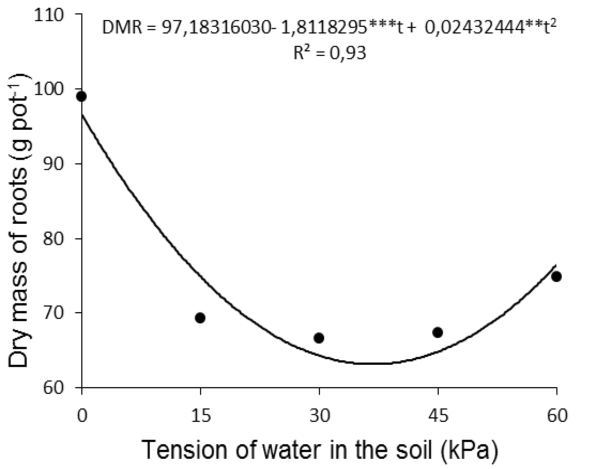

Fig 5. Dry mass of roots of rice plants that were submitted to the soil water tensions of a Cerrado Oxisol. DMR=dry mass of root, T=tension of water in the soil. ***,**, significant at 0.1% and 1% probabilities, respectively.

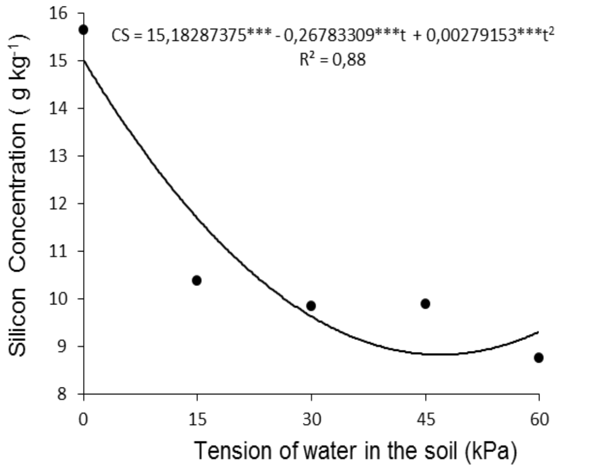

Fig 6. Silicon concentration in the flag leaf of rice plants under the soil water tensions of a Cerrado Oxisol. CS=concentration of silicon, T=tension of water in the soil. ***, significant at 0.1% probability.

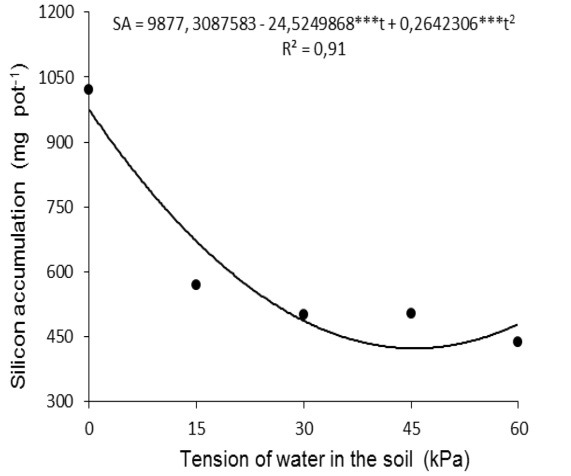

Fig 7. Silicon accumulation in rice plants under the soil water tensions of a Cerrado Oxisol. SA=silicon accumulation, t=tension of water in the soil. ***, Significant at 0.1 % probability.

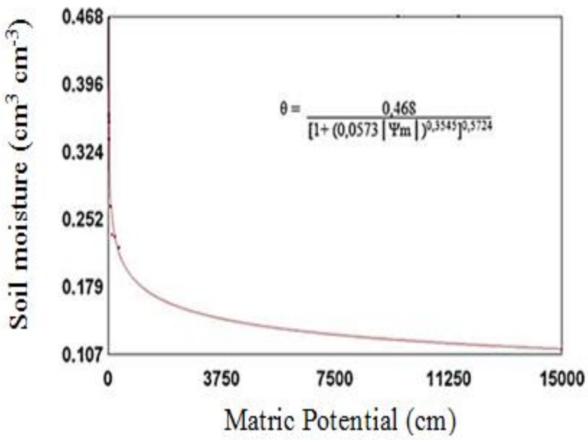

Fig 8. Characteristic curve of water retention in the soil.

The silicon dose of 751.75 mg dm^{-3} was responsible for the increased chlorophyll content (38.51). The chlorophyll content in rice plants that were fertilized with silicon demonstrates the beneficial effect of silicon on plant architecture, as reported in the literature. This assertion is based on the reduction of leaf angle (Fig. 1) caused by the increase in silicon levels; the dose of 785 mg dm^{-3} silicon resulted in the lowest leaf angle, followed by the dose of 752 mg dm^{-3} (Fig. 2), which had the highest chlorophyll content.

Silicon improves the architecture of rice plants by increasing the light utilization by the leaves of the plants, which generates an increase of the photosynthesis rate. The increased photosynthesis rate causes an increase in NADP, NADPH reducing power, and a consequently higher nitrogen assimilation capacity (Taiz and Zeiger, 2010). The chlorophyll content values that were obtained by the chlorophyll meter are proportional to the chlorophyll content in the plant. Because approximately 60% of the total nitrogen in the leaf is a constituent of chlorophyll and is involved in the carboxylation of enzymes present in chloroplasts and photosynthetic reactions (Pan et al., 2004; Taiz and Zeiger, 2010), the chlorophyll content generally correlates well with the nitrogen content in the leaf (Silveira et al., 2003; Godoy et al., 2008). Thus, the chlorophyll content constitutes an efficient method to help determine the nutritional status of the plants (Argenta et al., 2001). The chlorophyll content results that were obtained in this study corroborate those reported by Savant et al. (1999), who, working with sugarcane and silicon doses, found an increase in chlorophyll content. The chlorophyll results are also corroborated by Al-Aghabary et al. (2005), who observed an increase in the chlorophyll content in tomato crop leaves after providing silicon to the plants. Turner and Jund (1991) reported that chlorophyll content above the range of 40-42 corresponds to the critical level of chlorophyll meter readings for rice cultivation. These values are higher than those found in this study (38.51) because the chlorophyll content was measured during the reproductive stage of the rice crop, at which time large amounts of nutrients, mainly nitrogen, are remobilized from vegetative parts to function in the grain growth and filling (Alvim et al., 2011). Ávila et al. (2010) studied the interaction between silicon and nitrogen in rice cultivation and observed a maximum chlorophyll content of 41.5 under a silicon dose of 50 mg L^{-1} in nutrient solution. According to Agarie et al. (1998), increases in the photosynthetic capacity of the plants can be related to an improvement in the arrangement of the leaves due to the presence of silicon in the system, making them more upright and resistant to possible damage while reducing the evapotranspiration of leaves and improving the use of water.

Dry mass of grains

For the dry mass of grains, there was no isolated significant effect on the soil water tension with adjustment to the linear regression model (Fig. 3). The addition of water tensions caused a reduction of 46.4% in the mass of grains between the lowest soil water tension (0 kPa) with the highest tension (60 kPa). Akram et al. (2013), assessing the impact of water stress on rice cultivars in Pakistan, observed reductions of 9.78%, 7.69% and 4.87% in the mass of 1000 grains when the stress was applied in the grain filling phase, in the anthesis and in the panicle differentiation, respectively. Likewise, Suriyan et al. (2010) observed negative effects of water stress on the reproductive phase in four rice cultivars, with reductions in the size and mass of grains observed in all of the analyzed cultivars. The decrease in the mass of grains due to water deficit occurs by reducing photosynthesis, thereby causing a reduction in the translocation of carbohydrates for the grain filling (Kramer, 1974). Mostajeran and Eichi (2009) reported similar results with the observations that were made in this study, where water shortages negatively affected the rice yield by reducing the grain mass. With rice plants under water stress, Yue et al. (2006) found a decrease in grain yield due to the reduced fertility of the spikelets as well as the rate of fertile panicles and grain mass. Lafitte et al. (2006) and Suriyan et al. (2010) also observed variations in the productivity of rice grain genotypes when subjected to water deficits. When the water deficit occurs during the maturation phase, the grain mass is reduced (Prasertsak and Fukai, 1997). Because the treatments in this study were imposed during all phenological phases of culture, the reduction of the grain mass when the soil water tensions increased is justified.

Dry mass of shoot and root of rice plants

For the dry mass of the shoot, there was a significant effect of soil water tensions with the results adjusting to the quadratic regression model (Fig. 4). There was a reduction of 24.24% in the dry mass of the shoot between the lowest soil water tension (0 kPa) and the 45 kPa tension, which gave the smallest dry mass of the shoot (49.1 g pot^{-1}). The reduction in the dry mass of shoots corroborates with the results observed by Sariam (2009) when working with rice plants in a greenhouse; a reduction of 47% in the dry mass of shoots during the maturation phase in the irrigated treatment was obtained with soil water tension ranging from 30 to 50 kPa compared with the flooded soil conditions. According to Mauad et al. (2011), an increase in soil water tension up to 50 kPa reduces the dry mass of the shoot of rice plants. The increased dry mass of shoots of rice based on water slides was also reported by Crusciol et al. (2003). Amiri et al. (2009), studying eight varieties and one hybrid of rice cultivated in a greenhouse, reported a 101.5 pot^{-1} g dry mass of shoots of the hybrid grown under flooded conditions.

For the dry mass of the root, there was no significant difference in the soil water tensions with an adjustment to the quadratic regression model (Fig. 5). The dry mass of the root followed the same trend as that of the dry mass of the shoot (Fig. 4) with the lowest value for the soil water tension of 38 kPa. These results corroborate those of Beyrouty et al. (1992); working with cultivated rice under flooded conditions, Beyrouty et al. reported a significant increase in the dry mass of the root compared with that of cultivated rice with supplemental irrigation. The increase in the dry mass of the root with the same tensions was also obtained by Sariam (2009). Working with rice plants in a greenhouse with flooded soil, soil in field capacity and soil with water tension ranging from 30 to 50 kPa, Sariam (2009) found values for the dry mass of the root of 64.16, 63.4 and 16.24 g pot^{-1}, respectively. Cerqueira et al. (2013) worked in a greenhouse with pots of 3 dm^3 and noted that the imposition of water stress on rice cultivars promoted reductions in the dry mass of the shoot and root of the cultivar Jatobá of 41.70 and 58.22%, respectively; in the cultivar Catetão, these values were 21.60 and 56.69%, respectively, compared with values for treatment without water stress. In this study, we observed that under water restricted conditions with a soil water tension of 60 kPa there was a 15% increase in the production of roots relative to the production with a tension of 38 kPa. These results demonstrate that the increase mechanism of the root system was actuated by the effect of the water deficit and certainly by the osmotic adjustment in the growth zone of the roots, which induces increased pressure potential, thus favoring stretching and cell division and, consequently, root growth. According to Correia et al. (2004), this type of response may be associated with a mechanism of tolerance to water stress, and under conditions of low water availability in soil, plants produce more biomass in the root system to increase their nutrient absorption capacity. Rice plants under water stress increase the ABA accumulation and transport of auxin in the root apex, which increases the secretion of protons to maintain root growth (Xu et al., 2013). According to Kato and Okami (2011), morphological changes in rice plant roots are the main reasons for the adaptation of this crop in rainfed farming systems. As reported by Das and Jat (1977), when the water supply is adequate for the rice crop, there is an increase in the dry mass of the root.

Silicon concentration and accumulation by rice plants

The concentration of silicon in the flag leaf had a significant effect on the soil water tension with adjustment to the quadratic regression model (Fig. 6). The soil water tension of 47 kPa provided the lowest concentration of silicon. Under waterlogged soil conditions with a soil water tension of 0 kPa, the highest concentration of silicon was observed (15.18 g kg^{-1}), given that the rice plants had a higher value of dry mass of shoot in this treatment (Fig. 5), thus absorbing more water and nutrients. Rice plants passively absorb the silicon that is present in the soil in the form of monosilicic acid (H_4SiO_4), with the element following the water absorption (Jones and Handreck, 1967). Thus, the amount of water that is present in the soil directly affects the amount of silicon that is absorbed and accumulated by rice plants.

The silicon distribution in the plant is linked to the transpiration rate of the plant parts. In rice plants, 90% of the absorbed silicon is in the shoot (Korndörfer et al., 1999). Results that were superior to those found in this study were reported by Malavolta (1980), who reported concentrations ranging between 28 and 62.2 g kg^{-1} of silicon for the irrigated rice. When working with upland rice, Méndez Baldeón (1995) found a maximum concentration value of 35 g kg^{-1} of silicon in rice plants. Mauad et al. (2011) obtained results that do not support those observed in this study, where the silicon concentration in the shoots increased with the values of water tension in the soil. For soil water tensions of 25 kPa and 50 kPa, levels of 2.14 and 7.68 mg kg^{-1} of silicon were observed, respectively. According to Korndörfer et al. (1999), the silicon concentrations in the shoots of rice are classified as low, less than 17 g kg^{-1}; average, between 17 and 34 g kg^{-1}; or high, above 34 g kg^{-1}. The polynomial regression adjustment that was described for the silicon concentration in the leaf follows the same model as that for the dry mass of roots (Fig. 5), confirming the importance of the root system in the absorption of nutrients from the soil solution. According to Vilela and Anghinoni (1984), the efficiency of the absorption of nutrients by the plants varies in direct proportion to the morphology of the root system. The soil water tension influenced silicon accumulation in rice plants with adjustment to the quadratic regression model (Fig. 7), demonstrating that the soil water tension of 46.4 kPa was responsible for the lowest accumulation of silicone. Mauad et al. (2011), in a study that was conducted in a greenhouse with rice plants and maintaining the soil moisture at field capacity, observed a silicon accumulation in the shoot of the cultivar Caiapó of 36 mg plant^{-1} at the tillering stage. Silicon accumulation in the shoot consists of the product of the concentration with the dry mass of shoot and follows the same trend as that for these factors, i.e., quadratic response to the water tensions in the soil, and there was a decrease in the dry mass of the shoot and the concentration and accumulation of silicon under a tension of 45 kPa. The transport and accumulation of silicon can occur in favor of the flow of perspiration, and the accumulation can be adjusted by the dry mass production (Sangster et al., 2001), which can justify the higher accumulation of silicon (987.3 mg pot^{-1}) at a soil water tension of 0 kPa, where there was a greater water supply and higher production of the dry mass of shoots. Jones and Handreck (1967) observed a relationship between the absorption and accumulation of silicon and the production of dry mass of the shoots of rice plants. Silicon accumulation in plants is positively correlated with an increasing water-use efficiency and with the rate of photosynthesis, given that these two factors favor silicon absorption, dry mass production and the accumulation of this nutrient (Epstein, 1999; Walker and Lance, 1991).

Materials and Methods

Location and characteristics of the soil

The experiment was conducted from June to October 2014 in a greenhouse at the Federal University of Mato Grosso - UFMT, campus Rondonópolis, Brazil, with geographical coordinates of 16º28' Latitude South and 50º34' Longitude West and an altitude of 284 m. The soil that was used in the experiment was classified as an oxisol (Embrapa, 2013), collected from a layer of 0-0.20 m, with the following chemical and textural characteristics (Embrapa, 1997): pH 4.1 ($CaCl_2$); 2.4 mg dm^{-3} P; 28 mg dm^{-3} K; 0.3 cmolc dm^{-3} Ca; 0.2 cmolc dm^{-3} Mg; 4.2 cmolc dm^{-3} H; 1.1 cmolc dm^{-3} Al; 5.9 cmolc dm^{-3} CEC; base saturation of 9.8 (V%); 22.7 g dm^{-3} OM; 549 g kg^{-1} sand; 84 g kg^{-1} silt; and 367 g kg^{-1} clay. Liming was performed to increase the base saturation to 50% (Sousa and Lobato, 2002). The acidity was corrected by applying limestone with a PRNT of 80.3% in the soil and incubating for 30 days, maintaining the soil moisture at 60% of the maximum water-holding capacity in the soil.

Experimental design and plant material

Five water tensions in the soil were studied (0, 15, 30, 45 and 60 kPa) combined with five silicon doses (0, 120, 240, 480 and 960 mg dm^{-3}) to study the response surface based on central composite design modified from a 5×5 fractionated factorial according to Littel and Mott (1975) and distributed in a randomized block design with four replications. Thus, the 13 combinations of water tensions in the soil and silicon levels, in kPa and mg dm^{-3}, were, respectively, 0-0; 0-240; 0-960; 15-120; 15-480; 30-0; 30-240; 30-960; 45-120; 45-480; 60-0; 60-240; and 60-960. Each experimental unit consisted of a plastic pot with an 8 dm^3 volume and a tensiometer. The growing upland rice that was used was BRS Esmeralda, as recommended by Embrapa for Mato Grosso crops, with moderate resistance to major diseases of rice and lodging and increased tolerance to drought stress, ensuring a more rustic.

Soil fertilization and seeding

The fertilizer planting was carried out using 200 mg dm^{-3} P_2O_5 in the form of simple superphosphate and 80 mg dm^{-3} K_2O in the form of potassium chloride. The nitrogen dose of 200 mg dm^{-3} was divided into two equal applications, with the first application performed 15 days after sowing and the second 30 days after sowing. The silicon source was silicon dioxide (SiO_2), with 95% silicon. The doses corresponding to treatments (0, 120, 240, 480 and 960 mg dm^{-3} Si) were incorporated into the soil at planting. Seeding was conducted on June 18, 2014, with ten seeds per pot at a depth of 3 cm. The thinning occurred ten days after emergence, leaving four plants per pot.

Management of irrigation

To manage irrigation, the characteristic curve of soil water retention was used, as determined in the layer of 0.0-0.20 m (Fig. 8). Irrigations were performed manually and calculated to increase the values of water tension in the soil to field capacity (5 kPa) for treatments when the set tensions (treatments) were achieved. The readings in the tensiometer were made using a digital tensiometer twice a day: once in the morning and another in the afternoon.

Analyzed variables

At 83 days after sowing, the following were evaluated: the leaf angle was measured with a protractor. The reference for the measures of the angle was the main stem of rice plants, and the results are given in degrees. Three plants were measured per experimental plot. The chlorophyll content was

obtained from the average of five readings taken in the flag leaves with a portable chlorophyll meter (SPAD-502 model).
At 121 days after sowing, the following were evaluated: the mass of grains was obtained by harvesting all of the panicles of the plot. The path of the grains (panicles) was determined manually, and the grains were then placed in a forced-circulation oven for 24 hours at 65 °C. For the dry mass of shoots, plants were cut close to the ground, wrapped in paper bags, identified and transferred to an oven at 65 °C until obtaining constant mass. To obtain the dry mass of the root, the roots were washed and placed in paper bags, identified and transferred to an oven at 65 °C until obtaining constant mass. The silicon concentration was determined by the flag leaf method as described by Korndörfer et al. (2004). Silicon accumulation was calculated by multiplying the total dry mass of the shoots with the concentration of silicon.

Statistical analyses

All of the variables received the recommended statistical treatment, with response surface analysis using the "Statistical Analysis System" (SAS, 2002). An analysis of variance was initially performed for the combinations of doses of silicon and soil water tensions due to the significance level of the F test to such combinations; a polynomial regression study (response surface) was performed via the RSREG procedure. A 5% significance level was used for all of the statistical tests.

Conclusions

Silicon fertilization improved the architecture of rice plants by reducing the leaf angle and increasing the chlorophyll content at silicon doses of 785 and 750 mg dm^{-3}, respectively. The soil water tension of 45 kPa soil decreased the dry mass of the shoot, dry mass of the root, and the concentration and accumulation of silicon, demonstrating the importance of water in development and silicon absorption in upland rice plants.

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