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BASIC AREA - Article

Potential of calcium silicate to mitigate water deficiency in maize

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ABSTRACT: The aim of this study was to evaluate the potential of calcium silicate to mitigate the effects of water deficiency in maize plants yield. A completely randomized factorial design, consisting of five combinations of calcium silicate (0, 25, 50, 75, and 100%) and five different soil moisture levels (30, 70, 100, 130, and 160%), was adopted. The following parameters were evaluated: soil matric potential, xylem water potential, silicon concentration, leaf dry weight, and dry mass production. Matric potential monitoring confirmed that the irrigation depths employed resulted in different environments for maize plant development during the experiment. Confirming the hypothesis of the study, at the lower irrigation depths, the maize production has accompanied the increase in calcium silicate used as corrective up to the proportion of 50%. These results indicate that silicon mitigated the impact of water deficiency in maize plants and increased the xylem water potential.

Key words: Dry matter, irrigation, silicon, stress.

INTRODUCTION

The world population is increasing, especially in the poorest and most vulnerable countries of the Third World, where food production is insufficient to maintain this growing population because they live in marginal agricultural areas characterized by water and nutrient deficiency (Giehl and Wirén 2014; Rockström and Falkenmark 2000). The development of strategies to reduce water stress in arid and semiarid regions is a sustainable alternative to mitigate the negative impacts of global climate changes. In view of the complexity of drought stress, only an approach that will consider soil-plant-environment interactions may generate relevant knowledge that can be used in the near future to guarantee sustainability. The conditions for the development of maize crops were unfavorable throughout Brazil in 2013, since the rain recorded during crop cycle period was not sufficient to replenish soil moisture levels. Furthermore, temperatures continued to be high, a fact which contributed to the maintenance of high rates of evapotranspiration. As a consequence, many maize fields in 2013 are already under the effect of water stress, reducing the crop yield potential (Boletim Agrometeorológico Semanal 2014).

The scarcity of water resources in conjunction with global warming has exerted negative effects on the planet's agricultural activity over the last ten years (IBGE 2010). In this respect, lines of research focusing on the understanding, behavior and improvement of cultivated species in response to inadequate environmental situations have captured substantial resources and gained more visibility (Stenseth 2002). The increase in temperature due to global warming may cause losses in maize grain yields of R$ 7.4 billion already in 2020 — a number that could rise to R$ 14 billion in 2070. The most pessimistic predictions estimate a temperature increase of 2 to 5.4 °C until 2100, and the most optimistic ones estimate an increase of 1.4 to 3.8 °C until 2100 (Assad and Pinto 2008). →

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In Brazil, about 20% of the maize planted area, corresponding to approximately 8.5 million hectares, is affected by drought, resulting in a production loss of these crops of more than 23.7 million tons. In specific years and places, drought may even lead to total production loss (Durães et al. 2002).

In order to mitigate the effects of abiotic and biotic stress, silicon exerts several specific functions (Moro et al. 2015), and its absorption by plants has several benefits, protecting against saline stress, metal toxicity, water deficit, radiation damage, high temperature and frost and regulating nutrient balance. These beneficial effects are attributed to the high accumulation of silica in plant tissues (Ma 2004). The mechanisms used by plants in situations of stress include the activity of enzymes involved in the protection against oxidative stress, such as catalase, superoxide dismutase, peroxidases, and glutathione.

The aim of the present study was to evaluate the effect of calcium silicate as an option to mitigate water stress in maize crops.

MATERIAL AND METHODS

The experiment was carried out at the Department of Soil Science of the Federal University of Lavras, Minas Gerais, Brazil (lat 21°14′S; long 45°00′W; 915 masl), under greenhouse conditions. Seeds of *Zea mays* L. (cv. BR 106) were used, which are adapted to the conditions of Brazil, characterized by a plant height of 2.4 m, ear length of 0.16 m, and yield of 5.5 $t \cdot ha^{-1}$ (Embrapa 2013). The soil of the region is classified as Red Latosol-Oxisol (Embrapa 2006).For soil physico-chemical characterization (Table 1), the following proprieties were determined: pH in water (1:2.5), P and K by Mehlich-1 extraction, Mg and Al extractable by 1 M KCl solution, P in the equilibrium solution according to Álvarez et al. (2000), and level of organic matter according to Anne (1945). The soil granulometry was determined by the pipette method. A completely randomized factorial design consisting of five corrective combinations (0, 25, 50, 75, and 100% of calcium silicate indicated for liming of this soil) and five different soil moisture conditions (30, 70, 100, 130, and 160% of amount necessary for water replenishment in this soil), with four repetitions, was used. The volume of each pot was 15 L.

Table 2 shows the amounts of calcium silicate ($CaSiO_3$) and calcium carbonate ($CaCO_3$) present in the different combinations. Additionally, calcium was applied in the form of calcium chloride ($CaCl_2$) to balance the amount of this element in the treatments. After treatment application, the soil was incubated for 45 days. Macro and micronutrient fertilization (Table 3) was carried out as described by Novais et al. (1991). The Chemical composition of the soil after the corrective associations is summarized in Table 4.

The water retention curve (Figure 1) was used to water characterization of the soil, and data were applied in the formulas $\theta = 0.4215 \times [1 + (0.2040 \times |\Psi_m|)^{1.8757}]^{-0.4669} + 0.2670$ and $\Psi_m = [1/\alpha\,(1/m)\,1/n]$, in agreement with van Genuchten (1980), where θ is the humidity current ($cm^3 \cdot cm^{-3}$), Ψ_m is the tension in soil (kPa), α, *m*, and *n* are parameters linked to equation adjustment in the model proposed by van Genuchten.

The field capacity was estimated by equation $\theta_i = (\theta_s - \theta_r) \times [1 + 1/m]^{-m} + \theta_r$, as proposed by Dexter (2004), where θ_i is the humidity in inflexion point of the curve ($cm^3 \cdot cm^{-3}$), θ_s is the humidity of saturation ($cm^3 \cdot cm^{-3}$), and θ_r is the humidity residual ($cm^3 \cdot cm^{-3}$). The value of humidity calculated in field capacity of this study was 0.3458 $cm^3 \cdot cm^{-3}$ to tension of −40 kPa.

Table 1. Chemical and physical compositions of the soil used in this study.

Chemical																	
pH	P	K	Si	Zn	Cu	Mn	S	B	Fe	EP	Ca	Mg	Al	H + Al	T	m	V
	($mg \cdot dm^{-3}$)			($mg \cdot L^{-1}$)						($mmol_c \cdot dm^{-3}$)						(%)	
5.0	53.7	20.0	2.7	0.6	1.3	17.7	6.7	0.1	31.1	36.3	1.5	0.4	0.5	3.6	5.6	20.4	35.1

Physical			
Sand (%)	Silt (%)	Clay (%)	OM ($dag \cdot kg^{-1}$)
38	13	49	2.1

pH in water (1:2.5), P and K by Mehlich-1 (Bortolon and Gianello 2010) extraction, Mg and Al extractable by 1 M KCl solution (Thomas 1982); P in the equilibrium solution (EP) according to Álvarez et al. (2000); level of organic matter (OM) according to Anne (1945). The soil granulometry was determined by the pipette method (Day 1965). T = Cation exchange capacity at pH 7.0; m = Aluminum saturation index; V = Base saturation index (Olsen and Watanabe 1957).

Table 2. Amounts of $CaSiO_3$, $CaCO_3$, and $CaCl_2$ used in different associations.

Association (%)	$CaSiO_3$ (g·pot^{-1})	$CaCO_3$ (g·pot^{-1})	$CaCl_2$ (g·pot^{-1})
100	12.20	0.00	0.00
75	9.15	2.63	1.03
50	6.10	5.25	2.06
25	3.05	7.88	3.09
0	0.00	10.50	4.12

Table 3. Nutrients, recommended amounts, and sources used in fertilization in this study.

Nutrient	Concentration (mg kg per soil)	Source
N	300	$NH_4H_2PO_4$
P	300	KH_2PO_4
K	200	KH_2PO_4
S	40	K_2SO_4
Mg	46	$MgSO_4{\cdot}7H_2O$
B	2.5	H_3BO_3
Cu	7.5	$CuSO_4{\cdot}5H_2O$
Mo	0.5	$(NH_4)_6MO_7O_{24}{\cdot}4H_2O$
Zn	2.5	$ZnSO_4{\cdot}7H_2O$

Table 4. Chemical composition of the soil after the corrective associations**.**

Corrective associations		Measurements											
$CaSiO_3$	$CaCO_3$	pH	P	K	EP	Ca	Mg	Al	H + Al	T	m	V	OM
(%)			(mg·dm^{-3})		(mg·L^{-1})		(cmolc·dm^{-3})				(%)		(dag·kg^{-1})
100	0	5.3	118.1	139	27.3	3.5	1.1	0.1	3.6	8.6	2.0	57.8	2.6
75	25	5.2	114.7	122	34.1	3.5	1.1	0.1	3.6	8.6	2.0	57.8	2.6
50	50	5.1	143.6	131	38.3	3.2	1.2	0.1	3.6	8.4	2.1	56.8	2.6
25	75	5.3	125.0	109	39.4	2.9	1.0	0.1	3.6	7.8	2.4	53.4	2.6
0	100	5.2	121.5	150	37.2	2.5	1.0	0.1	4.0	8.0	2.5	49.4	2.6

pH in water (1:2.5), P and K by Mehlich-1 (Bortolon and Gianello 2010) extraction, Mg and Al extractable by 1 M KCl solution (Thomas 1982); P in the equilibrium solution (EP) according to Álvarez et al. (2000); level of organic matter (OM) according to Anne (1945). The soil granulometry was determined by the pipette method (Day 1965). T = Cation exchange capacity at pH 7.0; m = Aluminum saturation index; V = Base saturation index (Olsen and Watanabe 1957).

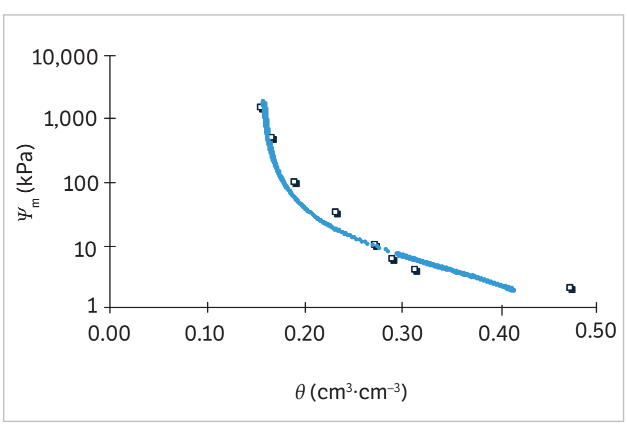

Figure 1. Water retention curve for Red Latosol used in the experiment. θ = volumetric water content (cm^3·cm^{-3}).

The soil was irrigated when the soil water tension reached a value of –40 kPa at each irrigation depth (30, 70, 100, 130, and 160% of the depth necessary for water replenishment in this soil). All measurements were made daily at 5:00 PM, and soil moisture meters (Watermark, model 200SS-5) were installed to quantify the matric potential (Figure 1) only at the three highest tensions (30, 70, and 100% of ideal depth). The water volume necessary for irrigation was calculated by the equation: $V = (\theta_{fc} - \theta_{treat}) \times V_{soil}$, where V is the water volume to be applied (mL), θ_{fc} is the water content at field capacity (cm^3·cm^{-3}), θ_{treat} is the water content in the treatment (cm^3·cm^{-3}), and V_{soil} is the soil volume (mL).

The electrical conductivity (EC) of the saturated paste extract was determined as described by Richards (1954). Dry mass was determined by drying the leaves of maize plants in an oven with ventilation at 60 °C until a constant mass was obtained. The xylem water potential (Ψ_w) was measured in fully expanded leaves under light between 5:00 and 6:30 AM and between 1:00 and 2:00 PM, corresponding to the predawn and midday potential, respectively. The water potential was measured with an analogue plant moisture system (Skye Instruments, model SKPM 1405/50), which is based on technical pressure chamber (Scholander et al. 1964), according to the procedure by Turner (1988).

Data were subjected to analysis of variance. When significant differences were observed, the Scott-Knott test was applied at a $p > 0.05$ level of error probability (Steel et al. 2006). Standard errors were calculated for all means. All statistical procedures were carried out using the SAS software (SAS Institute 1996).

RESULTS AND DISCUSSION

Figure 2 illustrates the soil matric potential data before and after irrigation corresponding to 30% (Figure 2a), 70% (Figure 2b) and 100% (Figure 2c) of the recommended irrigation depth, while Figure 2d shows the matric potential readings obtained with the Watermark sensor for irrigations corresponding to 30 and 70% of the recommended depth (Figures 2a,b) and the tensiometer (100% of the recommended irrigation depth). Before irrigation, the highest readings of soil water tension were obtained for the treatment applying 30% of the recommended irrigation depth (Figure 2a), ranging from −90 to −160 kPa. The tension readings ranged from −40 to −130 kPA for the application of 70% (Figure 2b) and from −25 to −50 kPA for the application of 100% (Figure 2c). The tension gradient showed the same trend after irrigation; however, when 100% of the recommended irrigation depth was applied, the soil

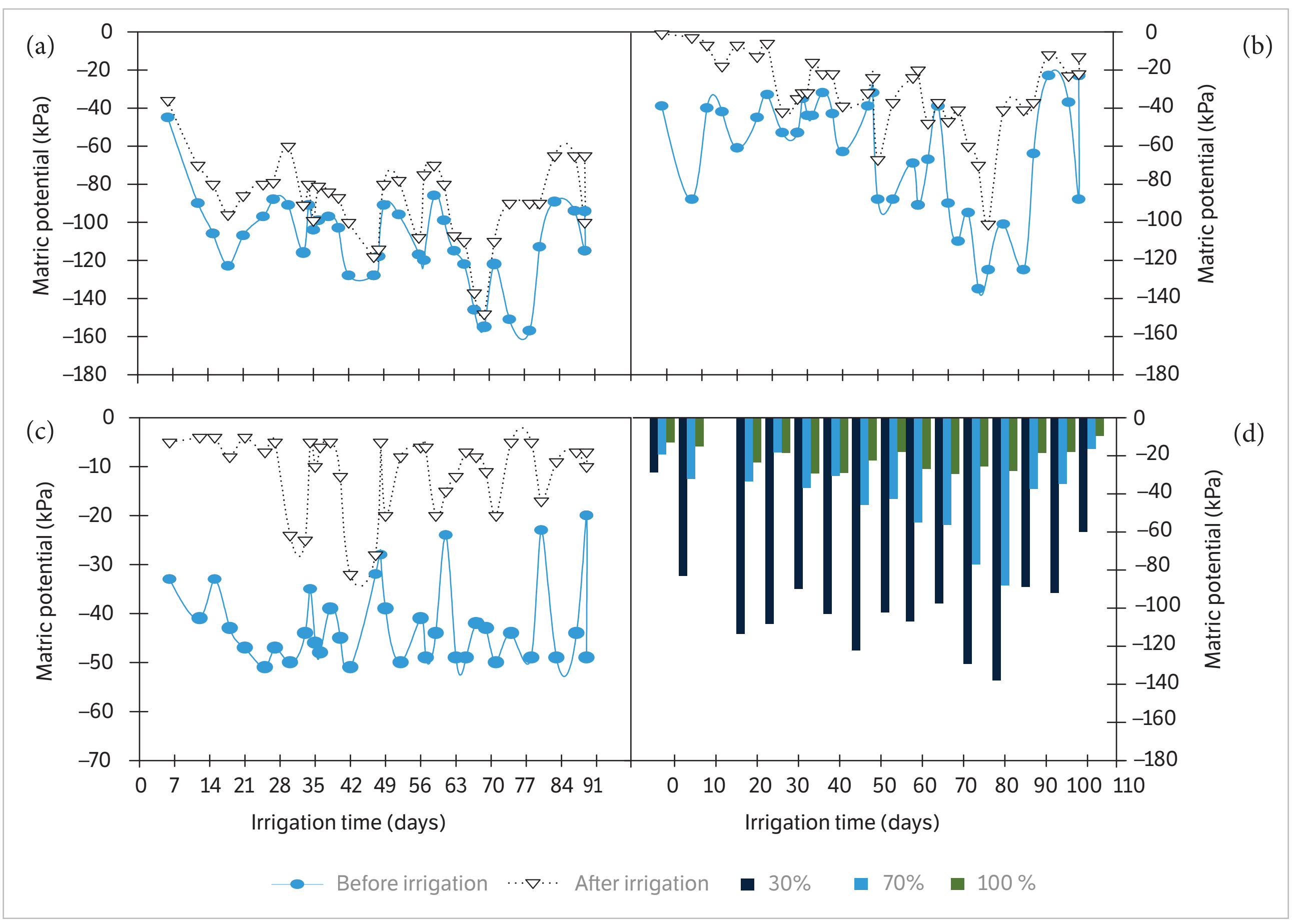

Figure 2. Matric potential of soil water before and after using it for irrigation depth of 30% (a), 70% (b), 100% (c) and monitoring of the matric potential of soil water using the Watermark sensor for the depth irrigation (30 and 70%) and the depth considered ideal for tensiometer (100%) (d).

water tension remained in the range of −5 to −30 kPa, a value lower than the tension at field capacity (−40 kPa), i.e. the amount of water applied at this depth increased soil moisture to a level above its field capacity. As can be seen in Figure 2d, soil water tension varied according to the amount of water applied. The highest tension readings were obtained when 30% of the recommended irrigation depth was applied, followed by 70 and 100% of the recommended depth. The study of Resende et al. (2008) serves as a reference of the water conditions prevailing in the study area, which showed a potential of −70 kPa in Brazilian *Cerrado* under summer conditions and in the semiarid region at any time of the year, and of −300 kPa during the winter. It appears, therefore, as it was the objective of the present study, that water application corresponding to 30 and 70% of the recommended irrigation depth induced water deficit conditions. This deficit was much more pronounced when only 30% of the recommended depth was applied.

The variation in electrical conductivity as a function of the interaction between irrigation depth and proportion of calcium silicate is shown in Figure 3. Electrical conductivity tended to decrease as the amount of water applied increased, irrespective of the proportion of calcium silicate. The highest EC values were observed with the application of 30% of the recommended depth, followed by a reduction to half when 70% of the recommended depth was applied. The lowest values were observed with the application of 130%. These results show that the smaller irrigation depth seems to increase the concentration of salts in soil, with a consequent increase in the osmotic potential of the soil solution. Soil salinization can result in nutritional disorders, inducing antagonistic relationships between nutrients in the plant, which significantly reduces crop yields (Grattan and Grieve 1999). These interactions can also occur between nutrients in the soil solution, affecting nutrient availability. Such interactions include antagonism, competitive and non-competitive inhibition and synergism, events that can change the dynamics between cations in the leaves and roots of plants. Cuartero and Fernández-Muñoz (1998) observed a reduction in the dry mass of tomato stems, leaves and roots under conditions of salinity. The high concentration of ions in soil can lead to an imbalance in the water and ion potential at the soil-plant interface and can be toxic to the plant, thus affecting its growth and phytomass production (Asch et al. 2000) due to the

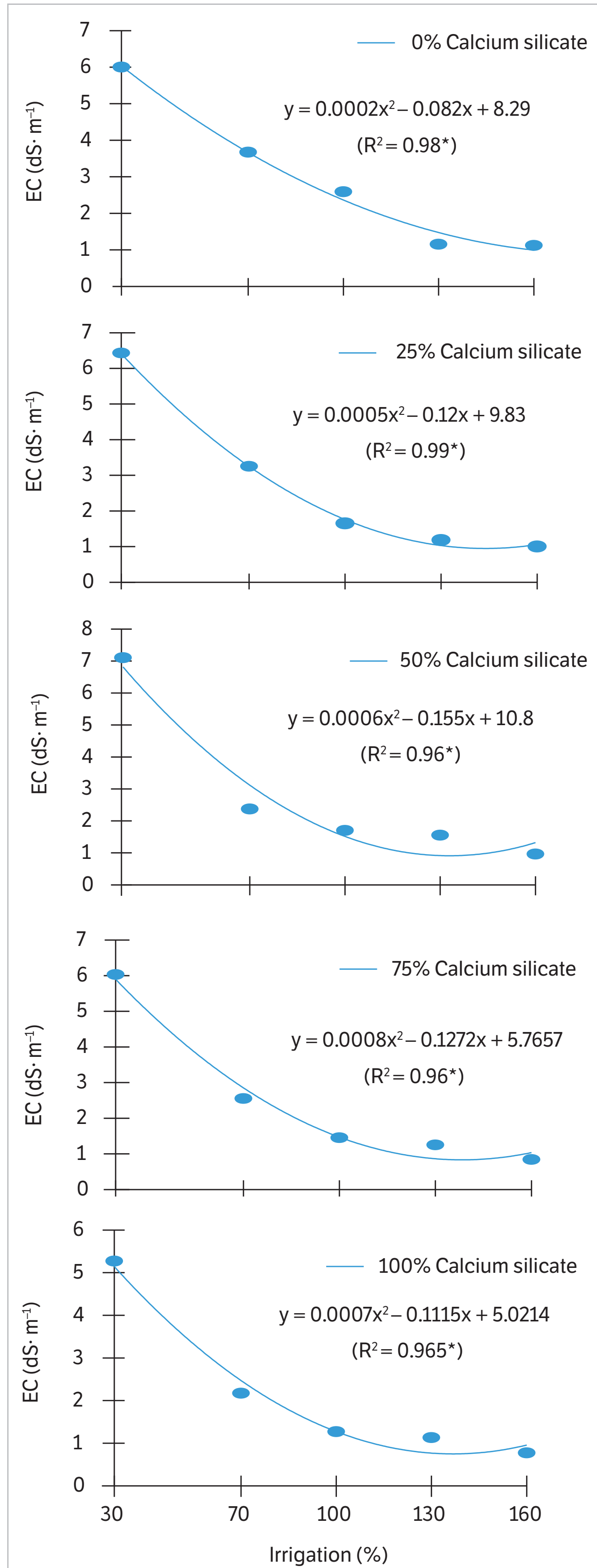

Figure 3. Soil solution electrical conductivity (EC) as a function of different irrigations in each proportion of calcium silicate.

reduction in the absorption of mineral nutrients such as potassium, calcium and manganese (Lutts et al. 1999).

Figure 4 shows the xylem matric potential (Ψ_w) of maize leaves at 30 (a and b) and 75 (c and d) days after planting according to the different proportions of calcium silicate and irrigation depths. At 30 and 70% of the recommended irrigation depth (Figure 4a), pure calcium silicate was superior than other proportions tested. However, when irrigation was increased to 100, 130 and 160% of the recommended depth, the proportion of 50% calcium silicate was superior for readings performed between 5:00 and 6:30 AM. In contrast, for readings performed between 1:00 and 2:00 PM, treatment with pure (100%) calcium silicate was superior at 30, 70 and 130% of the recommended irrigation depth, while 0% calcium silicate provided superior results only at 100% of the recommended depth (Figure 4b). At 75 days after planting (Figure 4c), in the morning (5:00 to 6:30 AM), pure calcium silicate (100%) was superior for application of 30 and 70% of the recommended irrigation depth. These depths are considered to be limiting. However, when irrigation was increased to 100, 130 and 160%, the application of 0% calcium silicate was superior compared to the other irrigation depths. Regarding Ψ_w, determined between 1:00 and 2:00 PM (Figure 4d), for application of 30% of the recommended irrigation depth, the calcium silicate proportion of 50% provided the highest Ψ_w compared to the other proportions for the same treatment. However, when the irrigation depth was increased proportionally, the application of pure calcium silicate (100%) was superior to the other proportions tested. In the presence of a water deficit, the plants use drought tolerance mechanisms such as osmotic adjustment, in which the cell absorbs water and maintains the pressure potential at adequate levels. The reduction in the osmotic potential in response to water deficit may

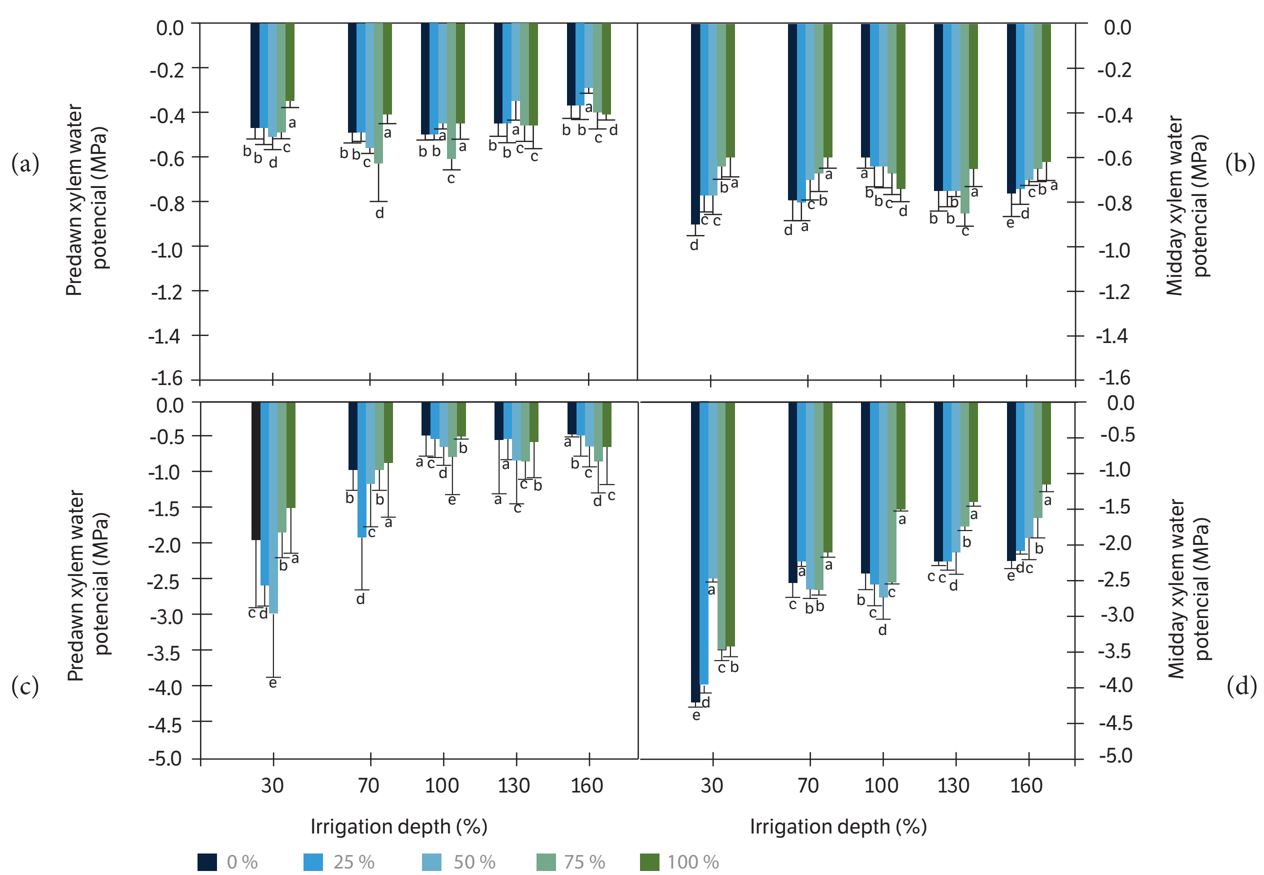

Figure 4. Xylem water potential (ψ_w) in Zea mays (cv. 106 BR) 30 (a and b) and 75 (c and d) days after planting, depending on irrigation, in different proportions (0, 25, 50, 75, and 100%) of calcium silicate.

be the result of the passive accumulation of solutes as a consequence of dehydration of the cell or of active accumulation of solutes; however, only the latter can be considered osmotic adjustment (Patakas et al. 2002). Approximate leaf Ψ_w values of −0.5 MPa are considered to be adequate for good development of maize and sorghum, while a value of −0.8 MPa inhibits photosynthesis and leaf growth and −1.5 MPa is the wilting point (Salah and Tardieu 1997; Klar and Porto 1998). About 95% of the water absorbed by the plant is used to maintain the thermal balance through transpiration.

Figure 5 illustrates the trend in leaf dry mass production as a function of increasing irrigation depth for each calcium silicate proportion. As can be seen, leaf dry mass increased with increasing amount of water applied at the different irrigation depths, irrespective of the proportion of calcium silicate. The trend in dry mass production according to irrigation depth at all proportions of calcium silicate can be described by quadratic functions. Leaf dry mass reaches maximum values with the application of 130% of the recommended depth and tends to decline thereafter. According to Malavolta et al. (1997), water stress reduces leaf dry mass production and crop yield. This reduction depends on the extent to which the water deficit has affected the areas of photosynthetic activity and on the rate and degree of recovery after the cessation of water stress. Considering the water stress conditions induced by the irrigation depths of 30 and 70%, the calcium silicate proportions of 50, 75 and 100% promoted the highest production of leaf dry mass. These data are important since they emphasize the benefit of silicon in mitigating water stress in maize crops. The use of the silicate-lime combination, notably the proportion of 50%, demonstrated the complementarity of these correctives, since calcium silicate has a lower neutralization power than lime, which is more soluble.

Plant species vary in their capacity to absorb and accumulate silicon in tissues and can be classified according to the percentage of SiO_2 in dry matter: (a) accumulator plants containing more than 4% SiO_2, which includes many grasses such as rice; (b) intermediate plants with an SiO_2 content ranging from 2 – 4% (cereals, sugarcane, and few dicotyledons); (c) non-accumulator plants containing less than 2% SiO_2, which includes most dicotyledons such as beans (Ma and Takahashi 2002; Hodson et al. 2005). These differences in silicon

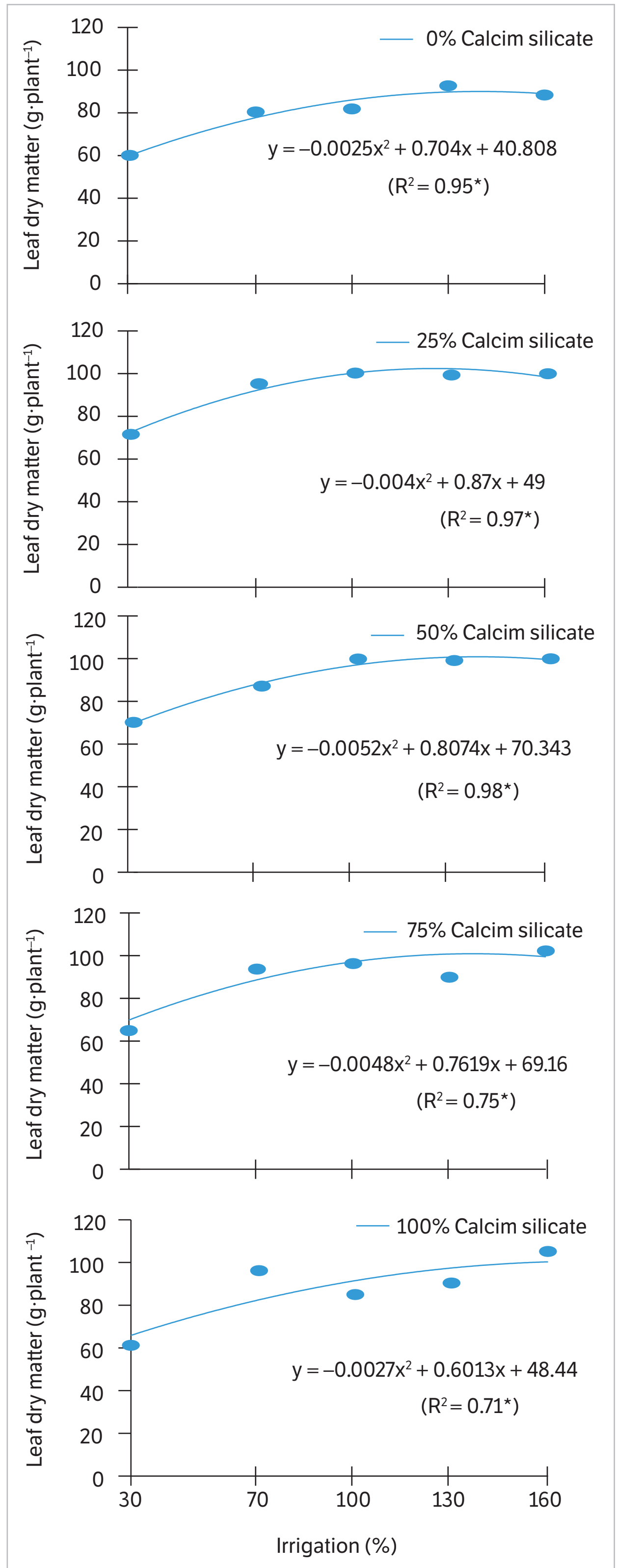

Figure 5. Leaf dry weight of maize plants (cv. BR 106), depending on irrigation, in different proportions (0, 25, 50, 75, and 100%) of calcium silicate.

accumulation have been attributed to the ability of roots to absorb this nutrient (Takahashi et al. 1990), but the exact mechanism is not fully understood. Figure 6 shows the concentrations of silicon in the stem (a), leaf (b), ear husks (c), cob (d) and grains (e) of maize according to the proportion of calcium silicate for each irrigation depth. In general, Si concentrations in the leaf and ear increased with increasing irrigation depth, irrespective of the proportion of calcium silicate. In the stem, cob and grains, Si concentrations did not vary between the irrigation depths used. The different proportions of calcium silicate in the corrective did not affect Si concentrations in maize stem, cob or grains. Most intriguingly, the highest Si concentrations were observed in the stem at 30% of the recommended irrigation depth, in cobs at 130% of the recommended depth and in grains in the absence of silicate in the corrective. On the other hand, the presence of calcium silicate in the corrective had positive effects on Si concentrations in leaves and ears. At all irrigation depths, Si concentrations were associated with higher proportions of calcium silicate. The greater Ψ_w (Figure 4) of maize leaves may explain the higher silicon content of leaves which increases the efficiency of gas exchanges. These results agree with those of Hashemi et al. (2010), who suggested Si to be an element that confers greater resistance to biotic and abiotic stress in plants.

Figure 7 compares grain production between the different proportions of calcium silicate according to irrigation depth. As a general trend, production increased with increasing irrigation depth. At 30% of the recommended irrigation depth, higher production was observed for calcium silicate proportions of 50, 75 and 100%. In contrast, at 70% of the recommended depth, grain production was higher for the proportions of 50 and 75% calcium silicate. These results indicate that silicon mitigated water deficit in maize plants grown under water stress. For applications of 100, 130 and 160% of the recommended irrigation depth, no significant differences in maize production were observed at the different calcium silicate proportions tested. In rice, an increase in grain production has been observed after application of calcium silicate, particularly when the plants were exposed to lower amounts of water available in soil. Thus, the lower the field capacity of soil, the greater the response of plants to silicon (Moro et al. 2015). The H_4SiO_4 monomer is the silicon compound present in the liquid phase of soil in the

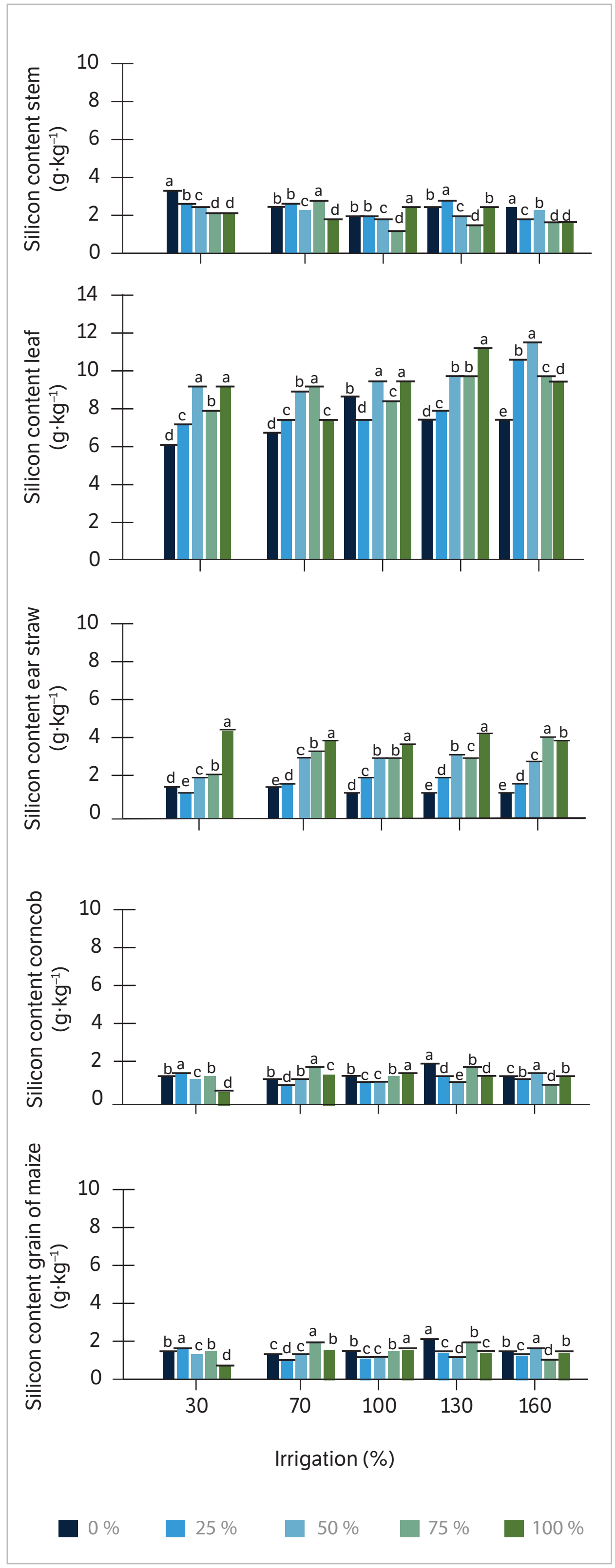

Figure 6. Silicon concentration in the stem (a), leaf (b), ear husks (c), cob (d) and corn grain (e) for the different irrigation levels and proportions of silicate calcium.

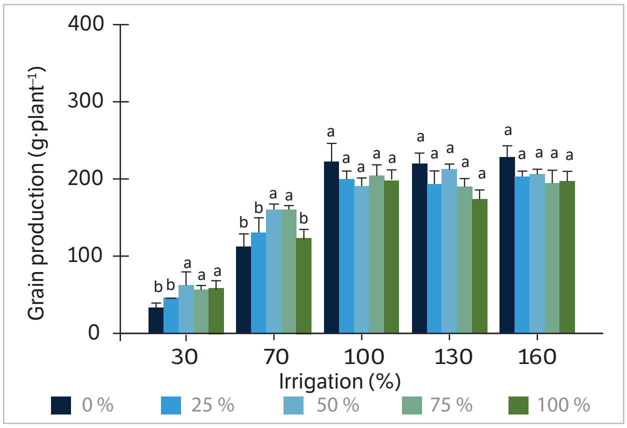

Figure 7. Grain production in maize plants (cv. BR 106) exposed to five corrective associations (0, 25, 50, 75, and 100% of calcium silicate) and five irrigation depths.

pH range of 4 to 9 (Marschner 1995), which is absorbed by plant roots in a passive or active manner mediated by specific membrane transporters. Many studies have been conducted in an attempt to better adapt crops to regions with limited water resources and to make them more tolerant to acidity (van Raij et al. 1998). However, the yield of species under stress lags behind their production potential, including maize, which is poorly tolerant to water deficit (Silva et al. 1984) and whose cultivation in the semiarid regions of northeastern Brazil is of the utmost importance not only to directly meet the food requirements of the population, but also for the regional agro-industry. The absorption of Si has benefits for crops, including an increase in lodging resistance and in photosynthetic activity. Silicon is a chemical element involved in physical functions that regulate evapotranspiration and is able to form a mechanical barrier against fungal and bacterial invasion of the plant, as well as pest insect attack (Costa et al. 2009). This protective effect is mainly attributed to the deposition of Si in the form of amorphous silica ($SiO_2 \cdot nH_2O$) in the cell wall. The accumulation of silicon in the stomata leads to the formation of a double layer of cuticular silica, which, by reducing transpiration (Datnoff et al. 2001), lowers the water requirements of plants. This can be extremely important for plants growing in tropical soils, where they are subjected to dry spells. Photosynthesis plays an important role in crop production (Wullschleger and Oosterhuis 1990), since grain yield is potentially influenced by the duration of the carbohydrate accumulation rate (Crafts-Brandner and Poneleit 1992). According to Jordan (1983), water deficit conditions can affect the use of carbohydrates basically by altering the efficiency at which photoassimilates are converted for the development of new parts of the plant. Water deficit causes changes in carbohydrate partitioning inside the plant, which results in the development of adaptation and resistance mechanisms by the plants.

CONCLUSION

Matric potential monitoring confirmed that the irrigation depths employed resulted in different environments for maize plant development during the experiment.

Confirming the hypothesis of the study, it was found that the smaller water depths of maize production were proportional to the increase in calcium silicate dose to the ratio of 50%. These results indicate that silicon mitigated the water deficit in maize plants grown under water stress and increased the xylem water potential.

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