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Combined effect of silicon and nitrogen doses applied to planting furrows on sugar, biomass and energy water productivity of sugarcane (*Saccharum* spp.)

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ABSTRACT

Brazil has the largest cultivated area for sugarcane in the world, with a predominance of rain-fed production systems (64%) and marginal areas that are subject to frequent water deficits. The remaining 36% under cultivation is equipped with irrigation systems; however, a significant portion of these irrigation systems (76%) is dedicated to crop maintenance. Their primary purpose is to provide water for initial plant maintenance during planting and regrowth of ratoons, which helps to alleviate drought stress caused by water scarcity during dry periods. The remaining 24% of the irrigated sugarcane production areas use deficit and full irrigation strategies to partially (50%) and fully (100%) meet the plants' water demands, respectively. Therefore, a large part of the cultivated area for sugarcane in Brazil is subject to a water deficit at one or more stages of the crop's development cycle, which can retard plant growth, nutrient use and productivity. One potential strategy for mitigating these harmful effects is the application of silicon (Si) in the furrow at planting, which can also increase crop water productivity (WP_c). The objective of this research was to determine the effects of different applications of Si and nitrogen (N) on WP_c, in terms of sugar (SWP_c), biomass (BWP_c) and energy ($ENWP_c$) for sugarcane crop. The research was conducted at the University of São Paulo (USP/ESALQ), Piracicaba, São Paulo State, Brazil. The experimental design involved randomized blocks, with four blocks and 12 treatments. The treatments consisted of three applications of Si, 175, 350 and 525 $kg \cdot ha^{-1}$ and four N treatments of 15, 30, 60 and 90 $kg \cdot ha^{-1}$. Biometric responses, effects on juice quality, and indices related to yield and WP_c were determined. The water consumption and agricultural yield (AY) of sugarcane were clearly influenced by the treatments. The lowest water consumption was obtained with the 15Nx350Si treatment, 561 mm per year. The treatment with the highest AY value was 60Nx350Si (162.3 $Mg \cdot ha^{-1}$). The SWP_c, BWP_c and $ENWP_c$ of the sugarcane crop were affected by the different application rates of N and Si. In general, the highest average WP_c values were obtained with the 15Nx350Si treatment (SWP_c=2.6 $kg \cdot m^{-3}$, BWP_c=10 $kg \cdot m^{-3}$ and $ENWP_c$=224.5 $MJ \cdot m^{-3}$). The different N and Si treatments did not significantly affect biometric variables (except for fresh biomass and leaf area) or juice quality; therefore, Si application did not compromise the quality of the end-product.

1. Introduction

Sugarcane (*Saccharum* spp.) is cultivated on a total area of 26.1 million ha around the world. In the year 2022, world production was approximately 1.9 billion Mg of sugarcane, with an average yield of 73.7 $Mg \cdot ha^{-1}$. Brazil is the country with the largest area devoted to sugarcane cultivation in the world, 9.9 million ha, with an annual production of 724 million Mg of sugarcane, which represents 38% of the world production (FAOSTAT, 2024). The markets for bioenergy, sugar and derivatives are also led by Brazil, with emphasis on the Center-South region and, mainly the state of São Paulo, which produces more than half of the sugarcane processed in the country (CONAB, 2023).

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In Brazil, sugarcane production systems are distributed throughout practically the entire national territory and in different edaphoclimatic conditions, with an average productivity of 72.3 $Mg·ha^{-1}$ (CONAB, 2023). Rain-fed production systems are utilized in 64% of the area cultivated with sugarcane in Brazil, and the marginal areas are subject to frequent water deficits. The remaining 36% is equipped with irrigation systems; however, a considerable proportion of these irrigation systems (76%) was used for crop maintenance irrigation, providing water only to guarantee the initial maintenance of the plants during planting and regrowth of ratoons, partially reducing the stress due to water deficit in the dry period. The other 24% of the areas of the irrigated sugarcane production system use deficit and full irrigation, which aim to partially (50%) and totally (100%) supply the plants' water demand, respectively (ANA, 2023). Thus, most of the area cultivated with sugarcane in Brazil is subject to water deficit in one or more stages of the crop's development cycle, which can affect its biomass yield and juice quality (Marin and Nassif, 2013; Vianna and Sentelhas, 2014; Dias and Sentelhas, 2019).

Water deficit can retard growth and reduce nutrient use and productivity of the sugarcane crop, especially when it occurs at the beginning of the tillering period or in the final phase of vegetative growth. The relative elongation rate of stalks and leaves is extremely sensitive to water availability. Water deficit reduces water uptake by roots, resulting in osmotic dysregulation and stomatal closure, which lowers transpiration and carbon dioxide capture, reducing photosynthetic rate, carbon assimilation, carbohydrate synthesis, vegetative development and production of dry biomass (Silva et al., 2008; Marchiori et al., 2017; Sarah et al., 2021; Misra et al., 2023). However, water availability should be lower in the period prior to harvest to ensure the accumulation of sucrose in the culm and for crop maturation (Inman-Bamber and Smith, 2005; Camargo et al., 2017, 2019; Hoang et al., 2019; Teixeira et al., 2020, 2022).

A possible strategy to mitigate the harmful effects of water deficit in sugarcane cultivation is the addition of silicon (Si) to the soil. Si is considered a beneficial element as it improves plant growth and productivity, especially under stress conditions. Si's potential role in providing tolerance against both abiotic and biotic stresses suggests that increasing Si content in plants may be a viable approach for increasing a crop's resistance to environmental stresses such as drought (Zhu and Gong, 2014; Oliveira Filho et al., 2021; Misra et al., 2023). This occurs due to Si deposition in tissues subjected to water stress, which reduces transpiration and regulates physiological and biochemical processes. In the vast majority of plants, the leaf epidermis is covered by a cuticle that waterproofs the leaf, preventing water loss directly into the atmosphere without passing through the plant's stomata. Cuticular transpiration occurs through pores in the cuticle of the leaves, but accounts for only 10% of a plant's total water loss. The effect of a greater absorption of Si by the sugarcane crop would be to reduce the cuticular transpiration of the leaves, by reinforcing the Si shield and closing cuticular pores. To increase plant tolerance, Si also promotes photosynthesis by favoring the exposure of leaves to sunlight (Sahebi et al., 2015; Gaur et al., 2020; Lacerda et al., 2022).

Si appears in high concentrations in sugarcane leaves, varying from 0.14% in young leaves to 6.7% in old leaves (Marafon and Endres, 2013). The increase in Si content in sugarcane leaves is observed when amorphous Si is applied to quartzarenic (sandy) soils. Amorphous Si is mainly present in the biogenic form (phytoliths) in soils. Both, clay and sandy soils have Si in the mineral form, but clay soils have more secondary minerals than sandy soils which have mainly quartz (primary mineral). Secondary minerals are more prone to weathering than primary minerals and, therefore, clayey soils have higher levels of dissolved Si than sandy soils. Thus, the greatest benefit from Si application in sugarcane cultivation occurs in sandy soils, which are more subject to water stress (Barreto et al., 2022; Basto et al., 2010; Borges et al., 2016). In general, sugarcane crops respond favorably to Si fertilization, particularly in soils with low levels of this element. However, the application of Si via soil can promote other effects that have been little studied, such as the improvement of nutrient use efficiency and crop water productivity (WP_c). Studies with rice, for example, reported an interaction of nitrogen (N) with Si in which the Si content in the aerial parts decreased with increasing N fertilization (Mauad et al., 2003; Fonseca et al., 2009; Fallah, 2012). With regard to sugarcane, some researches showed that nitrogen fertilization in combination with Si did not affect juice quality and resulted in better crop yield, better physiological performance and greater tolerance to biotic and abiotic stresses (Silva et al., 2015; Souza Junior et al., 2022; Barão, 2023; Costa et al., 2023).

Concerning WP_c, it is expected that research on optimizing Si application levels when combined with N will result in the production of more biomass and energy per unit of consumed water. However, there have been no conclusive studies on the use of Si combined with N on sugarcane and its effects on WP_c. The central hypothesis of this research stated that there is an optimal dose of N and Si applied to the soil that allows the sugarcane crop to develop anatomical and physiological mechanisms capable of protecting plant tissues from the detrimental effects of water deficiency, providing a higher WP_c and better biometric and juice quality responses.

The objectives of this research were to determine the effects of different N and Si application rates on WP_c, in terms of sugar (SWP_c), biomass (BWP_c) and energy ($ENWP_c$), as well as biometric and juice quality responses for the sugarcane crop. The potential role of Si in reducing crop water consumption and N requirement is discussed.

2. Material and methods

2.1. Location and characterization of the experimental area

The research was carried out in the experimental area of the Biosystems Engineering Department at the University of São Paulo, in Piracicaba-SP, Brazil. The geographical coordinates of the experiment site are: 22°42'39" south latitude and 47°37'44" west longitude, with an altitude of approximately 548 m. The climate of the region is considered humid subtropical (Cwa) according to the Köppen climate classification, with hot and rainy summers, cold and dry winters, average temperature of 21.6°C, average relative humidity of 73% and annual precipitation of 1280 mm (Alvares et al., 2013).

The soil in the experimental area was classified as Oxisol typic Hapludox (USDA, 1999). The chemical characterization of this soil was determined after sample collection and laboratory analysis. In the collection of soil samples an auger was used. Simple samples were collected to form a composite sample from depths of 0–0.20, 0.20–0.40 and 0.40–0.60 m (Table 1). The physical and water characteristics of the soil were also determined using undisturbed soil samples from the three layers. The values obtained by laboratory analysis are shown in Table 2.

2.2. Experimental design and treatments

The experimental design adopted was randomized blocks, with four blocks and 12 treatments, totaling 48 experimental plots. The experimental plots were composed of six plants, resulting in a stand of 288 plants evaluated throughout the experiment. The treatments were arranged in a 3 ×4 factorial scheme, with three doses of Si (175, 350 and 525 $kg·ha^{-1}$) and four doses of N (15, 30, 60 and 90 $kg·ha^{-1}$).

N treatments were defined according to van Raij et al. (1997). As there is no optimal level of Si absorption for sugarcane, the amount of the Si application was determined based on values obtained from Camargo et al. (2013) and Camargo et al. (2019).

2.3. Planting and crop management

The research was developed from July 8, 2015 to June 30, 2016. The material used in the experiment for seedling production was the

Table 1
Chemical characterization of soil in the experimental area at depths of 0–0.2, 0.2–0.4 and 0.4–0.6 m.

Depth	pH $CaCl_2$	OC	Available P	S^{2-}	Fe^{2+}	Na^+	K^+	Ca^{2+}	Mg^{2+}	$H^+ + Al^{3+}$	SB	CEC	Base saturation	Total N	NH_4^+	NO_3^-	Si
m		$g \cdot dm^{-3}$	$mg \cdot dm^{-3}$				$mmolc \cdot dm^{-3}$						%	$g \cdot kg^{-1}$			
0–0.2	6.0	22	27	26	22	285	1.4	34	11	18	46.4	64.4	72	1.40	0.014	0.011	0.008
0.2–0.4	5.8	21	24	67	67	305	0.9	30	14	20	44.9	64.9	69	1.82	0.014	0.042	0.009
0.4–0.6	5.9	23	30	67	67	315	1.1	31	16	20	48.1	68.1	71	1.54	0.011	0.039	0.008

pH - hydrogen potential; OC - organic carbon; SB - sum of bases; CEC - cation exchange capacity; NH4+ - ammonium ion; NO3- - nitrate ion. Methods: OC - dichromate/colorimetric (Nelson and Sommers, 1996); available P, exchangeable K+, Ca2+, Mg2+ and Na+ - resin and double acid (Delgado et al., 2016); S - monocalcium phosphate, Ca(H2PO4)2; Fe - DTPA (Katyal and Sharma, 1991); H++Al3+ - SMP (Doerge and Gardner, 1998); Total N, NH4+ and NO3- - sulfuric acid/Kjeldahl digestion (Mitamura, 1994); Si - calcium chloride (CaCl2) (Rodrigues et al., 2003).

Table 2
Physical and hydraulic characteristics of soil in the experimental area at depths of 0–0.2, 0.2–0.4 and 0.4–0.6 m.

Depth m	θ_{Fc}	θ_{wc}	AWC mm	D_s	D_p	Sp %	Granulometric fractions		
							Sand %	Silt	Clay
	$cm^3 \cdot cm^{-3}$			$g \cdot cm^{-3}$					
0–0.2	0.23	0.11	22.22	1.5	2.7	44.44	75.1	7.8	17.1
0.2–0.4	0.23	0.10	25.62	1.5	2.7	44.44	74.5	8.0	17.5
0.4–0.6	0.24	0.13	21.76	1.7	2.6	34.62	74.4	8.6	17.0

θFC - moisture at field capacity; θWP - moisture at the wilting point; AWC - available water capacity; Ds - soil bulk density; Dp - soil particle density; Sp - total soil porosity. Physical and hydraulic soil characteristics were determined using the methodology proposed by the EMBRAPA (1997).

sugarcane variety developed for irrigated cultivation, RB92579 (RB75126 x RB72199), which was developed by the improvement program of the Inter-University Network for Development of the Sugar-Energy Sector (RIDESA). The seedlings were transplanted at a height of 0.30–0.40 m when the number of expanded leaves was 4–5. The seedlings were planted at a depth of 0.15 m and a spacing of 0.30 m between plants, with row spacing of 1.5 m.

The nutritional management was carried out based on the results of the chemical analysis of the soil and followed the recommendations of van Raij et al. (1997) for a minimum expected productivity of 150 $Mg \cdot ha^{-1}$. In the planting furrows, 100 $kg \cdot ha^{-1}$ of P and 40 $kg \cdot ha^{-1}$of K were applied, using simple superphosphate and potassium sulfate, respectively. N was applied in the form of ammonium nitrate in all treatments. Topdressing fertilizations were carried out with potassium sulfate and ammonium nitrate fertilizers, referring to the recommended installments.

To provide Si, Agrosilicon Plus fertilizer (25% Ca, 6% Mg and 10.5% Si) was used. To prevent changes in soil Ca and Mg levels from interfering with the results, plants treated with <525 $kg \cdot ha^{-1}$ of Si were supplemented with limestone (33.6% Ca and 2.7% Mg) and magnesium oxide (52% Mg), so that the total amount of Ca and Mg applied in the treatments was equal, following the recommendations of Camargo et al. (2013). The fertilizers were distributed manually and incorporated into the 0–0.20 m soil layer, before transplanting the seedlings. To complement the nutritional management and to prevent deficiencies, 10 $kg \cdot ha^{-1}$ of CanaMicro fertilizers (5% B, 4.5% Cu, 2% Mo, 11% Zn, 4.5% Mn) were applied via the irrigation system.

2.4. Irrigation management and micrometeorological monitoring

Micrometeorological monitoring was carried out using a Campbell Scientific automatic meteorological station installed in the experimental area. This station recorded global solar radiation with a pyranometer sensor (LP02-L12, Campbell Sci.). Air temperature and relative humidity were monitored by a Vaissala sensor (HMP45C-L1,2 Campbell Sci.). Both sensors were installed at a height of 2 m. Data were collected every minute and integrated every 15 minutes through a data acquisition system (Campbell Datalogger CR 1000). For later use in irrigation management calculations, data were integrated on a daily basis.

The irrigation system utilized drip irrigation with self-compensating emitters at a nominal flow of 0.002 $m^3 \cdot h^{-1}$. Each experimental plot had two lateral lines with five emitters spaced 0.20 m apart, totaling 0.02 $m^3 \cdot h^{-1}$ per plot. The main line was a PVC tube (0.025 m diameter), and branch lines were polyethylene microtubes (0.008 m diameter). Independent irrigation for each plot was facilitated by a vertical panel with a sphere register. A motor pump set provided system pressure (0.5 hp, 3450 rpm), with a service pressure of 0.196 MPa monitored by a Bourdon manometer.

The functioning of the irrigation system was evaluated before the implementation of the experiment by measuring variation in the emitter discharge and calculating the Christiansen uniformity coefficients (CUC) and distribution coefficients (CUD). Mean CUC and CUD values were 95.9 and 93.7%, respectively indicating that the discharge variations were within the acceptable range.

The soil irrigation management program controlled the soil moisture content and replaced the water consumed by the plants based on field capacity and readings of soil water tension by tensiometers installed at three depths, 0.15, 0.30 and 0.50 m representing the layers of 0–0.20, 0.20–0.40 and 0.40–0.60 m, respectively. The criterion for triggering irrigation was when the soil matric potential reached an average of −20 kPa in the three monitored layers. The data were collected using digital tensiometers calibrated with a mercury column manometer.

The conversion of the current soil matric potential (Ψ) obtained by the tensiometers to the soil volumetric water content (θ) was performed using Eqs. 1 and 2 and the data in Table 3, as well as the parameters of

Table 3
Values of the terms in the equation for soil in the experimental area (van Genuchten, 1980).

Depth	θs	θr	α	m	n
m	$cm^3 \cdot cm^{-3}$	$cm^3 \cdot cm^{-3}$	cm^{-1}		
0–0.2	0.421	0.098	1.3464	0.180	2.718
0.2–0.4	0.412	0.085	1.5708	0.165	2.503
0.4–0.6	0.374	0.122	1.1291	0.275	1.562

θs - saturated soil moisture; θr - residual soil moisture is the value below which it is no longer possible to extract water from the soil with increased suction; α - parameter with dimension equal to the inverse of the tension; n - regression parameter of the equation; m - regression parameter of the equation representing the shape parameter governing the soil water retention curve, m = 1–1/n.

van Genuchten (1980).

$$\psi = L + hc \quad (1)$$

where ψ is the soil matric potential in kPa, L is the reading on the tensiometer in kPa and hc is the pressure equivalent to the height of the water column in the tensiometers at −3, −5 and −7 kPa, which represent the layers at 0–0.20, 0.20–0.40 and 0.40–0.60 m, respectively.

$$\theta = \theta_r + \frac{(\theta_s - \theta_r)}{(1 + (\alpha \times \psi)^n)^m} \quad (2)$$

where θ is the soil volumetric water content in $cm^3 \cdot cm^{-3}$, θ_r is the soil residual volumetric water content in $cm^3 \cdot cm^{-3}$, θ_s is the volumetric water content of the saturated soil in $cm^3 \cdot cm^{-3}$, n is a regression parameter of the equation, m is the regression parameter of the equation representing the shape of the soil water retention curve, m = 1–1/n. This parameter describes how rapidly the soil retains water as the soil water content decreases. The values of m typically range between 0 and 1, with lower values indicating a faster decrease in water retention as soil water content decreases, and higher values indicate a slower decrease. The parameter α has a dimension equal to the inverse of the tension in cm^{-1}, and Ψ is the matric potential in kPa. The irrigation depths to restore soil moisture up to field capacity were determined in each treatment with the moisture data estimated by Eq. 2. The depths required by each soil layer were calculated by means of Eq. 3:

$$LI = \sum_{i=20}^{60} (\theta cci - \theta i) Zi \quad (3)$$

where L_I is the depth in mm needed to raise soil moisture to field capacity, θcci is the volumetric moisture at field capacity for layer i in $cm^3 \cdot cm^{-3}$, and θi estimated current volumetric moisture for layer i in $cm^3 \cdot cm^{-3}$ and Zi is the thickness of layer i in mm.

The irrigation time required for each treatment was calculated using Eq. 4:

$$TI = \frac{60 \quad LI \quad A}{Q \; Ea} \quad (4)$$

where T_I is the irrigation time in minutes, L_I is the depth required to raise soil moisture to field capacity in mm, A is the soil surface area of the experimental plot in m^2, Q is the flow rate for each treatment in $L \cdot h^{-1}$ and Ea is the system efficiency for each treatment.

2.5. Harvest and analyzed variables

Harvesting involved cutting, counting, bagging and weighing unproductive tillers, productive tillers, and separating green leaves, dry leaves, sheaths, tops and stalks. Each of these parts was identified, stored in paper bags and weighed as the fresh biomass (FB). Pointers were used to assess chlorophyll and leaf area (LA). To obtain the dry biomass (DB), samples of the aerial parts of the plant were dehydrated in an electric oven with forced air ventilation at a temperature of 65°C until a constant weight was reached. The DB was determined by summing the masses of the leaves, sheaths, tips and unproductive tillers. For culms, dry matter was estimated as a function of its moisture content.

Stalk diameter (SD) and plant height (SH) were measured using the methodology of Sinclair et al. (2005). Two stalks per plot were selected and crushed using a sugarcane disintegrator. The juice quality analysis involved the utilization of the methodology recommended by CONSECANA (2006) to conduct determinations of the juice parameters Brix (Bx), juice Pol (Pol in %), juice apparent purity (Pur in %), sugarcane fiber (% fiber), moisture content of sugarcane stalks (%), reducing sugar in the cane (RS in %), and total recoverable sugar (TR in $kg \cdot Mg^{-1}$).

The Falker chlorophyll index (FCI) was determined using a Chlorophylog (Falker CFL1030). Three measurements were performed on two plants per plot and these measurements were taken in the middle third of the leaf +1. The harvest index (HI) was determined based on the aerial biomass of the plants using the equations presented by Kapur et al. (2013).

Leaf area (LA) was determined on a LI 3100 LA integrator (LI-COR Biosciences). Readings were taken on two representative tillers from each plot. Agricultural yield, AY, was calculated as a function of fresh biomass (FB) and plot area (A), using Eq. 5:

$$AY = \frac{10 \; FB}{A} \quad (5)$$

where AY is the agricultural yield in $Mg \cdot ha^{-1}$, FB is the fresh biomass of stalks in kg, A is the area of the plot in m^2 and 10 is the conversion factor from units of $kg \cdot m^{-2}$ to $Mg \cdot ha^{-1}$. The sugar yield, SY, represents the sugar production per unit area ($Mg \cdot ha^{-1}$), taking into account the previously calculated AY and TR. SY was calculated using Eq. 6:

$$SY = \frac{(TRAY)}{1000} \quad (6)$$

where SY is the sugar yield in $Mg \cdot ha^{-1}$, TR is the total recoverable sugar in $kg \cdot Mg^{-1}$ and AY is the agricultural yield in $Mg \cdot ha^{-1}$.

The WP_c was analyzed for the different products that could be obtained from this crop. Crop water productivity in terms of sugar (SWP_c), biomass (BWP_c) and energy ($ENWP_c$) was calculated, all of which were related to the total volume of irrigation water applied (IWU). SWP_c was determined as a function of the total amount of sugar produced in each plot, TSpar, and the I, and calculated using Eqs. 7 and 8:

$$TSpar = TR \frac{FBc}{1000} \quad (7)$$

where TSpar is the total sugar produced in the plot in kg, TR is the total recoverable sugar in $kg \cdot Mg^{-1}$ and FBc is the fresh biomass of stalks in kg. After calculating the TSpar, the SWP_c was determined using Eq. 8:

$$SWPc = \frac{TSpar}{IWU} \quad (8)$$

where SWP_c is the sugar water productivity in $kg \cdot m^{-3}$, TSpar is the total sugar produced in the plot in kg, and IWU is the total volume of irrigation water applied to the plot in m^3.

BWP_c was calculated through the relationship between DB and IWU, using Eq. 9:

$$BWPc = \frac{DB}{IWU} \quad (9)$$

where BWP_c is the biomass water productivity in $kg \cdot m^{-3}$, DB is the dry biomass of the aerial parts of the plants in kg, and IWU is the total volume of irrigation water applied to the plot in m^3. To determine the $ENWP_c$, it was necessary to estimate the values of straw energy, bagasse energy, sugar energy and energy of the total aerial parts (ENtotal), all measured in $MJ \cdot m^{-2}$. For this, we used the calorific power ratios recommended by Coelho et al. (2019). Once the ENtotal values were determined, the $ENWP_c$ was calculated using Eq. 10:

$$ENWPc = \frac{ENtotal}{IWU} \quad (10)$$

where $ENWP_c$ is the energy water productivity in $MJ \cdot m^{-3}$, ENtotal is the total area of the energy parts of the plants in MJ and IWU is the total volume of irrigation water applied to the plot in m^3.

2.6. Data analysis

Data normality was evaluated using the Shapiro-Wilk test ($p>0.05$), and homogeneity using the Bartlett test ($p>0.05$). Subsequently, the data were submitted to analysis of variance considering the factorial through the F test (ANOVA). For significant F values ($p<0.05$), means were compared using Tukey's test at a 5% probability level. All analyses were performed using the statistical software R version 4.1.2.

3. Results

3.1. Environmental conditions and water consumption

According to the micrometeorological data, the mean daily temperature varied between 11.7°C at 265 days after planting (DAP) to 30.8°C at 25 DAP. The minimum daily temperature ranged from 2.8°C at 266 DAP to 23.9°C at 59 DAP, with an average of 19.1°C for the period. The maximum temperature varied between 20.5°C and 45.5°C at 252 DAP and 25 DAP, respectively, with an average of 35.3°C throughout the crop cycle. The average value for global solar radiation recorded during the experimental period was 9.9 MJ·m^2·day^{-1}, with extremes of 17 and 1.5 MJ·m^2·day^{-1} at 39 and 252 DAP, respectively. The average relative humidity during the period was 76%, reaching a maximum value of 97.4% at 113 DAP and a minimum value of 53.5% at 3 DAP (Fig. 1).

The amount of water lost by evapotranspiration from the experimental sugarcane crop differed depending on the different N and Si treatments (Fig. 2). The 30Nx350Si treatment showed the highest water consumption throughout the crop cycle, totaling 824 mm per year, followed by the 30Nx175Si, 60Nx350Si, 60Nx175Si, 60Nx525Si, 90Nx525Si and 15Nx175Si treatments, with values of water consumption above 700 mm per year. The lowest water consumption was obtained with the 15Nx350Si treatment at 561 mm per year. Three other treatments (90Nx175Si, 15Nx525Si, 30Nx350Si) showed water consumption of less than 650 mm per year.

Considering the average values within each N treatment, it was found that for the doses of 15–30 kg·ha^{-1} N, the water consumption of sugarcane was lower when 350 kg·ha^{-1} Si was applied. In contrast, the combination of 60 kg·ha^{-1} N with a dose of 525 kg·ha^{-1} Si resulted in the lowest water consumption. In comparison, when 90 kg·ha^{-1} N was applied, the lowest water consumption was observed at a dose of 175 kg·ha^{-1} Si.

3.2. Biometric responses, impacts on juice quality and yield-related indices of sugarcane

No significant differences were observed in the variables of SH, SD, VC and DB with the different treatments. The mean values obtained in this research for the SH and SD were 2.9 m and 22.1 mm. The VC, as a variable derived from the two previous ones, had an average of 1184.9 cm^3, while the DB had an average of 6 kg (Table 4). The effects of treatments resulted in significant differences by the F test ($p<0.05$) for LA and FB. The highest LA values were found in the 60Nx525Si and 90Nx525Si treatments, with means of 4.6 and 4.3 m^2, respectively. For the FB variable, it was observed that the highest average values were found for the 60Nx350Si, 60Nx525Si and 90Nx525Si treatments at 20.8, 20.4 and 20.6 kg, respectively.

Regarding juice quality variables, no significant differences were observed for the variables Bx, Pol, Pur, fiber, RS, TR, SY and WS under the applied sugarcane treatments. The average values found for the variables of juice quality of sugarcane were: Bx (16.4 °Brix), Pol (11.4%), Pur (69.6%), fiber (10.8%), RS (1.1%), TR (104.5 kg·Mg^{-1}), SY (14.9 Mg·ha^{-1}) and WS (75%) (Table S1).

For the agricultural yield (AY), significant differences were observed depending on the applied treatment. The treatment that produced the highest average value of AY was 60Nx350Si (162.3 Mg·ha^{-1}) and the treatment with the lowest average value of AY was 15Nx525Si (133.7 Mg·ha^{-1}). The average value of AY over all treatments was 142.8 Mg·ha^{-1} (Fig. 3). It was found that for the low dose of N (15 kg·ha^{-1}), AY was little affected by Si doses. For intermediate N applications of (30

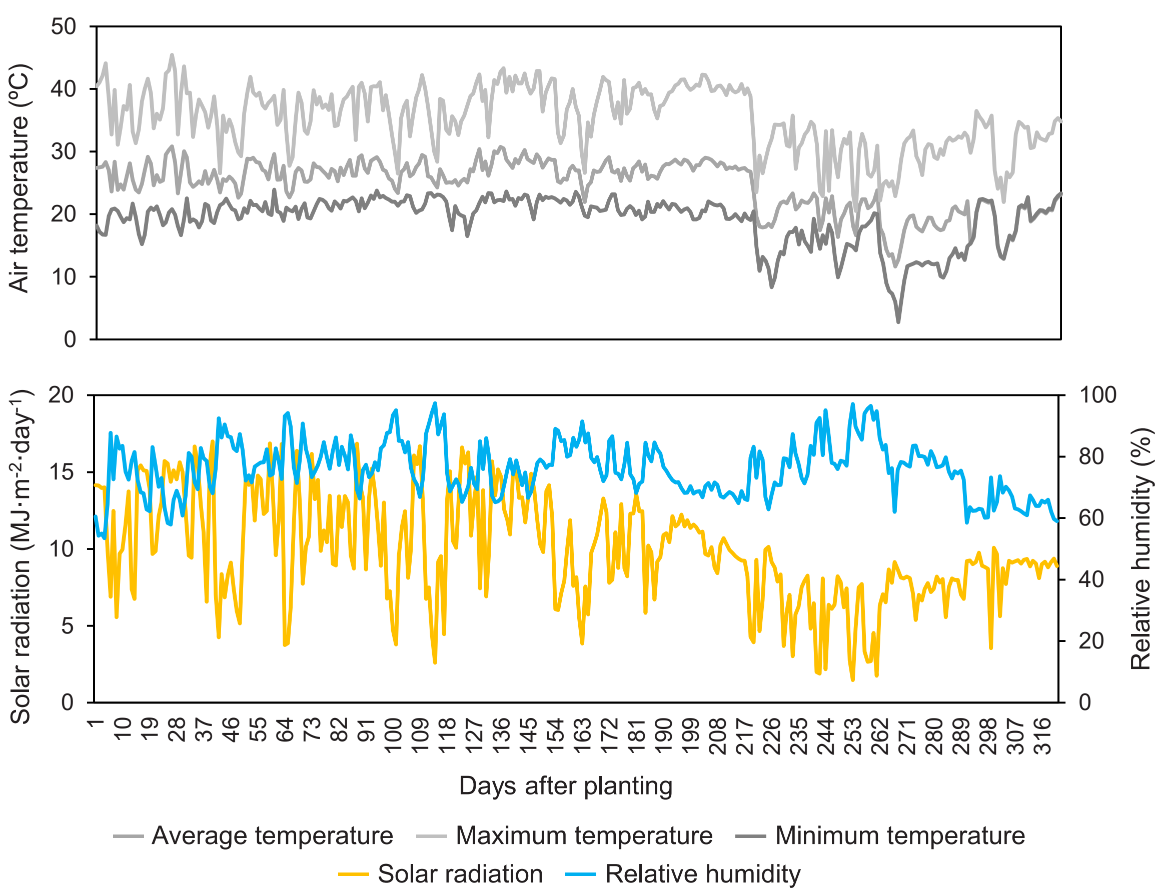

Fig. 1. Maximum, minimum and average air temperature, relative humidity and global solar radiation recorded during the sugarcane cultivation cycle in the experimental area of the University of São Paulo.

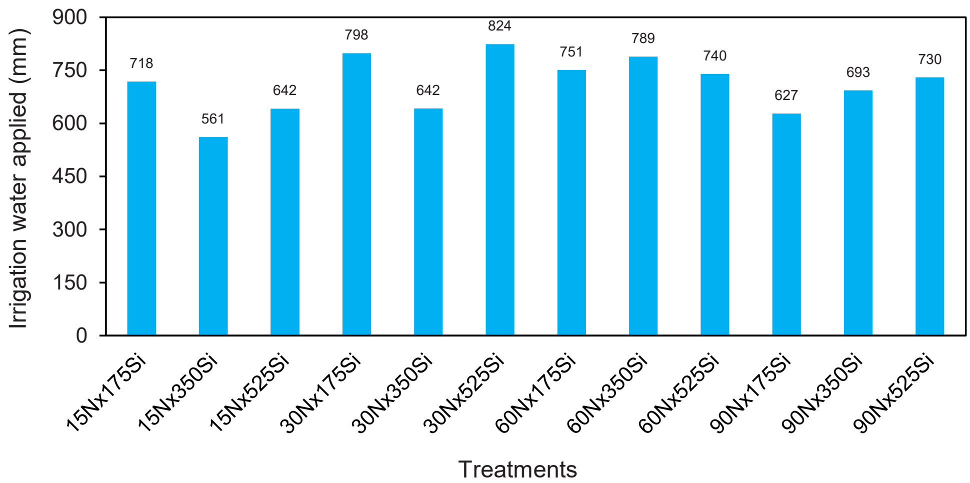

Fig. 2. Amount of water applied to the sugarcane crop during the experimental period and according to the treatments with different dosages of nitrogen (N) and silicon (Si).

Table 4
Biometric responses and agricultural yield of the sugarcane crop with different applications of nitrogen and silicon.

Treatments	AY	SH	SD	VC	LA	FB	DB
	$Mg \cdot ha^{-1}$	m	mm	cm^3	m^2	kg	kg
15Nx175Si	137.2 b	3.0 a	21.8 a	1159.6 a	2.5 ab	18.0 ab	5.8 a
15Nx350Si	135.5 b	2.8 a	21.5 a	1088.7 a	3.1 ab	17.5 ab	5.6 a
15Nx525Si	133.7 b	2.8 a	21.8 a	1096.1 a	3.3 ab	17.8 ab	5.7 a
30Nx175Si	150.9 ab	3.1 a	22.0 a	1226.7 a	3.8 ab	20.2 ab	6.3 a
30Nx350Si	140.9 ab	2.8 a	23.1 a	1252.7 a	2.0 b	18.5 ab	6.1 a
30Nx525Si	152.3 ab	3.0 a	22.4 a	1207.5 a	4.0 ab	19.7 ab	6.2 a
60Nx175Si	143.3 ab	3.0 a	21.8 a	1161.3 a	4.0 ab	19.0 ab	6.0 a
60Nx350Si	162.3 a	3.0 a	22.4 a	1256.3 a	4.0 ab	20.8 a	6.4 a
60Nx525Si	153.8 ab	3.1 a	22.5 a	1273.1 a	4.6 a	20.4 a	6.3 a
90Nx175Si	135.5 b	2.9 a	23.1 a	1261.4 a	3.1 ab	18.3 ab	5.8 a
90Nx350Si	140.6 b	2.8 a	20.6 a	1076.7 a	2.8 ab	19.0 ab	5.9 a
90Nx525Si	153.6 ab	3.0 a	22.1 a	1213.7 a	4.3 a	20.6 a	6.3 a

AY - agricultural yield; SH - plant height; SD - stalk diameter; VC - volume of the cane; LA - leaf area; FB - fresh biomass; DB - dry biomass. The treatments were arranged in a 3 ×4 factorial scheme, with three doses of Si (175, 350 and 525 kg·ha-1) and four doses of N (15, 30, 60 and 90 kg·ha-1). Different letters indicate significant differences between the means using Tukey's test ($p < 0.05$).

and 60 $kg \cdot ha^{-1}$), the Si effect on AY was higher at low and high Si rates (175 and 525 $kg \cdot ha^{-1}$) and lower, in both cases for Si at 350 $kg \cdot ha^{-1}$. Finally, at 90 $kg \cdot ha^{-1}$ N, the Si effect was linear; the greater the Si application, the higher the AY.

No significant differences were observed for the FCI and HI variables, and the mean values for these indices were 29.8 and 0.26, respectively.

3.3. Crop water productivity in terms of sugar, biomass and energy

For the variables SWP_c, BWP_c and $ENWP_c$, significant differences were observed depending on the applied treatment. The mean values of SWP_c, BWP_c and $ENWP_c$ were 2.2 $kg \cdot m^{-3}$, 8.5 $kg \cdot m^{-3}$ and 191.4 $MJ \cdot m^{-3}$, respectively (Fig. 4). With respect to the effects of different applications of N and Si on SWP_c, BWP_c and $ENWP_c$, the highest means were observed with the 15Nx350Si treatment. The mean values of 15Nx350Si were 2.6 $kg \cdot m^{-3}$, 10 $kg \cdot m^{-3}$ and 224.5 $MJ \cdot m^{-3}$ for SWP_c, BWP_c and $ENWP_c$, respectively. The 30Nx350Si treatment also showed good performance with average SWP_c, BWP_c and $ENWP_c$ values close to those produced by 15Nx350Si. The worst performance in terms of BWP and ENWP was observed with 30Nx525Si. The average values observed in 30Nx525Si were 7.5 $kg \cdot m^{-3}$ and 170.1 $MJ \cdot m^{-3}$, for BWP_c and $ENWP_c$, respectively.

Considering the average values of SWP_c, BWP_c and $ENWP_c$ for each N treatment, it was found that for 15–30 $kg \cdot ha^{-1}$ N, the crop water productivity in terms of sugar, biomass and energy was greater when 350 $kg \cdot ha^{-1}$ Si was applied. With 60 and 90 $kg \cdot ha^{-1}$ N, no significant differences were found among Si treatments of 175, 350 and 525 $kg \cdot ha^{-1}$.

4. Discussion

The purpose of the combined application of N and Si on the sugarcane crop was to minimize water consumption without compromising yield, juice quality, or the achievement of the maximum WP_c in terms of sugar, biomass and energy. Our findings indicate that the N and Si application increased the WP_c without compromising sugarcane juice quality.

4.1. Sugarcane yield and reduction of water consumption

The total amounts of irrigation water applied (IWU) in the treatments showed an average value of 705 mm (Fig. 2). This value represented approximately 79% of the water consumption of sugarcane in São Paulo State, Brazil (896 mm), as reported by Hernandes et al. (2018). It also represented 90% of the water demand of sugarcane grown with application of N without Si (788 mm) in similar environmental conditions using the same genetic material, as reported by Santos et al. (2019). The findings of this study support the conclusion that the combined application of N and Si can substantially reduce the water consumption of sugarcane.

The treatment with the lowest water requirement for irrigation was 15Nx350Si, with an average value of 561 mm (Fig. 2). This value represents 63% of the water consumption of sugarcane grown in Brazil, where higher doses of N were used and little Si is applied (Hernandes et al., 2018). With an application of 15–30 $kg \cdot ha^{-1}$ N, the dose of Si that resulted in lower water consumption was 350 $kg \cdot ha^{-1}$. For the range of

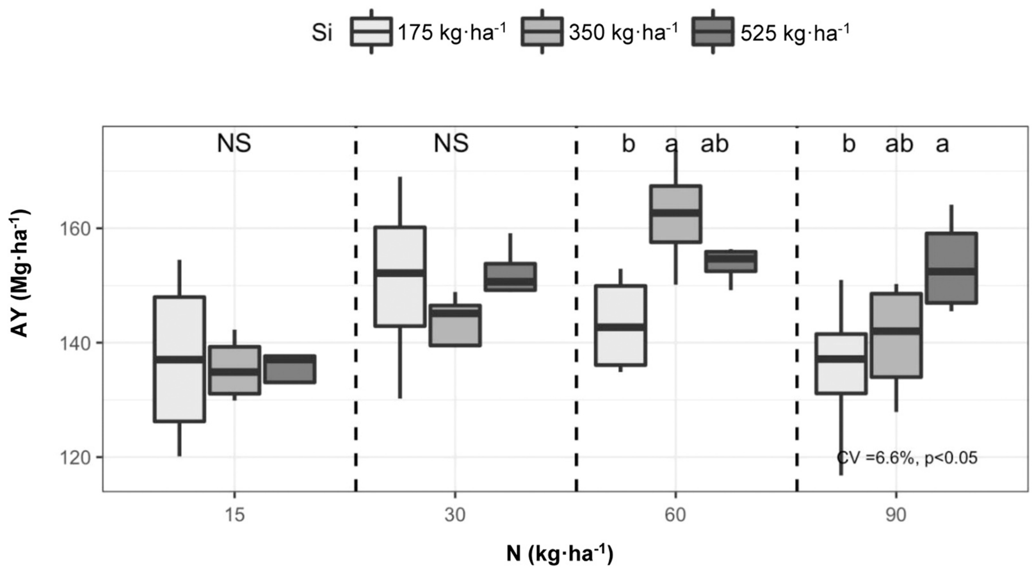

Fig. 3. Agricultural yield (AY) as a function of treatments with different dosages of nitrogen (N) and silicon (Si) applied via soil. The box represents the interquartile range (IQR) and 'whiskers' represent the range of data. The median is depicted by a horizontal line within the box.

60–90 kg·ha^{-1} N, an application of 350 kg·ha^{-1} Si resulted in an average performance when compared to the doses of 175 and 525 kg·ha^{-1}. According to Desalegn et al. (2023), at higher doses of N, sugarcane tended to have greater vegetative growth and, consequently, greater water consumption. Therefore, even if silicon was being applied at high doses, its combination with high doses of N did not result in a significant reduction in water consumption by plants when compared to combined treatments of low doses of N and high doses of Si.

With respect to AY, N x Si treatments resulted in an average value of 145 Mg·ha^{-1} (Fig. 3), which was 71% higher than those reported by Hernandes et al. (2018) for AY of sugarcane (81 Mg·ha^{-1}) in the São Paulo State, Brazil. In general, treatments with 15 N and 90 N combined with Si resulted in the lowest average AY values compared with treatments of 30 N and 60 N. It was observed that, depending on the N treatment, the effect of applied Si doses on the AY was different. Muchovej and Newman (2004) observed that the yield of fresh cane plant stalks and first ratoon were not significantly affected by increased application of nitrogen fertilizers. Even nitrogen fertilizer rates higher than 170 kg·ha^{-1} N did not increase sugarcane AY. Rose et al. (2015) suggested that sugarcane responded differently to different N treatments, and that a higher N rate did not always result in higher productivity; therefore, it can be problematic to quantify the response of the crop to N. According to these authors, the 100 N level (the 100Nx100Si iteration) gave the best performance because it resulted in the highest average value of AY (160.4 Mg·ha^{-1}).

The treatment with the highest AY value was 60Nx350Si (162.3 Mg·ha^{-1}) (Fig. 3). The 15Nx350Si treatment (lower water consumption) had an average AY value of 135.5 Mg·ha^{-1}, showing that despite the excellent performance in terms of water consumption, there was a reduction in AY under this treatment. Treatments of plants with lower doses of NxSi reduced water consumption and water potential, but induced oxidative stress, which impaired photosynthetic efficiency and consequently decreased AY, corroborating the results found by Teixeira et al. (2022).

In this research, the effects of treatments on water consumption and AY of sugarcane crops indicated that the growing conditions, soil type, climate and variety must be considered so that addition of N combined with Si results in higher WP_c. Although the optimal AY values were obtained in the 60Nx350Si treatment, water consumption was lower in the 15Nx350Si treatment. Thus, if the farmers' goal is to obtain a reasonable AY (economic gain) commensurate with good water and N savings (economic and environmental gains), they should opt for 15Nx350Si; but if his priority is to obtain the highest AY possible he should opt for 60Nx350Si.

4.2. Biometrics and juice quality of sugarcane

The application of combined N plus Si soil treatments did not result in different biometric responses (Table 4). Costa et al. (2011) stated that biometric variables usually show less significant responses, as these variables depend on the genetic characteristics of the plant. Our results corroborated those obtained by Chaves et al. (2013) and Clemente et al. (2017) who found that the application of correctives and silicates to sugarcane did not have a significant influence on biometric variables such as SH and SD. Therefore, the application of combined N + Si treatments could improve some environmental indicators (reduced water consumption and use of nitrogen fertilizers) and the sugarcane yield without compromising the biometric variables.

With respect to juice quality, we found that the application of combined N and Si soil treatments did not result in significant responses (Table S1). Thus, the use of Si does not compromise the end product quality. Oliveira et al. (2012) suggested that some sugarcane varieties differed in their capacity to accumulate sucrose, and increasing N application may not affect the juice quality. Borges et al. (2016) using the RB 855156 variety, determined that the use of slag or limestone in combination with N did not affect sugarcane juice quality. Likewise, Sobral et al. (2011) reported that increasing applications of slag did not result in a significant increase in the industrial variables of sugarcane, corroborating the results found in this research.

4.3. Enhancing WP_c through combined application of N and Si

The average WP_c values (SWP_c=2.2 kg·m^{-3}, BWP_c=8.5 kg·m^{-3} and $ENWP_c$=191.4 MJ·m^{-3}) obtained in this research indicate that the combined application of N and Si results in the production of more sugar, biomass and energy using a smaller amount of irrigation water on the sugarcane crop (Fig. 4). In research evaluating SWP_c, Santos et al. (2019) found mean values of 1.5 kg·m^{-3}, for eight sugarcane varieties subjected to different irrigation depths. Leal et al. (2017) evaluated the SWP_c for a group of varieties planted in two types of soil and subjected to different irrigation treatments, obtaining average values of 2.1 kg·m^{-3} for the RB 92579 variety, indicating that the combined application of

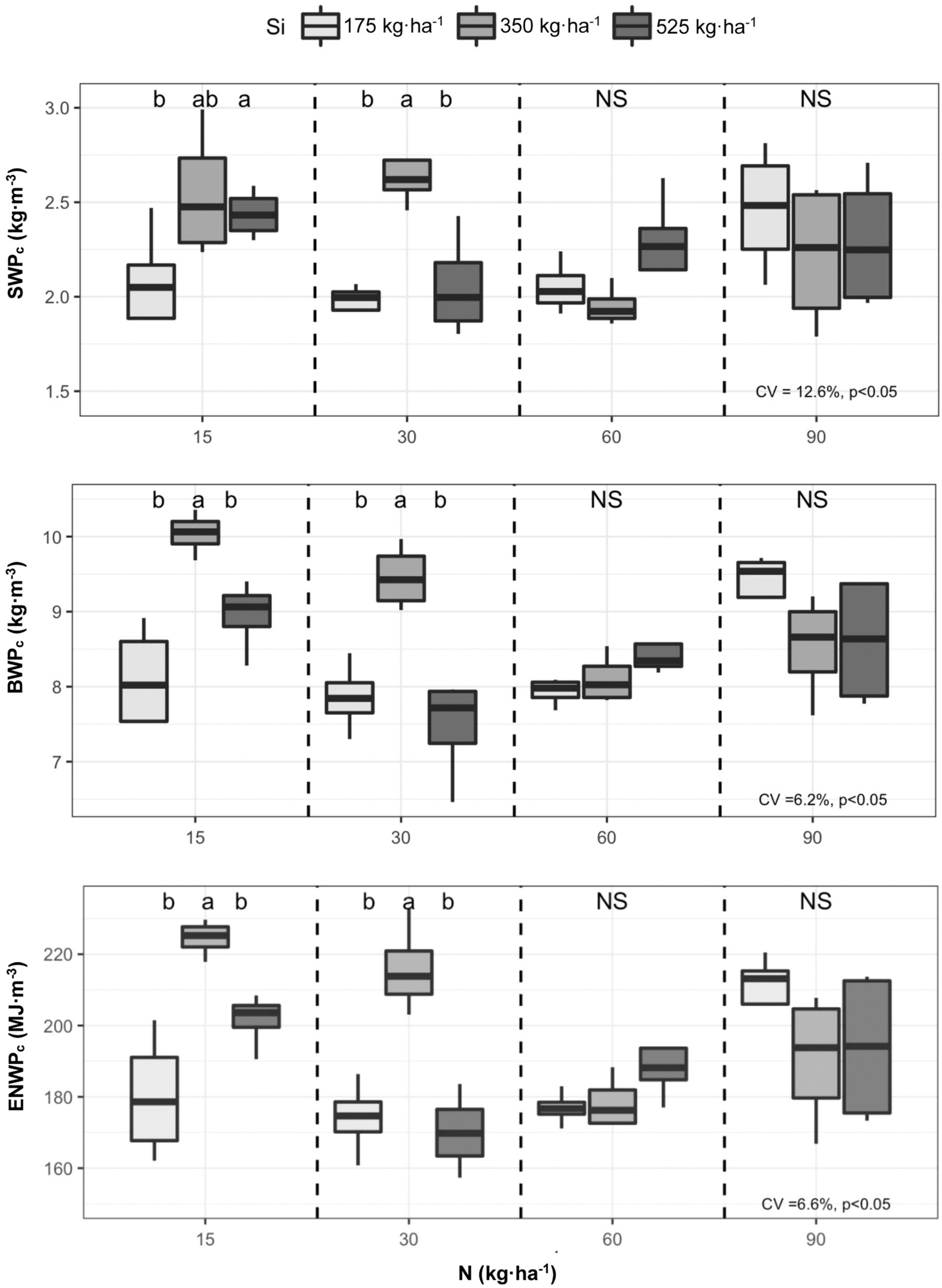

Fig. 4. Sugar water productivity (SWP_c), biomass water productivity (BWP_c) and energy water productivity ($ENWP_c$) as a function of treatments with different dosages of nitrogen (N) and silicon (Si) applied via soil. The box represents the interquartile range (IQR) and 'whiskers' represent the range of data. The median is depicted by a horizontal line within the box.

NxSi resulted in higher SWP_c values when compared to the results under similar environmental conditions and genetic background, but without Si application.

In research evaluating BWP_c, Singh et al. (2007) obtained an average of 7.1 kg·m^{-3} for plant cane and 6.3 kg·m^{-3} for ratoon cane. Santos et al. (2019) studied eight cultivars in different cycles (plant cane and ratoon cane) and determined an average BWP_c of 5.7 kg·m^{-3} and 7.3 kg·m^{-3}, respectively. With regard to the $ENWP_c$ of the sugarcane crop, Leal et al.

(2017) observed mean values of 105.1 $MJ \cdot m^{-3}$ for plant canes. Coelho et al. (2019), compared different sugarcane varieties and observed a variation from 101.2 to 159.5 $MJ \cdot m^{-3}$ in the average $ENWP_c$ values for varieties grown in clayey soil, and from 110.2 to 145.5 $MJ \cdot m^{-3}$ for varieties cultivated in sandy loam. Within the studied varieties, RB92579 stood out with higher average values of 145.1 $MJ \cdot m^{-3}$.

The treatment yielding the highest WP_c values was 15Nx350Si (SWP_c=2.6 $kg \cdot m^{-3}$, BWP_c=10 $kg \cdot m^{-3}$ and $ENWP_c$=224.5 $MJ \cdot m^{-3}$) (Fig. 4). The good performance of the 15Nx350Si application indicated that SWP_c, BWP_c and $ENWP_c$ were optimal with an intermediate Si treatment of 350 $kg \cdot ha^{-1}$. The drop in WP_c with increasing Si application could be related to the chemical corrective effect of silicate in the soil. For example, an initial application of limestone together with high doses of silicates, which have corrective power even without drastic increases in pH, can cause imbalances in some micronutrients that affect the development and yield of sugarcane (Basto et al., 2010, Borges et al., 2016, Barreto et al., 2022). By comparing the treatments, 15Nx350Si and 30Nx350Si (equal dosage of 350 $kg \cdot ha^{-1}$ of Si), with respect to the variables SWP_c, BWP_c and $ENWP_c$ after application of N at 15 $kg \cdot ha^{-1}$ (15Nx350Si) and 30 $kg \cdot ha^{-1}$ (30Nx350Si), we noted a potential effect of Si in reducing the requirement for N by the sugarcane crop.

We also observed that the intermediate dose of Si was insufficient to increase BWP_c and $ENWP_c$, confirming the need for a combination of N and Si to achieve the best WP_c performance in the sugarcane crop. In general, we observed that intermediate Si applications combined with non-zero N treatments resulted in lower water consumption. The improvement in SWP_c, BWP_c and $ENWP_c$ was greatest when the crop received intermediate amounts of Si combined with N, as highlighted by the 15Nx350Si treatment.

5. Conclusions

The water consumption of sugarcane was influenced by combined soil treatment with N and Si. The treatment that presented the lowest water requirement for irrigation was 15Nx350Si (561 mm), which was approximately 63% of the water consumption of sugarcane under conditions where doses of N were used and Si was not applied or applied at very low levels. Thus, the combined application of N and Si can considerably reduce sugarcane water consumption.

Agricultural yield (AY) was clearly influenced by NxSi treatment with an average value of 145 $Mg \cdot ha^{-1}$. The treatment with the highest AY value was 60Nx350Si (162.3 $Mg \cdot ha^{-1}$). The 15Nx350Si treatment (lower water consumption) had an average AY value of 135.5 $Mg \cdot ha^{-1}$, showing that despite the excellent performance in terms of water consumption, this treatment resulted in a reduction in the AY of sugarcane.

The crop water productivity (WP_c) in terms of sugar (SWP_c), biomass (BWP_c) and energy ($ENWP_c$) of the sugarcane crop was also influenced by the different soil application rates of N and Si. In general, the treatment that presented the highest average values of WP_c was 15Nx350Si, SWP_c=2.6 $kg \cdot m^{-3}$, BWP_c=10 $kg \cdot m^{-3}$ and $ENWP_c$=224.5 $MJ \cdot m^{-3}$. The application of Si to the soil increased the WP_c, thus showing its potential to improve water use efficiency in commercial crops.

Treatments with different dosages of N and Si applied via soil did not significantly influence the juice quality, therefore the use of Si does not compromise the quality of the end product. The biometric variables of the sugarcane crop, with the exception of crude fiber and leaf area, were also not influenced by combined NxSi treatments.

CRediT authorship contribution statement

Rubens Duarte Coelho: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Timóteo Herculino da Silva Barros:** Writing – review & editing, Writing – original draft, Visualization, Validation, Formal analysis, Data curation. **Asdrubal Jesus Farias-Ramírez:** Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Jéfferson de Oliveira Costa:** Writing – review & editing, Writing – original draft, Visualization, Validation, Formal analysis, Data curation. **Maria Alejandra Moreno-Pizani:** Writing – review & editing, Writing – original draft, Visualization, Validation, Formal analysis, Data curation. **Sergio Nascimento Duarte:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.agwat.2024.108796.

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