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RESEARCH ARTICLE

Effect of subsurface irrigation on the productivity and technological quality of sugarcane

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ABSTRACT

The aim of the study was to evaluate the effect of irrigation depths, via subsurface drip, on the technological quality, productivity, and water use efficiency (WUE) of sugarcane cultivars. The experimental design was of balanced blocks with 12 blocks and two factors: cultivars (CTC 4, IACSP93-3046, RB86-7515, IACSP95-5000 and IAC91-1099) and irrigation depths (dry, deficit and supplementary). From the estimated evapotranspiration (ETc), irrigation depths equivalent to 100% of crop ETc were defined for the supplemental treatment and 50% for deficit. The amounts of sucrose in the juice (POL) and the cane (PC) did not differ among the cultivars; however, additional irrigation provided higher values of the evaluated parameters. The purity levels of all treatments were superior to those recommended (85%) and differed between the cultivars. In the supplementary irrigation regime, the IAC91-1099 cultivar had the highest total recoverable sugar value (TRS), equal to 165.62 kg Mg^{-1}, and the highest yields of stalks and sugars, 157.02 and 26.01 Mg ha^{-1}, respectively. The WUE was superior in the dry regime for the CTC4 and RB86-7515 cultivars, and these were considered tolerant to the water deficit. The deficit irrigation provided average gains in the yield of sugarcane and sugar similar to supplementary irrigation; consequently, there were substantial reductions in water use and irrigation requirements in addition to energy savings.

Keywords: water use efficiency; Drip irrigation; *Saccharum* spp

INTRODUCTION

Sugarcane (*Saccharum* spp.) stands out as one of the main agricultural crops produced in the world, mainly in tropical and subtropical regions, because of its importance in the production of sucrose, ethanol and energy. Brazil is the world's leading producer of the crop, with 620.0 million tons of sugarcane processed in 10.1 million hectares during the 2018/19 harvest (Conab, 2019). However, the productivity of 72.2 and 80.4 tons per hectare in Brazil and world (Fao, 2019), respectively, is considered low due to the irregular distribution of rain throughout the year, the non-adoption of technology and, often, incorrect crop management.

In many sugarcane-producing regions, rainfall does not meet the water demand of the crop. In view of this, water becomes limiting to production (Inman-Bamber and Smith, 2005), as it plays a fundamental role in the biochemical and metabolic processes of plants (Taiz and Zeiger, 2013). Irrigation is one alternative to reduce the effects of the water deficit, but in some situations, it becomes impracticable due to high implantation and maintenance costs or the scarcity of water resources close to the cultivated area. Therefore, there is a need for the selection of water deficit tolerant sugarcane cultivars that use less water to maintain or increase their productivity (Holanda et al., 2014).

Deng et al. (2015) emphasized that the agricultural sector has the lowest water use efficiency (WUE). Thus, the search for alternatives to reduce the amount of water used in agricultural crops is of growing importance. Varietal management is indispensable, especially in irrigated crops, because there are cultivars that present greater potential of production when irrigated, and others are adapted to environments with water restriction (Silva et al., 2013). Therefore, more tolerant cultivars should be identified using indexes, such as water efficiency (Ko and Piccini, 2009) and virtual water content (Bessembinder et al., 2005), which can be defined as the amount of water used to produce a productivity unit (Fader et al., 2010; Sun et al., 2013). According to Olivier and Singels et al. (2015), the WUE is influenced by the cultivar, emphasizing the

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importance of the correct choice, since the genotype leads to more efficient use of water and higher productivity.

Studies of sugarcane varieties grown under water restriction conditions will become increasingly important, so some work has been developed. Sánchez-Román et al. (2015), analyzing the productivity of sugarcane subjected to different water replacements, observed that for every 25% water replacement, there was an increase between 9.64 and 19.29 Mg ha^{-1}. Santos et al. (2019) in a study of deficit irrigation, by drip irrigation in sugarcane, indicated that the plant biomass yield is reduced by lack of water. However, the combination of moderate reductions in irrigation water with varieties more tolerant to the deficit of water can provide savings in irrigation costs without reducing the sugar produced. Dalri et al. (2021) observed that the correct choice of sugarcane cultivar in an irrigated production system may increase productivity by more than 50%.

Based on the hypothesis that water consumption by the plants differs between crops, cultivars, regions, environmental and climatic conditions and soil moisture as well as between irrigated and non-irrigated systems (Liu et al., 2007; Fader et al., 2010; Silva et al., 2013; Dalri et al., 2021), the use of water efficiency indexes is essential to define cultivars that are responsive to different crop management practices. Tayade et al. (2020) observed that the correct choice of a sugarcane cultivar and the irrigation management may increase water use efficiency by more than 40%. These results demonstrate the need for studies to guide more assertive management in irrigated agriculture.

The present study aimed to evaluate irrigation depths, via subsurface drip, on the technological quality, production and water use efficiency of five sugarcane cultivars, in the third crop cycle.

MATERIALS AND METHODS

Area description

The experiment was conducted in an experimental area in the São Paulo State University (Unesp), Brazil with the geographical coordinates: 21º14'50" S e 48º17'05" W at 570 m above sea level. The predominant climate is Aw (Alvares et al., 2013), according to the classification of Köppen; it is characterized as subtropical with summer rains, relatively dry winters and an average rainfall of 1425 mm per year. With annual average air temperatures of 22.2 ° C, there is a maximum and minimum annual mean of 28.9 ° C and 16.8 ° C, respectively.

The soil of the experimental area is classified as an Oxisol (Soil Survey Staff, 2014) with a clay texture (220 g · kg^{-1} of sand, 580 g · kg^{-1} of clay and 200 g · kg^{-1} of silt) and a density of 1.29 g · cm^{-3} in depths from zero to 30 cm (Embrapa, 1997).

Soil chemical analysis was performed after the second crop cycle in the 0 to 20 cm layer (Raij et al., 2001), presenting: pH = 5.0; organic matter equal to 25 g · dm^{-3}; P = 35 mg · dm^{-3}; S = 30 mg · dm^{-3}; H+Al = 31 $mmol_c$ · dm^{-3}; Al = 0 $mmol_c$ · dm^{-3}; K = 2,9 $mmol_c$ · dm^{-3}; Ca = 30 $mmol_c$ · dm^{-3}; Mg = 9 $mmol_c$ · dm^{-3}; B = 0,25 mg · dm^{-3}; Cu = 3,5 mg · dm^{-3}; Fe = 12 mg · dm^{-3}; Mn = 19,7 mg · dm^{-3}; Zn = 1,6 mg · dm^{-3}; SB = 42,0 $mmol_c$ · dm^{-3}; CTC = 73,2 $mmol_c$ · dm^{-3} and V (%) = 57. Mineral fertilization was performed according to Spironello et al. (1997) as a function of the chemical analysis; it was divided eight times for the irrigated treatments, via fertigation, and in two for the dry treatment, which was applied manually.

The crop was planted in 2014, using pre-budded seedlings with spacing of 0.5 m between plants and 1.5 m between rows. The sugarcane cultivars used were CTC 4, IACSP93-3046, RB86-7515, IACSP95-5000 and IAC91-1099, which stand out as some of the most cultivated cultivars in Brazil.

Experimental design

The experimental design was in balanced blocks with two or three cultivars per plot. The experiment consisted of two factors: irrigation (dryland, deficit and supplementary, which corresponded to 0, 50 and 100% of ETc) and five cultivars with 12 blocks. The experimental plots consisted of four lines of sugarcane with 4.5 meters in length and three or two plots per block. The irrigation factor was allocated in the plots and the cultivars in the subplots.

Irrigation system and application of treatments

The dripper used in the experiment has a flow rate of 1.30 L· h^{-1}, characterized by Fischer Filho (2015), with spacing between the emitters equal to 0.30 m and a tube diameter of 16 mm. Tubes were buried at a depth of 0.30 m under the planting row.

The application of the irrigated treatments started after the second harvest of the crop and was performed on May 16, 2016. It is noteworthy that rainfall occurred shortly after harvesting that was sufficient for the soil to reach the field capacity and, from this moment, the water management of the crop was started.

Irrigation management was carried out via climate, with climatic and precipitation data obtained daily at the automated agroclimatological station near the area. The reference evapotranspiration (ETo) was estimated daily by the Penman-Monteith equation (Allen et al., 1998), and the ETc was estimated by the ETo product and the crop coefficients (kc), according to Doorenbos and Kassam (2000).

Irrigation was interrupted 30 days before harvest, aiming at capturing the accumulation of sucrose in the stalks and the increase of sugar yield, a practice known as "dry-off" (Inman-Bamber, 2004).

Irrigation was performed whenever there was an accumulated water deficit of the 20 mm crop, that is, when the sum of ETc less the total precipitation was greater than 20 mm (Dalri and Cruz, 2001), as demonstrated in Equation 1, and for the treatment with deficit irrigation was applied half the water depth compared to supplemental irrigation.

$$\sum_{i=1}^{n}\left(ETc_i - P_i\right) \geq 20\ mm \quad (1)$$

Where:
ETci = evapotranspiration of the crop on the i-th day, mm, and
Pi = total precipitation on the i-th day, mm.

Parameters assessed

During harvesting and 412 days after cutting (DAC), seven stems were separated from each plot to perform technological analyses (Consecana, 2006) relevant to the industrial quality of sugarcane: total soluble solids (ºBrix), fiber content (%), sucrose in the juice (POL) and the cane (PC) in %, purity (%) and total recoverable sugar (TRS) in kg Mg^{-1}.

In order to evaluate the productivity of the crop, the plants contained in two meters of line from each experimental unit were harvest and weighed and their productivity in Mg ha^{-1} was estimated (Dalri et al., 2021). Based on the sucrose content and yield of stalks, sugar yield was estimated.

For the identification of cultivars that are more tolerant to water deficit, the water use efficiency index (WUE) was used, which may be defined as the relation between the yield of cane produced per unit and the total use of water in the crop. Besides that, was calculated for each treatment using expression similar to that proposed by Lu et al. (2000), Equation 2.

$$WUE = Yr / Wt \quad (2)$$

Where:
WUE is water use efficiency in Mg ha^{-1} mm^{-1};
Yr is crop yield in Mg ha^{-1};
Wt is total water use by the crop (irrigation and rainfall) in mm.

Statistical analyzes

The analysis of variance was performed for all evaluated response parameters and the t test when statistical difference ($p < 0.05$) occurred. Statistical analyzes were performed using the SAS software (version 9.3, SAS Institute Inc).

RESULTS AND DISCUSSION

Temporal evolution of rainfall, evapotranspiration and irrigation

The total rainfall in the period between 05/17/2016 and 07/17/2017 was 1497.9 mm. The average annual rainfall of the region is 1425 mm, so rain values were within the expected range (Fig. 1). It should be noted that the crop requires a water depth between 1500 and 2500 mm per cycle (Doorenbos and Kassan, 2000), that is, part of this water must be applied via irrigation.

There were 32 irrigations in the area and the total water applied was 640.0 mm for the supplemental treatment and 320.0 mm for the deficit.

The estimated maximum daily evapotranspiration of the crop was 7.1 mm and occurred at 282 and 301 DAC, justifying the application of higher irrigations in these periods. Therefore, irrigations occurred more frequently in the months of September/October 2016 and February/May 2017, during which time the crop was in full development phase and, consequently, had high daily ETc values. Therefore, the crop necessitated a higher water requirement (Fig. 1). Finally, the adequate application of water during the vigorous growth phase provided the formation of longer internodes, positively affecting crop production (Doorenbos and Kassan, 2000).

Technological variables of sugarcane

No statistical differences were found between the treatments for the total soluble solids and fiber content, with values higher than 20 º Brix and 11%, respectively (Table 1).

The amount of sucrose in the sugarcane (PC) did not present significant statistical differences between the cultivars or in the interaction irrigation x cultivar. However, there were significant statistical differences for the irrigation depths within the CTC4 and IAC91-1099 cultivars, in which the rainfall and supplementary irrigation provided higher values of 15.64 and 16.77%, respectively. The cultivars IACSP93-3046, IACSP95-5000 and RB86-7515 had no differences between irrigation depths and presented values close to 16%. The statistical differences found for sucrose in the juice (POL) were similar to the PC, with the dry regime and supplementary irrigation being higher for the cultivars CTC4 and IAC91-1099, respectively (Table 1).

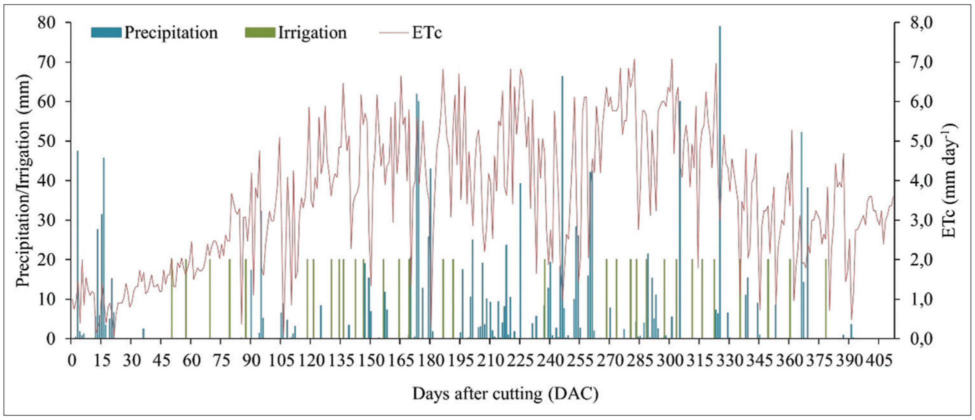

Fig 1. Observed values of precipitation and daily crop evapotranspiration (ETc) in the experimental period and applied irrigation depths.

Table 1: Mean values of relevant technological variables in the quality of sugarcane

Cultivars	Total soluble solids (Brix)			Fiber content (%)		
	Dry	Deficit	Supplementary	Dry	Deficit	Supplementary
CTC4	21.23^{aA}	19.97^{aA}	20.64^{aA}	11.68^{aA}	10.92^{aA}	11.44^{aA}
IAC91-1099	20.49^{aA}	20.68^{aA}	21.57^{aA}	11.31^{aA}	11.06^{aA}	11.35^{aA}
IACSP93-3046	20.00^{aA}	21.26^{aA}	21.06^{aA}	11.53^{aA}	10.84^{aA}	11.13^{aA}
IACSP95-5000	20.73^{aA}	21.15^{aA}	21.48^{aA}	11.43^{aA}	10.84^{aA}	11.35^{aA}
RB86-7515	21.39^{aA}	20.40^{aA}	21.20^{aA}	11.80^{aA}	11.13^{aA}	11.49^{aA}
Cultivars	**PC (%)**			**POL (%)**		
	Dry	**Deficit**	**Supplementary**	**Dry**	**Deficit**	**Supplementary**
CTC4	16.43^{aA}	14.92^{bA}	15.64^{abA}	19.29^{aA}	17.31^{bA}	18.30^{abA}
IAC91-1099	15.47^{bA}	16.06^{abA}	16.77^{aA}	18.07^{bA}	18.66^{abA}	19.58^{aA}
IACSP93-3046	15.21^{aA}	16.06^{aA}	16.28^{aA}	17.82^{aA}	18.58^{aA}	18.95^{aA}
IACSP95-5000	16.46^{aA}	16.19^{aA}	16.59^{aA}	19.24^{aA}	18.75^{aA}	19.37^{aA}
RB86-7515	15.86^{aA}	15.54^{aA}	16.23^{aA}	18.67^{aA}	18.07^{aA}	19.00^{aA}
Cultivars	**Purity (%)**			**ATR (kg t^{-1})**		
	Dry	**Deficit**	**Supplementary**	**Dry**	**Deficit**	**Supplementary**
CTC4	90.84^{aA}	86.40^{bB}	88.47^{abA}	162.29^{aA}	149.02^{bA}	155.42^{abA}
IAC91-1099	88.17^{aAB}	90.33^{aA}	90.83^{aA}	153.88^{bA}	159.00^{abA}	165.62^{aA}
IACSP93-3046	89.08^{aAB}	87.71^{aAB}	89.94^{aA}	151.11^{aA}	159.65^{aA}	161.14^{aA}
IACSP95-5000	90.96^{aA}	90.41^{aA}	90.15^{aA}	162.57^{aA}	160.22^{aA}	164.08^{aA}
RB86-7515	87.28^{aB}	88.49^{aAB}	89.56^{aA}	157.83^{aA}	154.40^{aA}	160.75^{aA}

*Averages followed by the same capital letter in columns and lowercase letter in rows do not statistically differ by test t at 5% probability.

Statistical analysis of purity did not show significant differences in the cultivar x irrigation interaction; therefore, the factors were acting independently on the variable (Table 1). Supplementary irrigation did not promote differences between the cultivars; however, deficient irrigation provided higher purity values, higher than 90% for IAC91-1099 and IACSP95-5000 cultivars, which differed from CTC4 with 86.4%. For the dry treatment, the CTC4 stood out with greater purity, close to 91%, and was superior to the deficient regime, allowing the inference that it presented a certain tolerance to the water deficit. Recommended purity values for the sugarcane harvest are those greater than 85% (Ripoli and Ripoli, 2004), so there is no restriction for the treatments of this work.

Among the attributes analyzed, the total recoverable sugar (TRS) is one of the most important, as it is in function of its value that the industrial units determine the price paid to the producers, according to methodology created by CONSECANA (2006). The analysis of variance for this parameter presented statistically significant differences only for the water regimes within the cultivars CTC4 and IAC91-1099, highlighting the dry regime with 162.29 kg · Mg^{-1} and the additional irrigation with 165.2 kg · Mg^{-1}, respectively for each cultivar, with the last one being the highest TRS among all treatments.

The highest increase of TRS between the dry and supplementary regimes occurred for the cultivar IAC91-1099, which was equal to 7.6%. The high values of the technological attributes of the irrigated cultivars can be associated with the full irrigation management, which intensifies tillering and elongation of the stem and, consequently, anticipates the physiological maturation of sugarcane and promotes the increase of sucrose levels in the stem cells (Oliveira et al., 2011).

With values similar to those found in this study, Gonçalves et al. (2017), while studying water relations and productivity of cane irrigated with domestic wastewater through subsurface drip, did not observe significant differences between treatments for any of the technological parameters, with mean values of total soluble solids, POL, purity, fiber and TRS equal at 21.50 ° Brix; 19.21%; 89.33%; 11.02% and 16.39 kg · Mg^{-1}, respectively.

The few significant statistical differences found in the technological parameters of sugarcane stress that the implantation of irrigation by subsurface drip irrigation has no effect on the reduction of sucrose concentration, which makes it possible to obtain higher yields of sugarcane and sucrose in irrigated areas.

Sugar and stems yield

Statistically significant differences were found between the average yields of stems and sugar in relation to water regimes and cultivars in isolation (Table 2).

Only CTC4 did not present significant statistical differences in relation to water regimes, that is, water was not a determining factor for the productive increase of the cultivar. The other cultivars differed statistically, with the dry treatments being inferior to the deficit and supplementary treatments, which were even. Thus, it can be inferred that prolonged periods with low water availability negatively affect the technological quality of the crop and yield of stalks and sugar (Inman-Bamber and Smith, 2005).

As sugarcane is a plant of metabolism C4, it presents greater efficiency in the use of water in comparison to plants of metabolism C3 (Taiz and Zeiger, 2013). Therefore, the water depth of 320.0 mm (applied in the deficit regime) was sufficient for the cultivars to present similar performance to the treatments with 640 mm of additional irrigation without water deficit (Fig. 2). In view of this, the application by irrigation of smaller amounts of water gave the crop similar productivities to that achieved with the application of larger irrigation depths.

The cultivar IAC91-1099 stood out from the others with stem yields for the supplementary and deficit systems of 157.02 Mg · ha^{-1} and 147.83 Mg · ha^{-1}, respectively, which did not differ and were superior to the other cultivars for their respective water regimes. In the dry system, although it was lower than the other regimes, the IAC91-1099 was more productive in comparison to the other cultivars, with 121.11 Mg · ha^{-1}.

Differences in production between water regimes and between cultivars were also found by Costa et al. (2016) when they evaluated the irrigation depth that promoted higher productivity of two sugarcane cultivars and observed that for the cultivar RB855453, the maximum yield of stalks (189 Mg · ha^{-1}) was reached with 75% of ETc; for the cultivar RB96-5902, the maximum productivity (173 Mg · ha^{-1}) was obtained with a level equivalent to 150% of ETc.

Bastos et al. (2015) evaluated the application of nitrogen and irrigation in sugarcane productivity and observed that there was an increase of 90.61 Mg · ha^{-1} in yield of stems from the dry treatment to that of 100% irrigation.

The sugar yield was similar to the yield of stems, that is, the productivity of the sucrose increased due to the improvement in crop productivity, excepting the cultivars CTC4 and RB86-7515. According to Inman-Bamber and Smith (2005) the vegetative growth of sugarcane is very sensitive to soil water levels; however, the amount of water does not affect photosynthesis or the accumulation of sucrose.

For the cultivars IIAC91-1099, IACSP93-3046 and IACSP95-5000, increases of 39.5; 59.7 and 25.3% were found in sugar yield, respectively, in treatments with supplementary irrigation without water deficit when compared to the dry. Gava et al. (2011) evaluated the yield of stalks from three sugarcane cultivars (second cycle) and found statistically higher production for irrigated treatments, with an average increase of 24% in stems and 23% in sugar when compared to treatments that were not irrigated. Therefore, the use of subsurface irrigation provides higher sugar yield, favoring the economic return of the crop.

Table 2: Mean values of yields of stems and sugar

Cultivars	Yields of stems (Mg ha^{-1})			Yields of sugar (Mg · ha^{-1})		
	Dry	Deficit	Supplementary	Dry	Deficit	Supplementary
CTC4	112.40^{aAB}	128.72^{aA}	122.46^{aB}	17.39^{aAB}	19.55^{aA}	19.54^{aB}
IAC91-1099	121.11^{bA}	147.83^{aA}	157.02^{aA}	18.65^{bA}	23.51^{aA}	26.01^{aA}
IACSP93-3046	95.90^{bB}	126.96^{aA}	145.34^{aAB}	14.49^{bB}	20.28^{aA}	23.14^{aAB}
IACSP95-5000	105.10^{bAB}	132.09^{aA}	131.45^{aB}	17.26^{bAB}	21.16^{aA}	21.62^{aB}
RB86-7515	111.57^{bAB}	132.41^{aA}	132.40^{aB}	17.42^{aAB}	20.30^{aA}	21.34^{aB}

Averages followed by the same capital letter in columns and lowercase letter in rows do not statistically differ by test t at 5% probability

Water use efficiency

Deficit irrigation provided higher values of WUE for the cultivars IIAC91-1099, IACSP93-3046 and IACSP95-5000, and the dry regime for the cultivars CTC4 and RB86-7515, the latter being considered tolerant to the water deficit (Table 3).

It is observed that greater water application did not necessarily point to higher productivity. According to Tolk and Howell (2003), the WUE decreases with increasing irrigation application. Additionally, Azevedo et al. (2006) pointed out that the application of a high volume of irrigation water does not result in high productivity. This situation can happen because the WUE is influenced by different aspects, such as crop morphology, soil conditions, agricultural practices and atmospheric variables (Hatfield et al., 2001).

Alamilla-Maganã et al. (2016) observed higher values of WUE when there was higher soil moisture tension, that is, application of smaller irrigation slides, but crop productivity was generally higher for a lower soil water tension identified similar results. Silva et al. (2013) found WUE values of 0.083 and 0.073 $Mg \cdot ha^{-1} \cdot mm^{-1}$ for irrigations with 100 and 50% of crop evapotranspiration, respectively. Finally, Basnayake et al. (2012) reported that in several field experiments, interactions between sugarcane genotypes and environments (water) were surprisingly small, despite the large impacts that water stress causes on average crop yields.

Fig 2. Sugarcane height in three water regimes.

Table 3: Efficiencies of water use according to cultivars and water regimes

Cultivars	WUE ($Mg \cdot ha^{-1} \cdot mm^{-1}$)		
	Dry	Deficit	Supplementary
CTC4	0.075	0.071	0.057
IIAC91-1099	0.081	0.081	0.073
IACSP93-3046	0.064	0.070	0.068
IACSP95-5000	0.070	0.073	0.061
RB86-7515	0.074	0.072	0.062
Total water (mm)	1497.9	1832.4	2166.9

(WUE – water use efficiency (rain or rain plus irrigation).

For the efficient use of water by sugarcane, it is essential to identify the amount of ideal water responsible for the maximum yields (Wiedenfeld and Enciso, 2008). Thus, by evaluating the WUE values (Table 3), it is possible to observe that deficit irrigation provided higher efficiencies with the same amount of water for all cultivars studied. With emphasis on cultivar IAC91-1099 that presented 0.012 $Mg \cdot ha^{-1} \cdot mm^{-1}$, the more in the deficit regime compared to the supplementary one. Thus, it was found that the application of 50% of ETc is sufficient for sugarcane cultivars to better express their productive potential.

CONCLUSION

The deficit irrigation provided average gains in the yield of sugarcane and sugar similar to supplementary irrigation; consequently, there should be substantial reductions in water use and irrigation requirements as well as increases in efficiency of the water use index. Cultivar management is essential for the determination of cultivars that are better adapted to different conditions and specific management, and it helps identify changes in yields with the use of irrigation.

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Author contributions

The authors acted in equal proportion in the elaboration, planning, conducting, evaluating, collecting data, analysis, statistical interpretation, literature review and final writing.

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