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Productivity, Technological Attributes and Water Use Efficiency of Sugarcane Cultivars Under Regulated Deficit Irrigation

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Abstract

Irrigation systems with high water application uniformity, adapted cultivars, and management of regulated deficit irrigation (RDI) are some ways to increase water use efficiency in agriculture. RDI is a practice that aims to provide a smaller amount of water than that consumed by crops without significantly affecting agricultural yield. Objectives of this study were to evaluate the technological characteristics (Bx, Juice POL, Fiber, TRS and Cane POL), water use efficiency (WUE), number of stalks, and sugar and stalk yield of five sugarcane cultivars subjected to RDI and non-irrigation. The experiment was conducted at the School of Agricultural and Veterinatian Sciences, São Paulo State, Brazil. The treatments were distributed in a partially balanced incomplete-block design. The RDI provided 50% of the evapotranspiration water by the crop. At each 30 mm water deficit a 15 mm depth was applied. The evaluated sugarcane cultivars were 'CTC 4', 'IACSP 93-3046', 'RB 86-7515', 'IACSP 95-5000', and 'IAC 91-1099'. The total irrigation depth applied during the cycle was 180 mm. The RDI reduced the technological characteristics of sugarcane. However, it increased the productivity of the stalks and sugar, and did not change the number of stalks per hectare, nor the water use efficiency. Among the cultivars, 'IAC91-1099' showed the highest sugar yield (21.81 t ha^{-1}), stalk yield (146.5 t ha^{-1}), and water use efficiency (146.7 kg ha^{-1} mm^{-1}). The cultivar 'CTC4' showed little responsiveness to RDI, presenting a lower number of stalks per hectare and water use efficiency in relation to its growth under non-irrigation conditions.

Keywords: irrigation management, ripening, stalk yield, sugar yield

1. Introduction

In the near future, irrigation management under the condition of water scarcity will be a common practice, being applied to millions of hectares of crops (Fereres & Soriano, 2007). To increase the water use efficiency (WUE) in irrigation, in addition to using efficient irrigation methods and excellent application uniformity, one should maximize the production per unit of water consumed. In this context, the management of regulated deficit irrigation (RDI) is a technique that seeks to both improve the WUE and reduce the production costs (Geerts & Raes, 2009; Garcia et al., 2012).

The decreasing water availability for agriculture, and the increase in energy costs, have made the effective use of water increasingly important (López-Mata et al., 2010). However, there is a lack of understanding of the mechanisms with which plants respond to RDI. In particular, little is known about how RDI can increase crop production by reducing the amount of water applied and increasing their efficiency (Chai et al., 2016). The deficit irrigation can be associated with the risk of loss of productivity, impacting upon the yield of agricultural production, once water is applied in a smaller quantity than that of the crop evapotranspiration. Thus, the RDI must result in a higher production per applied water depth.

Of the various cultivated species, sugarcane has one of the highest conversions of dry matter per unit of water consumed. However, to obtain a high productivity, there is a need to supply water at a depth of between 1100 and 1800 mm (Carr & Knox, 2011). The supply and uniform distribution of rainfall during the life cycle of the sugarcane is an essential factor for high productivity (Inman-Bamber & Smith, 2005).

Due to the great differences in the growth and development of sugarcane cultivars when subjected to the same conditions (Castro-Nava et al., 2016), studies are needed to indicate the adaptation of these cultivars to different production environments. Thus, in tropical regions, where there is great variability of climatic conditions, studies on sugarcane genotypes and their responses to RDI are essential (Silva et al., 2013). In addition, even in regions with high precipitation and soils with high water retention, there are risks associated with the cultivation of sugarcane (Vianna & Sentelhas, 2014).

In this way, the objectives of this study were to evaluate the effect of RDI on the technological characteristics, WUE, number of stalks, and sugar and stalk yield of five sugarcane cultivars.

2. Material and Methods

2.1 Study Area and Experimental Design

The study was performed in the experimental field at the São Paulo Satate University (UNESP), School of Agricultural and Veterinatian Sciences (FCAV), Jaboticabal, São Paulo, Brazil (Figure 1) (21°14′50″ S, 48°17′5″ W), at an altitude of 570 m.

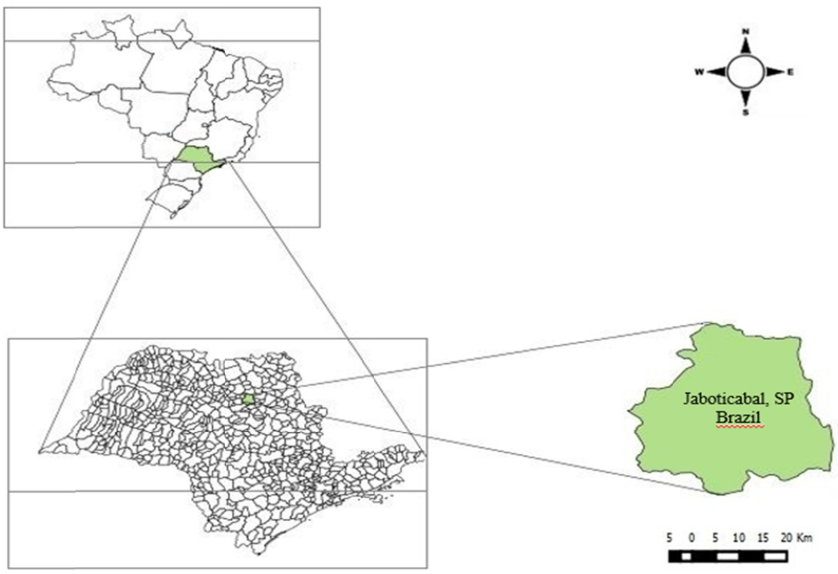

Figure 1. Development of experimental site in Jaboticabal, São Paulo State, Brazil

According to the Köppen climate classification (Alvares et al., 2013), the climate is Cwa-type, characterized by an average annual rainfall of 1,416 mm (1975-2015), with total averages for the wettest and driest months of 255 mm (December) and 25 mm (July), respectively. The soil of the experimental area is classified as Eutroferric Red Oxisol. The physical characteristics of the soil are presented in Table 1, and the chemical characteristics are shown in Table 2.

Table 1. Physical characteristics of the soil in the experimental area

Depth	Soil density	Sand	Clay	Silt	Soil texture
---------- cm --------	------- g cm^{-3} -------	------------------------------	g kg^{-1}	----------------------------	
0-20	1.29	220	580	200	Clayey
20-40	1.20	190	600	210	Clayey
40-60	1.07	160	650	190	Very clayey

Table 2. Chemical characteristics of soil in the experimental area

Depth	pH	Organic matter	P_{resin}	S	H + Al	Al	K	Ca	Mg	BS	CEC	BS%
--- cm ---	$CaCl_2$	---- g dm^{-3} ----	--- mg dm^{-3} ---		---------- mmol$_c$ dm^{-3} ----------							
0-20	5.4	25	41	45	32	1	1.8	51	21	73.6	105.4	70
20-40	5.2	18	19	53	34	0	1.6	31	13	45.4	79.4	56
40-60	5.0	11	7	50	36	1	1.4	14	8	23.4	45.4	52

Note. BS: Base saturation; CEC: Cation exchange capacity.

2.2 Preparation of Pre-sprouted Seedlings

Pre-sprouted sugarcane seedlings were planted on November 14, 2014, and harvested on May 16, 2015 to start the experimental period, which extended up to May 16, 2016. The production of the seedlings started by selection of micro-seed pieces, which are propagules containing only one bud. Before sowing, the micro-seed pieces were thermally treated, immersed in water at 52 °C for 30 minutes, and sprayed with fungicide and insecticide, thus ensuring high phytosanitary standards. They were then placed in tubes filled with the substrate, and were stored in a protected environment. They were irrigated three times a day, and humidity in the substrate was kept suitable for seedling development. After 30 days, acclimatization of the seedlings was started. They were exposed to direct sunlight and irrigation was suppressed gradually to increase the seedling establishment capacity in the field (Pinto et al., 2016). The seedling production time until planting in the field was approximately 60 days.

2.3 Management of Irrigation and Fertilization

Irrigation was applied with a subsurface drip system, installed before planting. The dripping pipe had a diameter of 16 mm, pipe wall of 500 µm, and emitters spaced 0.3 m apart. The water from the well was filtered by a 125 µm disc filter. The pressure of the irrigation system was stabilized by a flow regulator and monitored by a pressure gauge; it was kept at 100 kPa. The dipper flow rate was 5 L h^{-1} m^{-1}.

Irrigation was applied from planting until 45 days before harvesting, when a 30 mm water deficit was accumulated after a previous irrigation. The crop water deficit was calculated as the difference between the daily crop evapotranspiration and rainfall amount. The deficit irrigation provided 50% of the water requirement of the crop, that is, with each deficit of 30 mm, a 15 mm depth was applied. This criterion was based on the experiment of Dalri and Cruz (2002), in which a significant difference in stalk sugarcane productivity did not occur when irrigation depths of 10, 20, and 30 mm were applied. Crop evapotranspiration was calculated by the product of the crop coefficient and reference evapotranspiration during the growing season (Doorenbos & Kassam, 1979). Reference evapotranspiration was calculated by the Penman-Monteith equation, parameterized according to the FAO-56 method (Allen et al., 1998), using daily climate data from the FCAV/UNESP automated agrometeorological station.

Fertilization was performed with the application of 130 kg ha^{-1} of K_2O and 180 kg ha^{-1} N; the fertilizer sources were potassium chlorate and ammonium sulfate, respectively. There was no need for phosphate fertilizers due to the high phosphorus contents of the soil, determined through chemical analysis. In the irrigated plots, fertilization was performed through fertirrigation; the dose was divided into eight equal applications. In the non-irrigation management system, fertilizers were applied in July 2015, 30 days after cutting.

2.4 Technological Quality, Tillering, Water Use Efficiency, and Production

The crop was harvested in May 2016. The technological analyses were as follows (Consecana, 2006): total soluble solids (Brix [°Bx]), Juice polarization (POL), purity, fiber, and total recoverable sugar (TRS) (kg t^{-1}). The stalk productivity was determined by harvesting 5 m per line from each subplot. The number of stalks in each of the treatments was counted in the 5 m harvested for calculation of the productivity, and subsequently, the average number of stalks per hectare was estimated. The sugar productivity (TSH) was calculated by the product of the TRS by the stalk productivity (t ha^{-1}) divided by 1000. After harvesting and weighing, 10 stalks per sugarcane subplot were sent to the laboratory for technological analysis.

The WUE (kg ha^{-1} mm^{-1}) was obtained by analyzing the relationship between the productivity of the cultivars by the effective depth, in accord with Singh et al. (2007). The effective precipitation was calculated after deduction of the percolated water received by precipitation. A 30 mm soil storage (irrigation depth) was used for the calculation.

2.5 Statistical Analysis

The experiment consisted of treatments with two factors: irrigation, allocated in the plot, and sugarcane cultivar, allocated in the subplot (split-plot). The irrigation factor had two levels (irrigated and non-irrigated) and the cultivar factor had five levels (‘CTC 4’, ‘IAC 93-3046’, ‘RB 86-7515’, ‘IAC 95-5000’, and ‘IAC 91-1099’), with 12 replicates. The subplots included four sugarcane lines with 4.5 m length, spaced 1.5 m apart, and with seedlings spaced 0.5 m apart (13 333 seedlings ha^{-1}). The two side lines, as well as the 1 m space at each edge of the central lines, were considered buffers, so the usable area corresponded to 2.5 m in each central line.

The treatments were distributed in a partially balanced incomplete-block design, with three cultivars per block. This design is considered a good option to evaluate a great number of treatments, without increasing the magnitude of the experiment (Bose & Nair, 1939). The analysis of variance and the comparison of means were performed by SAS®. The data were submitted to an analysis of variance (*F*-test) and Duncan’s test (probability of 5%) of means comparison.

3. Results and Discussion

The temperature during the experimental period was within the expected (Figure 1). In the period between 150 and 270 days after planting (October to February), after tillering, the average temperature was 24.7 °C, favoring the growth of the stems. The closer the air temperature to 30 °C, the greater the tillering and the growth in height of the sugarcane (Bonnet et al., 2006). In addition, the average temperature for May was below 21 °C (20.8 °C), favoring the accumulation of sucrose in the stalks (Glover, 1971). However, sugarcane ripening is more intense when it is associated with low temperatures with water deficit (Cardozo & Sentelhas, 2013), and the accumulated deficit in the last 120 days of the cycle is the most important (Cardozo et al., 2015).

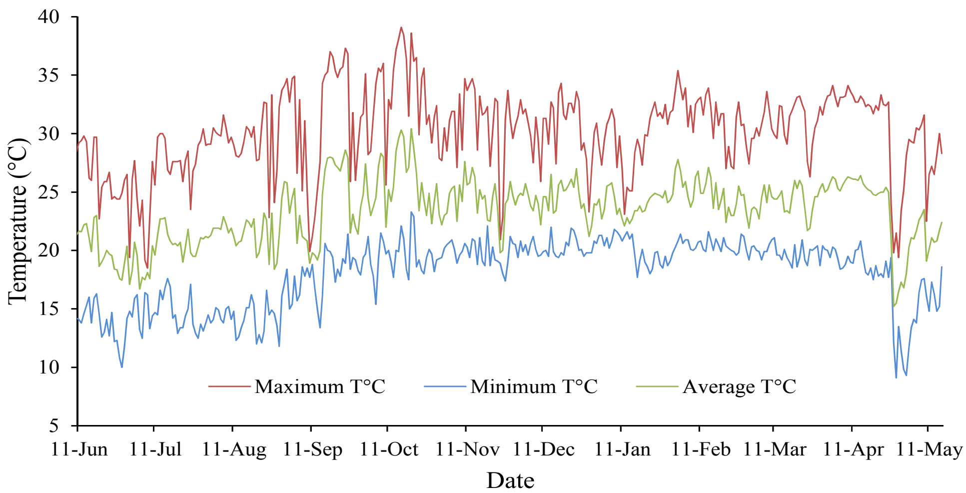

Figure 1. Maximum, minimum, and average temperatures during the experimental period in Jaboticabal, São Paulo State, Brazil

The crop evapotranspiration and accumulated precipitation during the experimental period were 1260 mm and 1740 mm, respectively (Figure 2). The precipitation of the period was 22% higher than the normal annual average of Jaboticabal, SP. The average daily evapotranspiration of sugarcane was 3.7 mm, with a peak of 7.92 mm day^{-1}. The accumulated irrigation depth was 180 mm, divided into 12 applications of 15 mm each.

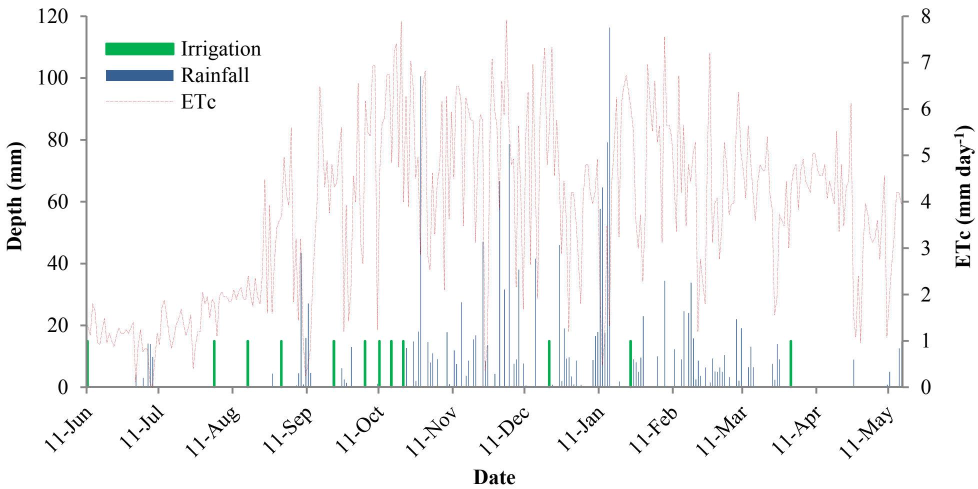

Figure 2. Rainfall and sugarcane evapotranspiration during the experimental period in Jaboticabal, São Paulo State, Brazil

RDI reduced all technological parameters of sugarcane (Table 3). In addition, there were differences between cultivars for all variables, except for fiber. Regardless of water management and cultivar type, all variables were within the minimum necessary values for the industrialization of sugarcane, with juice POL above 15%, Brix above 18, and cane POL above 13% (Consecana, 2006; Lavanhloli, 2008).

Table 3. Mean comparison and analysis of variance (ANOVA) for technological variables and tillering of five sugarcane cultivars cultivated under controlled deficit irrigated (I) and non-irrigation (NI) treatments

Cultivar	°Bx			Juice POL (%)			Fiber (%)		
	I	NI	Average	I	NI	Average	I	NI	Average
CTC 4	19.63	20.65	20.24 A	16.80	17.94	17.48 AB	10.63	10.86	10.77
IAC3046	19.91	20.81	20.40 A	17.21	18.23	17.76 A	10.16	10.95	10.59
RB7515	18.40	20.07	19.23 C	15.42	17.46	16.44 D	10.01	11.00	10.51
IAC5000	19.14	20.21	19.63 B	16.39	17.58	16.94 C	10.19	10.81	10.48
IAC1099	19.24	20.49	19.79 B	16.57	17.82	17.12 BC	9.88	10.66	10.23
Average	19.27 b	20.47 a		16.50 b	17.83 a		10.16 b	10.86 a	
ANOVA					F				
Irrigation (I)	98.0**			72.97**			27.87**		
Cultivar (C)	10.1**			7.03**			1.28ns		
I × C	1.2ns			1.2ns			0.89ns		
V.C. (%)	4.06			5.42			5.37		
Cultivars	TRS (kg t^{-1})			Cane POL %			Stalks ha^{-1}		
	I	NI	Average	I	NI	Average	I	NI	Average
CTC 4	145.52	154.41	150.86 AB	14.51	15.49	15.10 AB	102.500 ABb	122.778 Aa	114.667 A
IAC3046	150.27	156.41	153.62 A	15.04	15.72	15.41 A	90.000 Ba	96.111 Ba	93.333 B
RB7515	136.27	149.03	142.65 C	13.51	14.94	14.22 C	70.000 Ca	79.167 Ba	74.583 C
IAC5000	143.54	151.58	147.25 B	14.32	15.20	14.72 B	93.333 ABa	85.000 Ba	89.487 B
IAC1099	145.65	153.92	149.32 B	14.54	15.44	14.94 B	108.667 Aa	110.833 ABa	109.630 A
Average	144.46 b	153.31 a		14.41 b	15.38 a		93.466	99.358	
Irrigation (I)	54.2**			53.9**			2.9ns		
Cultivar (C)	8.1**			7.7**			14.9**		
I × C	0.75ns			0.8ns			2.0*		
V.C. (%)	4.53			4.97			18.86		

Note. * Averages followed by the same capital letter in columns, and lowercase letter in rows, do not statistically differ by Duncan's test at 5% probability; * significant at the 5% level; ** significant at the 1% level. TRS: Total recoverable sugar.

The cultivars 'CTC 4' and 'IAC3046', on average, presented higher °Bx, juice POL, TRS, and cane POL values that the other cultivars ($p < 0.01$). On average, the irrigation reduced, by 5.86%, 7.46%, 6.45%, 5.77%, and 6.30% Brix, juice POL, fiber, TRS, and cane POL, respectively. Comparing cultivars within water management, the genotype 'RB7515' presented the greatest reduction in the technological variables under irrigation conditions, compared to the non-irrigation conditions, while the cultivar 'IAC3046' presented the least reductions.

The reductions in °Bx, juice POL, and TRS for cultivar 'RB7515' were 8.32%, 11.68%, and 8.56%, respectively, for the irrigated condition, while for the cultivar 'IAC3046' the reductions were 4.32%, 5.60%, and 3.93%, respectively. Due to the sugarcane harvesting season, which starts at the beginning of the harvest (May), early cultivars, such as 'IAC3046', present greater adaptation and less variability between water conditions than the mid- and late-cycle cultivars. The adoption of the correct cutting season for each cultivar is fundamental, as it increases the technological efficiency of the sugarcane by up to 20% (Hagos et al., 2014).

RDI did not influence the number of stalks per hectare of sugarcane ($p < 0.05$). However, the cultivars 'CTC4' and 'IAC1099' presented higher numbers of stalks per ha than the other genotypes ($p < 0.01$). Comparing the cultivar within water management, it is observed that only the 'CTC4' cultivar presented a lower number of stalks (17%) in the irrigated condition ($p < 0.05$).

An explanation for the reduction of the values of the parameters under RDI conditions can be made based on the harvest season, climatic factors, and nitrogen fertilization. The ripening of sugarcane is conditioned, mainly, by a combination of low temperatures and water deficit (Cardozo & Sentelhas, 2013). If dealing with very clayey soil, as in the case of the present study, and treatment with irrigation, it was verified that one of the necessary conditions for the process (water deficit) was not satisfied. Thus, it is observed that for the maximization of the production of sugarcane under irrigation, it is necessary to make the harvest later, even for early cultivars ('IAC3046').

It was observed that high doses of nitrogen fertilizer, especially when greater than 100 kg ha^{-1}, and under irrigation, decreased the technological characteristics of sugarcane (Franco et al., 2010; Rhein et al., 2016). The lower concentration of sucrose in sugarcane stalks can be explained by the reduction of the dry matter content of the stalks when the crop is submitted to irrigation and high N rates, i.e., it has a higher water content (Muchow et al., 1996; Nogueira et al., 2016).

Additionally, fertirrigation increases the fertilization efficiency, especially of N fertilization (Kwong & Deville, 1994). As N prolongs the vegetative period of sugarcane (Casagrande, 1991) and promotes smaller sugar storage, since the carbon skeletons are consumed for the vegetative growth (Malavolta, 2006), one can expect a drop in the technological quality of fertigated sugarcane with high doses of N.

RDI promoted significant increases (17%) in the yield of sugarcane stalks ($p < 0.01$) (Table 4). In addition, the cultivar 'IAC1099' presented a higher productivity average of stalks (TCH) than the other cultivars ($p < 0.01$). Evaluating cultivars under water management conditions verifies that the cultivars 'IAC5000' and 'IAC1099' showed a higher TCH in the condition with RDI and the genotypes 'IAC1099' and 'CTC4' were higher under non-irrigation conditions ($p < 0.05$).

Table 4. Comparison of the productivity averages of stalks (TCH), productivity average of sugar (TSH), and water use efficiency (WUE) of the five sugarcane cultivars under controlled deficit irrigated (I) and non-irrigation (NI) treatments

Cultivar	TCH (t ha^{-1})			TSH (t ha^{-1})			WUE (kg ha^{-1} mm^{-1})		
	I	NI	Average	I	NI	Average	I	NI	Average
CTC 4	118.8 Ba	127.9 ABa	124.3 B	17.3 Ba	19.7 Aa	18.8 B	109.9 Bb	142.2 Aa	129.3 B
IAC3046	118.2 Ba	100.7 Ba	108.6 B	17.7 Ba	15.7 Ba	16.6 BC	109.4 Ba	111.9 Ba	110.7 C
RB7515	117.0 Ba	102.6 Ba	109.8 B	15.9 Ba	15.3 Ba	15.6 C	105.8 Ba	114.0 Ba	109.9 C
IAC5000	139.5 ABa	102.0 Bb	122.2 B	19.9 ABa	15.4 Bb	17.9 BC	129.1 ABa	113.4 Ba	121.9 BC
IAC1099	156.5 Aa	133.9 Ab	146.5 A	22.8 Aa	20.6 Aa	21.8 A	144.9 Aa	148.9 Aa	146.7 A
Average	131.7 a	112.7 b		19.0 a	17.27 b		121.6	125.2	
ANOVA									
I	9.84**			3.45*			1.34ns		
C	5.68**			7.08**			5.87**		
I × C	2.25*			2.65*			2.28*		
V.C. (%)	19.77			18.58			18.41		

Note. * Averages followed by the same capital letter in the columns, and lowercase letters in the rows, do not statistically differ by Duncan's test at 5% probability; * significant at the 5% level; ** significant at the 1% level; I: Irrigation; C: Cultivar.

The genotypes 'IAC5000' and 'IAC1099' were the only cultivars that presented a higher TCH under RDI, with increases of 36.7% and 16.84%, respectively, in relation to the treatment without irrigation. This occurs because the response of the cultivars to irrigation is variable (Costa et al., 2016), especially when the management of this is with the deficit of depth. Water-deficit-tolerant cultivars present greater a stomatal control and photosynthesis rate than those of sensitive genotypes (Graça et al., 2010). In addition, cropping techniques can be associated with irrigation deficit depths to minimize the effect of water deficit (for example, fertilization with silicon) (Camargo et al., 2017).

RDI increased the sugar yield (TSH) of sugarcane ($p < 0.05$) with an average increase of 10%. Among the genotypes, the cultivar 'IAC1099' showed the highest TSH ($p < 0.01$). Comparing water management, only the cultivar 'IAC5000' presented a higher TSH under irrigated conditions, compared to non-irrigation, with a 29% increase. The irrigation increases the sugar yield of the crop, because the average increase in stalk yield is proportionally higher than the reduction in the levels of the technological parameters (Cunha et al., 2016).

RDI did not increase the WUE of sugarcane ($p < 0.05$). However, only 'CTC4' showed a lower WUE in the irrigated condition ($p < 0.05$), compared to non-irrigation, indicating that it is a genotype that is not responsive to irrigation. Among cultivars, 'IAC1099' showed a higher WUE than the others ($p < 0.01$). Under non-irrigation water management conditions, the cultivars 'CTC4' and 'IAC1099' presented WUEs superior to the others, showing genotypes more adapted to water stress, since the WUE is widely used in the selection of cultivars tolerant to water stress and/or irrigation response (Ko & Piccinni, 2009).

For RDI, the genotypes 'IAC5000' and 'IAC1099' were superior to the other cultivars ($p < 0.01$). According to Olivier & Singels et al. (2015), the WUE is influenced by the cultivar, emphasizing the importance of the correct choice, since the genotype leads to a more efficient use of water and higher productivity. It is verified that irrigation depths of between 50% and 100% ETc do not affect the WUE of cultivars responsive to this system (Farias et al., 2008). However, for cultivars without response to irrigation, the WUE decreases significantly with increasing water depth.

4. Conclusions

(1) RDI reduced the technological characteristics of sugarcane. However, it increased the productivity of stalks and sugar, and did not change the number of stalks per hectare nor the WUE.

(2) Among cultivars, genotype 'IAC91-1099' showed the highest sugar and stalk yields and WUE.

(3) The 'CTC4' cultivar showed little responsiveness to controlled deficit irrigation, presenting lower number of stalks per hectare and water use efficiency, in relation to the non-irrigation conditions.

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