

Sugarcane yield response to rainfall partitioning and irrigation in contrasting cropping environments¹

Rendimento de cana-de-açúcar relacionado ao particionamento da precipitação e da irrigação em ambientes de cultivo contrastantes

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HIGHLIGHTS:

Annual precipitation is not a good predictor for estimating sugarcane yield.

Physical yield variables in sugarcane are more influenced by precipitation than agro-industrial characteristics.

For fully irrigated cropping environments, years with rainier winters result in a lower sugarcane yield.

ABSTRACT: Most sugarcane (*Saccharum officinarum* L.) in Brazil is produced through rainfed cropping, but several methods and management irrigation approaches coexist in some mills, creating different cropping environments. This work aimed to analyze the relationship between rainfall and sugarcane yield when cultivated in cropping environments with a high gradient in terms of water supply. A dataset of physical yield and agro-industrial characteristics was analyzed from a time series of 21 crop cycles. The cropping environments were categorized according to relief conditions in the landscape and the level of water supply for sugarcane cultivation: 1) hillside without irrigation; 2) rainfed tableland; 3) tableland with so-called “crop-saving irrigation”; 4) tableland irrigated by a linear moving irrigation system; 5) floodplain; and 6) tableland irrigated by a subsurface drip system. The total precipitation of the sugarcane cropping cycle was not a good yield predictor. For rainfed environments, summer rainfall resulted in the most positive correlations with sugarcane yield and an average increase of 53.2 kg ha⁻¹ mm⁻¹, a value similar to that of the saving irrigated and linear moving irrigated environments, with 54 and 57 kg ha⁻¹ mm⁻¹, respectively. In cropping environments with high frequency irrigation, the average increment was 17.6 kg ha⁻¹ mm⁻¹. In the rainfed and saving irrigated environments, cultivars RB92579 and CO997 stood out with the highest (91.3 kg ha⁻¹ mm⁻¹) and lowest (43.6 kg ha⁻¹ mm⁻¹) average increases, respectively. For rainfed cropping environments and drier summers, sugarcane yield losses could reach 21% compared to crop seasons with wetter summers.

Key words: varietal response, water use efficiency, rainfall efficiency, yield gap

RESUMO: A maior parte da cana-de-açúcar (*Saccharum officinarum* L.) no Brasil é produzida em cultivos de sequeiro, mas vários métodos e manejos da irrigação coexistem nas Usinas, configurando diferentes ambientes de produção. O objetivo do trabalho foi avaliar a relação entre a precipitação e o rendimento da cana-de-açúcar, quando cultivado em ambientes com elevado gradiente de suprimento hídrico. Foi utilizada uma base de dados com informações de produtividade física e tecnológica, em uma série histórica de 21 ciclos de cultivo. Os ambientes foram categorizados como: 1) encosta sem irrigação; 2) tabuleiro sem irrigação; 3) tabuleiro com “irrigação de salvamento”; 4) tabuleiro irrigado por sistema lateral móvel; 5) várzea e 6) tabuleiro irrigado por sistema de gotejamento subterrâneo. A precipitação total do ciclo de cultivo da cana-de-açúcar não foi um bom indicador de produtividade. Para os ambientes de sequeiro, a chuva de verão resultou em correlações positivas mais elevadas com a produtividade e um aumento médio de 53,2 kg ha⁻¹ mm⁻¹, valor semelhante ao dos ambientes com irrigação de salvamento e sistema de lateral móvel, com 54 e 57 kg ha⁻¹ mm⁻¹, respectivamente. Nos ambientes com irrigação plena, o incremento de produtividade médio foi de 17,6 kg ha⁻¹ mm⁻¹. Nos ambientes de sequeiro e com irrigação de salvamento destacaram-se as variedades RB92579 e CO997 com os maiores (91,3 kg ha⁻¹ mm⁻¹) e menores (43,6 kg ha⁻¹ mm⁻¹) incrementos médios, respectivamente. Nos ambientes de cultivo de sequeiro, as perdas de rendimento nos verões mais secos alcançam 21% em relação às safras com verões mais úmidos.

Palavras-chave: resposta varietal, uso eficiente da água, eficiência da precipitação, déficit produtivo

INTRODUCTION

Brazil stands out worldwide for the diversity and renewability of its energy matrix. In contrast to nonrenewable energy sources, hydroelectric, photovoltaic, wind, and biomass energy sources represent roughly 42.8% of the national supply (Santos et al., 2021). In addition to sugar production, energy from sugarcane (*Saccharum officinarum* L.) has a prominent role, representing 35.5% of Brazil's renewable energy supply in 2023 (EPE, 2025).

In northeastern Brazil, sugarcane is cultivated along the coastal strip, and its cropped area spans 784.2 thousand ha, accounting for 8.6% of Brazilian sugarcane production (IBGE, 2017). The use of so-called "crop-saving irrigation" on a larger scale and supplemental irrigation with different irrigation systems on a smaller scale is needed in the region to mitigate the effects of high levels of water stress during local dry summers.

The average rainfall in the main sugarcane production area of Brazil's northeast ranges from 1,500 - 2,000 mm (Barros et al., 2020), which is equivalent to the water demand of sugarcane (Doorembos & Kassam, 1979), but the rainfall distribution has historically been irregular throughout the year, and approximately 70% of the annual precipitation is concentrated in the winter months (April-August). The summer water deficit (October-March) reaches above 600 mm. This is one of the main factors responsible for low sugarcane productivity (Dias & Sentelhas, 2018), which ranges from 55 to 60 Mg ha⁻¹ in the main producing states of the northeast region (IBGE, 2017).

The relationship between rainfall in the crop cycle and yield has been evaluated in several annual crops (Lopes et al., 2019). In the case of biannual crops, such as sugarcane, the most common approach (Silva et al., 2009; Kumar et al., 2015; Viana et al., 2023) has been to evaluate this relationship based on a representation that considers either annual precipitation or the climatic or soil water balance and the consequent partition between water deficit and water surplus periods. In the southeast and central-western regions of Brazil, climatic

conditions allow for two modes of sugarcane cropping: 12-month and 16-18-month crop cycles. This is not always possible in northeastern Brazil due to restrictions on rainfall distribution throughout the year (Brunini, 2008).

Brazilian mills use the concept of "cropping environments" both for allocating the cultivars that will be used in each cropping season (Catelan et al., 2022) and as a planning tool on operational aspects, such as logistics of harvest fronts and plant aspects, related to the responsiveness to the water supply and the maturation cycle. Environmental cropping components include soil depth, soil fertility, soil texture, and soil water availability, with the latter being one of the main factors driving the yield potential (Prado et al., 2008).

Although the Prado et al. (2008) classification is quite accepted in Brazil, the cropping environments in the present study were categorized considering the relief of the landscape and conditions of crop water supply, the latter of which was derived from different irrigation systems. Thus, the objective of this study was to analyze the relationship between rainfall and sugarcane yield when cultivated in cropping environments with a high gradient in terms of water supply.

MATERIAL AND METHODS

The yield datasets evaluated were from the Coruripe Mill of Sugar and Alcohol, which is in the municipality of Coruripe, Alagoas, Brazil, with geographic coordinates of 10° 01' 29" S; 35° 16' 24" E (Figure 1). Based on a soil survey (semi-detailed scale) conducted by the Mill, the predominant soil classes, in descending order of occurrence, were Ultisol, Entisols, Alfisols, Oxisols, and Spodosols, according to soil taxonomy. These soils feature a low water holding capacity and an impediment layer of pedogenetic origin (cohesive layer) located at a depth of 0.30-0.40 m (Silva et al., 2020). According to Silva & Barbosa (2021), the local climate is tropical rainy, with dry summers and rainy winters. The mean air temperature is 24.4 °C.

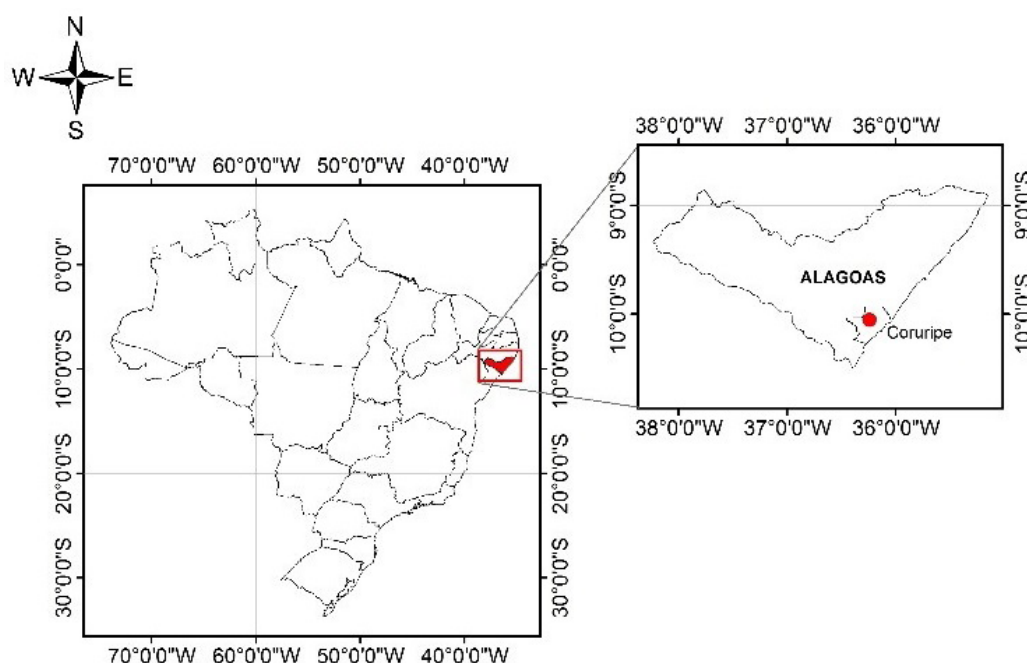


Figure 1. Coruripe Mill location in the municipality of Coruripe in the State of Alagoas, Brazil

A database was constructed containing information on stalk yield and agro-industrial characteristics. The database included data from the 1998/1999-2018/2019 harvests, corresponding to 21 cropping cycles. The database included 34,775 harvested area records covering 50 sugarcane cultivars planted in six cropping environments. The rainfall data represented the average value recorded by a network of five rain gauges systematically distributed across the Mill's area.

The average total harvested area of the Mill is approximately 27,000 ha by crop season. The planting area is structured in 235 blocks, with an average area of 107 ha. These blocks are divided into 1655 plots (average number in the time series), which constituted the smallest control unit in the Mill, with an average area of 15 ha. In most cropping areas, a single row spacing of 1.5 m was adopted. For sub-superficial drip irrigated sugarcane, a double-row spacing of 1.30×0.50 m was used. The fertilization schedule comprised 100, 60, and 200 kg ha⁻¹ of N, P, and K, respectively. The micronutrient fertilization comprised 6.5, 7.0, 6.0, and 10.0 kg ha⁻¹ of Borax, ZnO, CuO, and MnO₂, respectively. All other management practices were standard for sugarcane crop needs.

The cropping environments were classified based on landscape relief, the irrigation system, and the level of water supply for sugarcane cultivation, as follows: HS - hillside without irrigation; RT - rainfed tableland; TS - tableland with an irrigation schedule of so-called "crop-saving irrigation"; LM - tableland irrigated by a linear moving irrigation system; FP - floodplain; and SD - tableland irrigated by a subsurface drip system. A description and characterization of the cropping environments are presented in Table 1.

For each cropping environment, the sugarcane yield and cane quality variables were analyzed by considering both the average data (varietal pool) from the Mill and a specific set of cultivars.

Considering the temporal window of a given crop season (e.g., 2018/2019), a preliminary analysis using an electronic spreadsheet identified the period in which rainfall best

correlated with the Mill's average yield across the time series. The most relevant rainfall data corresponded to the months from January to December of year *n*, plus January of year *n*+1 - a total of 13 months within the crop season. From this information, the sugarcane yield and agro-industrial characteristics were correlated with the following: 1) summer precipitation corresponding to periods January-March + October-December of year *n* plus January of year *n*+1 of the crop season (total of 7 months); 2) winter precipitation corresponding to the months from April to September of year *n* of the crop season (6 months); and 3) total precipitation corresponding to the sum of summer and winter precipitation. Rainfall data used the average of five rain gauges located at different points in the Mill.

The variables considered included fresh stalk yield (FSY, Mg ha⁻¹), stalk sucrose content (SSC, %), theoretical sugar yield (TSY, kg Mg⁻¹), juice purity (PURITY, %), stalk fiber content (FIBER, %), and sugar yield (SY, Mg ha⁻¹, calculated from FSY and TSY). A correlation analysis between these variables and rainfall was performed using Pearson's coefficient.

A linear regression analysis was applied to relate the total, summer, and winter rainfall corresponding to each crop season with the respective FSY. This analysis was performed both on the set of cultivars in each cropping environment and on specific genetic materials cultivated in TS and RT environments. For this, eight cultivars with the largest harvested area in the time series were selected: RB92579, SP791011, RB93509, CO997, RB 867515, RB72454, RB951541, and RB83102, in descending order. These cultivars represented approximately 68% of the harvested area, which comprised the time series.

For yield gap (Yg) estimation, we assumed that the SD cropping environment was the closest to the potential production concept, Yp, as defined by Ittersum et al. (2013) and Fischer (2015), once this environment presented the best cultivation conditions both in terms of quantity and control of the applied water as well as in terms of nutritional and sanitary management. Following this concept, Yg was

Table 1. Total cropped area, number of cropping cycles, and physical description of the cropping environments

Cropping environment	Description	Total area (ha) ¹	Total number of harvests ¹
HS	Areas associated with hillsides, with a declivity of approximately 15–40%. Sugarcane cultivation was rainfed. The environment corresponded to 2.8% of the total harvested area in the time series.	14,900	1.237
RT	Flat or low-slope areas (0–5%) of the coastal tablelands environmental unit. Sugarcane cultivation was rainfed. The environment corresponded to 16.9% of the harvested area in the time series.	88,614	5.269
TS	Flat or low-slope areas (0–5%) of the coastal tablelands environmental unit. Irrigation consisted of two or three applications of 60 mm of water in the initial stage of sugarcane development (generally with the first one occurring after planting and with the following occurring 30 days thereafter) using a hose reel irrigation system. The environment corresponded to 66.1% of the harvested area in the time series.	345,743	23.321
LM	Flat or low-slope areas (0–5%) of the coastal tablelands environmental unit. A 45-mm water depth was applied biweekly ² using a linear moving irrigation system. The environment corresponded to 2.9% of the harvested area in the time series.	15,312	741
FP	Lower relief area formed by a floodplain under the influence of the Coruripe River. Irrigation management consisted of controlling the water table. The environment corresponded to 4.5% of the harvested area in the time series.	23,762	1.758
SD	Flat or low-slope areas (0–5%) of the coastal tablelands environmental unit. An average of 2.5 mm water depth was applied daily ² using a subsurface drip irrigation system. The environment corresponded to 6.7% of the harvested area in the time series.	34,838	2.201

¹Total area and number of harvests accumulated throughout the time series; ²Except in the last 30 days prior to harvest, to induce sugarcane ripening. HS - Hillside without irrigation; RT - Rainfed tableland; TS - Tableland with an irrigation schedule of so-called "crop-saving irrigation"; LM - Tableland irrigated by a linear moving irrigation system; FP - Floodplain; and SD - Tableland irrigated by a subsurface drip system. Cropping environments were categorized according to relief conditions of the landscape, the irrigation system, and the level of water supply for sugarcane cultivation that prevail in the Mill.

obtained from the difference between the 95th (Yp95) and 99th (Yp99) percentiles of yield in the SD environment and the actual yield (Ya) from other cropping environments for each year of the time series.

Based on the quartiles of the time series of summer rainfall, the years were categorized into three classes: drier, when summer precipitation was less than 290 mm; moderate, with rainfall of between 290 and 490 mm; and wetter, when it rained more than 490 mm in the summer. For each class, an analysis of variance (ANOVA) was conducted using SISVAR software (version 5.8) to compare sugarcane yield and Yg across cropping environments. The F-test was applied to assess the significance of the sources of variation, and means were compared using Tukey's test at $p < 0.05$ and $p < 0.01$.

RESULTS AND DISCUSSION

The annual and monthly rainfall distribution patterns in the Coruripe Mill are shown in Figures 2A and B, respectively, and correspond to a 22-year rainfall data series (1998-2019), averaging 1.408 ± 303 mm per year. Average summer and winter precipitation levels accounted for 24 and 76% of annual precipitation, respectively. The summer precipitation ranged from 10 to 38% of annual precipitation.

The correlation between sugarcane production variables and summer, winter, and total rainfall for each cropping environment is shown in Table 2. The influence of rainfall on sugarcane agro-industrial characteristics was differentiated according to the cropping environments and the considered partition of this precipitation.

In the HS, RT, TS, and LM environments, statistically significant correlations were found between summer rainfall and both FSY and SY, with Pearson coefficients ranging from 0.63 to 0.86 for FSY, similar to the coefficient of 0.77 obtained from the data presented by Silva & Barbosa (2021), who

correlated sugarcane production with dry season rainfall (from August to February).

There were no statistically significant correlations between total precipitation and FSY for any of the cropping

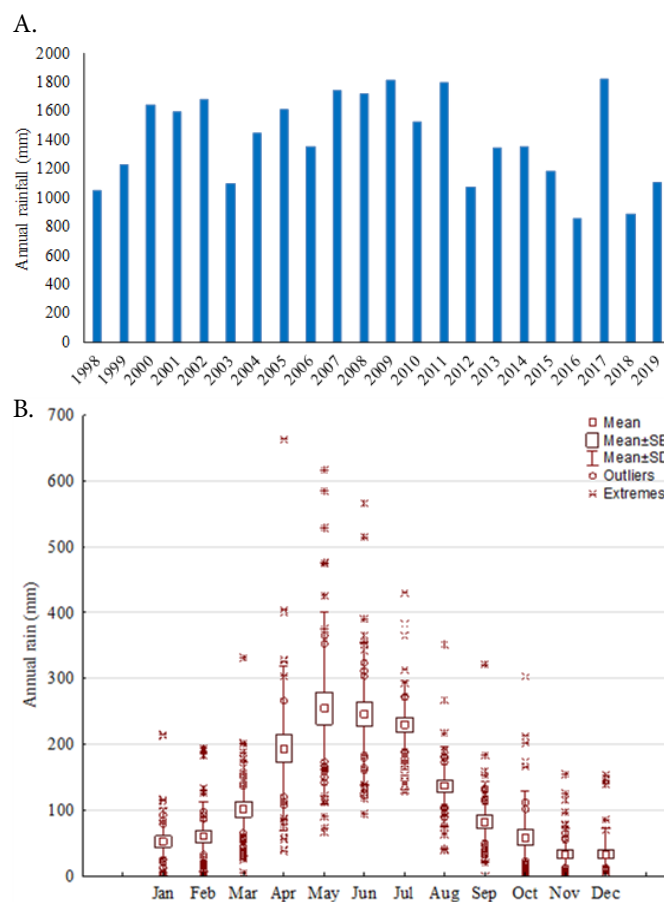


Figure 2. Total annual (A) and average monthly (B) rainfall data from Coruripe Mill, Coruripe, Alagoas, Brazil, in 1998-2019

Table 2. Pearson's correlation coefficient between sugarcane physical and qualitative yield characteristics and the seasonal and total rainfall of the cropping cycle for each cropping environment

Cropping environment	FSY	SY	TSY	SSC	PURITY	FIBER
Summer rainfall						
HS	0.74**	0.55**	-0.41	-0.40	-0.12	-0.34
RT	0.65**	0.53*	-0.14	-0.10	0.18	-0.27
TS	0.86**	0.76**	-0.19	-0.16	0.18	-0.49*
LM	0.63**	0.63**	0.09	0.11	0.21	-0.26
FP	0.20	0.10	-0.32	-0.31	-0.06	-0.29
SD	0.16	0.10	-0.21	-0.18	0.08	-0.35
Winter rainfall						
HS	-0.14	-0.12	-0.02	0.01	0.25	0.18
RT	-0.05	-0.05	-0.01	0.01	0.23	0.08
TS	0.01	0.04	0.11	0.14	0.58**	0.04
LM	-0.03	0.05	0.33	0.35	0.52*	0.26
FP	-0.42	-0.40	0.10	0.14	0.42*	0.37
SD	-0.01	0.02	0.11	0.14	0.50*	0.09
Total rainfall						
HS	0.18	0.13	-0.19	-0.16	0.18	0.02
RT	0.23	0.18	-0.07	-0.03	0.29	-0.04
TS	0.36	0.36	0.02	0.07	0.62**	-0.17
LM	0.24	0.32	0.35	0.38	0.58**	0.14
FP	-0.30	-0.33	-0.04	0.00	0.37	0.23
SD	0.06	0.06	0.01	0.05	0.50*	0.14

* and ** - Significant at $p < 0.05$ and $p < 0.01$, respectively, by the T-test; FSY - Fresh stalk yield; SY - Sugar yield; TSY - Theoretical sugar yield; SSC - Stalk sucrose content; PURITY - Juice purity; FIBER - Stalk fiber content; HS - Hillside without irrigation; RT - Rainfed tableland; TS - Tableland with an irrigation schedule of so-called "crop-saving irrigation"; LM - Tableland irrigated by a linear moving irrigation system; FP - Floodplain; and SD - Tableland irrigated by a subsurface drip system

environments. Although this suggests that annual rainfall is not an effective indicator for previewing sugarcane yield for coastal tableland areas. In the same region, Silva et al. (2009) found a positive and statistically significant correlation between 16-month rainfall and sugarcane yield. Otherwise, for São Paulo state, Marin et al. (2008) found a significant negative correlation between annual rainfall and an index coined by them as 'sugarcane cultivation efficiency'.

Regarding qualitative variables, in all irrigated cropping environments, there were positive correlations between winter precipitation and juice purity, showing that this variable is favored by precipitation, especially in cropping environments with greater water supply (TS, LM, FP, and SD). Except for FIBER in the TS environment, the other qualitative variables did not present a statistically significant correlation with precipitation. The weak relationship between the qualitative variables of sugarcane and the application of increasing levels of water depth was also observed by Oliveira et al. (2011) and Singh et al. (2018).

The angular coefficients of the regression that represent the relationship between sugarcane yield and rainfall (Table 3) reinforce the assertion that, for the study region, stalk yield is mainly related to summer rainfall.

In the HS, RT, TS, and FP cropping environments, the linear coefficient of the regression was significant at the 1% probability level, and each millimeter of summer rainfall resulted in increments of 54, 52, 54, and 57 kg ha⁻¹ of stalk, respectively. Except for the TS crop environment, the low R² in Table 3 suggests that, while precipitation does influence yield, other factors also play a significant role in explaining the observed variability. These rates are close to the 48 kg ha⁻¹ mm⁻¹ value observed by Pignède et al. (2021). Precipitation accumulated in the sugarcane maturation phase is less than that obtained by Oliveira et al. (2011) for several cultivars but higher than the 36.2 kg ha⁻¹ mm⁻¹ value calculated from data presented by Silva & Barbosa (2021), who considered rainfall in the dry season. Comparatively, water use efficiency values obtained in studies of the response of sugarcane to irrigation range from 111 to 183 kg ha⁻¹ mm⁻¹ of irrigation depth plus effective precipitation (Oliveira et al., 2011) and from 102 to 165 kg ha⁻¹ mm⁻¹ depending on the planting season and cultivar (Meneses & Resende, 2016).

In the LM, FP, and SD environments, where irrigation was applied throughout the sugarcane cropping cycle, a statistically significant relationship between SFY and summer precipitation was not only observed in LM. This difference may be attributed to variations in irrigation management, since in LM, irrigation was applied approximately every 15 days, whereas water was

applied at a much higher frequency in FP (continuously) and SD (daily). In these cropping environments, the difference between the water demand of the plant and precipitation was almost entirely supplied by irrigation, which tends to reduce rainfall effectiveness.

In all cropping environments, the regression slopes between SFY and both winter and total precipitation were not statistically significant, indicating that these variables were not key indicators of sugarcane yield. An exception was observed in the FP environment, where winter precipitation exhibited a significant negative coefficient (a: 104.99; b: -0.0176*; R²: 0.17), suggesting an inverse relationship between winter precipitation and productivity, as evidenced by the negative correlation coefficient (Table 2). By assessing extreme rainfall events on sugarcane yield in a tropical zone, Christina et al. (2021) observed that the annual actual yield loss increased by 0.6 Mg ha⁻¹ per rainfall day, which was higher than 29 mm per day along the annual crop cycle. Although Jaiphong et al. (2016) showed sugarcane adaptability to a shallow water table, the largest yield decrease in the FP environment was supposed to be related to the lesser possibility of control of the water table during the rainy season when the water balance tends to result in a water surplus in the soil, which varies from 525 to 728 mm at the present study site (Resende et al., 2021).

Winter rainfall did not influence stalk yield, even in cropping environments without irrigation (HS and RT) or with crop-saving irrigation (TS). This may be related to the low water storage capacity of the soil, which provides high water losses due to deep percolation, resulting in effective rainfall of almost half of the total rainfall during the sugarcane cropping cycle (Resende et al., 2021). Additionally, this period matches the lowest local air temperatures, reducing the plant growth rate and, therefore, the response to precipitation. This result differs from that obtained by Kumar et al. (2015), who pointed to a positive relationship between stalk yield and rainfall during the rainy season in 14 states of India. Although these authors did not characterize the season in terms of other climate variables, such a pattern is expected in regions with rainy summers, such as southeastern Brazil, where higher temperatures favor vegetative growth.

In the no irrigated cropping environments (HS and RT) and the TS and LM environments, there was a weak relationship between total rainfall and stalk yield. Therefore, even for rainfed sugarcane cropping, annual rainfall seems to be a poor parameter for predicting yield. Under climatic conditions similar to those in the present study, Silva et al. (2009) evaluated the relationship between total rainfall in the crop cycle and stalk yield and concluded that rainfall alone was insufficient to estimate sugarcane yield. Silva et al. (2008) also found nonsignificant regressions between annual precipitation and sugarcane yield in São Paulo state.

Similarly, for winter rainfall in the FP environment, total rainfall also resulted in a negative relationship with stalk yield, but in this case, it was not statistically significant.

The results presented thus far express the average behavior of the sugarcane cultivar group present in each production environment. Considering that the rainfed cropping environments (HS and RT) showed a higher average

Table 3. Linear regression parameters representing sugarcane yield and rainfall relationship for some cropping environment

Cropping environments	Summer rainfall		
	a	b	R ²
HS	43.12	0.0543**	0.54
RT	47.34	0.0521**	0.42
TS	54.85	0.0540**	0.70
LM	54.19	0.0570**	0.39

** - Significant at p < 0.01; HS - Hillside without irrigation; RT - Rainfed tableland; TS - Tableland with an irrigation schedule of so-called "crop-saving irrigation"; LM - Tableland irrigated by a linear moving irrigation system

correlation coefficient between rainfall and sugarcane yield compared to irrigated environments, we subsequently present the relationship between summer rainfall and the yield of the most cropped sugarcane cultivars in the time series (and still planted today) in these rainfed environments (Table 4).

For most sugarcane cultivars, the regression between FSU and summer rainfall yielded a statistically significant linear coefficient ($p < 0.05$), indicating a consistent relationship between these variables. However, the low determination coefficients suggest that although precipitation influenced yield, other factors also contributed to the observed variability. This reinforces the role of summer rainfall as a key determinant within the multifactorial framework affecting sugarcane productivity.

Considering the aforementioned constraint, cultivars RB92579, RB93509, and RB72454 exhibited the highest FSU increases per millimeter of precipitation (ranging from 77.0 to 94.4 kg mm⁻¹), whereas cultivars CO997 and SP791011 showed the lowest FSU increments (39.4-69.9 kg mm⁻¹). Comparatively, experiments with the RB 92579 cultivar in the municipalities of Teresina, PI (Silva et al., 2011), and Petrolina, PE (Silva et al., 2019), increments of 52.4 and 74.7 kg of stalk per millimeter of rainfall plus irrigation, respectively, were obtained. For cultivars RB867515 and RB951541, the angular coefficient was not significant for either the RT or TS environment. This fact is supposedly related to the small amount of cropping data available for the time series affecting the regression analysis.

The summers in each year of the time series were classified into three categories: drier, moderate, and wetter. The ANOVA of stalk yield in the cropping environments for each summer rainfall category is presented in Table 5. Considering such categories, six years were classified as drier, nine years were classified as moderate, and six years were classified as wetter.

The main differentiation of the yield potential of cropping environments occurred in crop seasons with drier or moderate summers, with the F test result being statistically significant ($p \leq 0.01$). Although the fully irrigated cropping environments (FP and SD) had a higher FSU in wetter summers, there was no significant difference compared to the other cropping environments ($p > 0.05$).

The HS, RT, and TS (Table 5) environments showed the greatest variations in FSU among the summer rainfall categories (12% average CV). For these cropping environments, summers classified as drier showed an average 21% reduction in FSU compared to those considered wetter, while for years classified as moderate, the yield gap was 13%. In drier summers, the average stalk yield was 59.4 Mg ha⁻¹ for cropping environments without irrigation (HS and RT), while in the moderate and wetter years, the average FSUs were 66.1 and 76.4 Mg ha⁻¹, respectively.

However, fully irrigated cropping environments (FP and SD) showed less yield variation between summer rainfall categories (3.9% average CV); sugarcane yield in the drier years was only 2.5% less than in the wetter years. Thus, in addition to showing an increase in the average sugarcane yield, this finding confirms the common-sense notion that irrigation provides greater yield stability. Although fully irrigated, the LM environment showed a similar level of cropping yield variability as TS (supplemental irrigation) considering the summer rainfall categories.

Figure 3 shows the potential yield (Y_p) established based on Y_{p95}, Y_{p99}, and the maximum yield (Y_{max}) obtained in the SD environment compared to Y_a for each cropping environment across the time series. For the average Y_{p95} and Y_{p99}, only the 10 most recent years of the time series were considered to avoid variability due to technological changes (Ittersum et al., 2013).

Table 4. Linear regression parameters for yield and summer rainfall in RT and TS cropping environments for each selected sugarcane cultivar

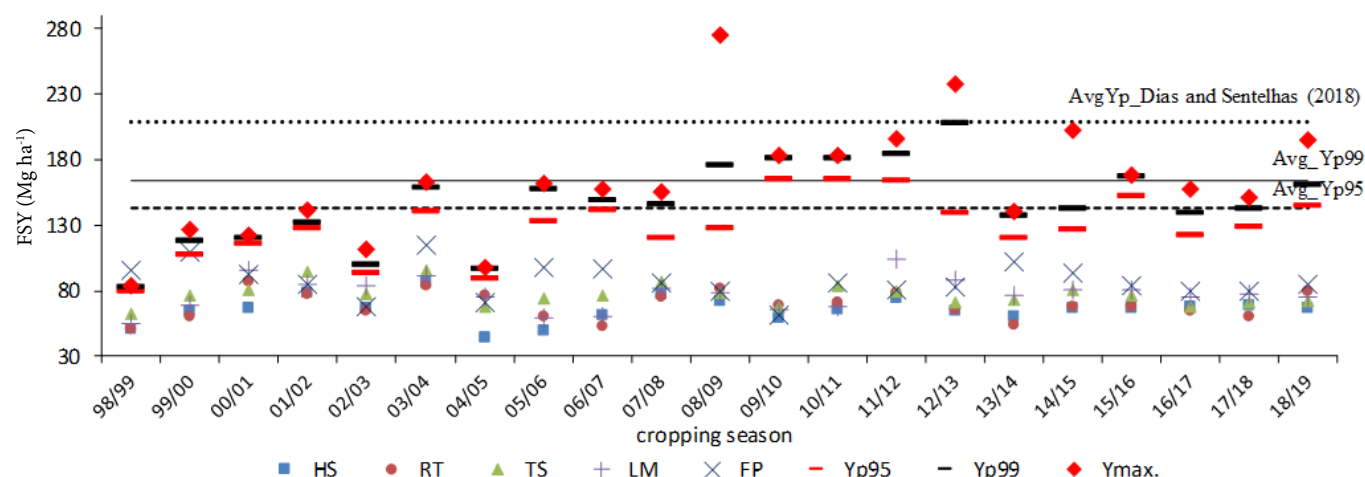
Sugarcane cultivar	RT			TS		
	a	b	R ²	a	b	R ²
RB92579	42.42	0.0944*	0.4	53.22	0.0883*	0.36
SP791011	37.87	0.0699**	0.43	46.29	0.0656**	0.43
RB93509	-	-	-	46.80	0.0884**	0.45
CO997	47.14	0.0479*	0.47	52.90	0.0394**	0.36
RB72454	-	-	-	41.25	0.0770*	0.42
RB83102	-	-	-	50.15	0.0368*	0.48

* and ** - Significant at $p < 0.05$ and $p < 0.01$, respectively, by T-test. RT - Rainfed tableland and TS - Tableland with an irrigation schedule of so-called "crop-saving irrigation"

Table 5. Average fresh stalk yield (FSU) (Mg ha⁻¹) in cropping environments for each summer rainfall category

Cropping environments	Summer rainfall category				
	Wetter (n=6)	Moderate (n=9)	Drier (n=6)	Average	CV
HS	74.6 a	63.6 d	59.4 b	65.8	11.9
RT	78.3 a	68.6 cd	59.5 b	68.8	13.7
TS	85.7 a	75.5 bcd	69.9 ab	77.0	10.4
LM	85.8 a	79.5 abc	65.3 b	76.9	13.7
FP	87.5 a	88.3 ab	85.1 a	86.9	1.9
SD	85.3 a	93.2 a	83.3 a	87.3	6.0
Average	82.8	78.1	70.4		
'F' test	ns	***	***		
CV	12.4	13.4	13.9		
DMS	18.0	14.6	17.2		

Different letters within a column indicate statistically significant differences (Tukey's test); CV - Coefficient of variation (%); *** - Significant at $p \leq 0.001$ by F-test; ns - Not significant by F-test; DMS - Difference minimum significative. HS - Hillside without irrigation; RT - Rainfed tableland; TS - Tableland with an irrigation schedule of so-called "crop-saving irrigation"; LM - Tableland irrigated by a linear moving irrigation system; FP - Floodplain; and SD - Tableland irrigated by a subsurface drip system



FSY - Fresh stalk yield. The Yp and Ymax values are estimated as the 95th (Yp95) and 99th (Yp99) percentiles and maximum yield, respectively, for each sugarcane cropping season in the SD cropping environment. Continuous and dashed lines denote the average Yp from the 10 most recent years of the time series of the SD cropping environment and Yp estimated from crop models by Dias & Sentelhas (2018). HS - Hillside without irrigation; RT - Rainfed tableland; TS - Tableland with an irrigation schedule of so-called "crop-saving irrigation"; LM - Tableland irrigated by a linear moving irrigation system; FP - Floodplain; and SD - Tableland irrigated by a subsurface drip system

Figure 3. Sugarcane actual yield (Ya), potential yield (Yp), and maximum yield (Ymax) along the cropping seasons (time series)

A growth trend in Yp and Ymax (both linked to the TG environment) was observed over the time series. This is probably due to the learning curve of subsurface drip irrigation system management by technical and operational staff of the Mill because TG had higher FSY increment rates along the time series of 1 Mg per year compared to -0.31, 0.24, and -0.56 Mg per year in the TS, LM, and FP environments, respectively. However, this growth does not occur for Ya in other cropping environments. The average Yp95 and Yp99 values were recorded as 142.9 and 164.2 Mg ha⁻¹, respectively, which are lower than the Yp of 208.5 Mg ha⁻¹ estimated for the same area by Dias & Sentelhas (2018) based on crop growth simulation models. In this regard, only in the most recent period of the time series (2008/09, 2010/11, 2011/12, 2012/13, 2014/15, and 2018/19) was Ymax achieved with values close to or higher than the Yp determined by those authors.

From this point of view, for each cropping environment and cropping season of the time series, we calculated the sugarcane Yg based on the difference between the average Yp99 and Ya. The average Yg, according to the summer rainfall category and cropping environments, are presented in Table 6.

Drier summers resulted in a higher average Yg across all environments. Although rainfed cropping environments (HS and RT) had a higher Yg, with 104 Mg ha⁻¹ recorded for the worst case (drier summers), there was no statistical

difference from Yg in the TS and LM environments. Yg in rainfed cropping environments was less than that caused by water deficit (named YG_{wd}), estimated as 116.3 Mg ha⁻¹ by Dias & Sentelhas (2018) for north/northeast regions of Brazil. Although the so-called 'crop-saving irrigation' associated with the TS cropping environment constitutes a limited means to address sugarcane water demand, it has a significant effect on reducing Yg relative to rainfed cropping environments (HS and RT), mainly in drier years. Additionally, in the wetter years, the yield gap of the TS environment was similar to that found in the fully irrigated cropping environments (LM and FP).

Considering the full irrigation conditions associated with the LM environment, both its high Yg in the driest summers (98.9 Mg ha⁻¹) and the stronger correlation between Yg and the summer rainfall category stand out. According to field technical staff of the Coruripe Mill, irrigation management in LM involves a 45-mm water depth applied biweekly, and the average daily irrigation depth (2.5 mm per day) is less than the 5.1-6.9 mm of crop evapotranspiration during the more critical sugarcane development stage (Meneses & Resende, 2016; Carvalho et al., 2019; Resende et al., 2021). It seems unreasonable that similarities in sugarcane yield were observed between the TS and LM cropping environments, considering their different levels of water supply from irrigation. Unsuitable genotype management in terms of better adaptation to irrigated

Table 6. Yield gap (Yg, Mg ha⁻¹) of each cropping environment in relation to average Yp99 values from the SD cropping environment for each summer rainfall category

Cropping environments	Summer rainfall category			Average
	Wetter (n=6)	Moderate (n=9)	Drier (n=6)	
HS	89.7 a	100.6 a	104.9 a	98.4
RT	85.9 a	95.6 ab	104.8 a	95.4
TS	78.5 a	88.7 ab	94.4 ab	87.2
LM	78.4 a	84.7 bc	98.9 a	87.4
FP	76.7 a	75.9 c	79.1 b	77.3
Average	81.8	89.1	96.4	
'F' test	ns	***	***	
CV	11.7	10.3	9.5	
DMS	16.2	12.3	15.6	

Different letters within a column indicate statistically significant differences (Tukey's test); CV - Coefficient of variation (%); *** - Significant at $p \leq 0.001$ by F-test; ns - Not significant by F-test; DMS - Difference minimum significative. HS - Hillside without irrigation; RT - Rainfed tableland; TS - Tableland with an irrigation schedule of so-called "crop-saving irrigation"; LM - Tableland irrigated by a linear moving irrigation system; FP - Floodplain; and SD - Tableland irrigated by a subsurface drip system

conditions (genotype responsivity to irrigation), irrigation management issues, or restrictions on the displacement of irrigation equipment between irrigated areas could explain this.

The FP environment showed the least variation in Yg among the three summer rainfall categories and the lowest yield reduction, with an average Yg of 77.3 Mg ha⁻¹ - more than twice the 34.2 Mg ha⁻¹ reported by Gasparotto et al. (2022) in southeastern Brazil.

CONCLUSIONS

1. Sugarcane (*Saccharum officinarum* L.) yield is more correlated with summer precipitation than with total crop season precipitation.

2. RB 92579 and SP 701011 sugarcane cultivars showed the strongest yield responses to increasing the water supply by precipitation, while the CO 997 cultivar showed the weakest response.

3. In rainfed cropping environments and crop seasons with drier summers, sugarcane yield losses could reach 21% compared to crop seasons with wetter summers. In fully irrigated cropping environments, this difference could be as low as 2.5%.

Contribution of authors: Ronaldo S. Resende was responsible for the conceptualization, methodology, data analysis and interpretation, investigation, visualization, and original draft preparation. Sandra M. da Silva contributed to data analysis and interpretation, visualization, and manuscript review and editing.

Supplementary documents: There are no supplementary sources.

Conflict of interest: The authors have no conflicts of interest to declare.

Financing statement: The authors received no financial support for the research, authorship, or publication of this article.

Acknowledgments: We gratefully acknowledge the Coruripe Sugar and Alcohol Mill for providing access to the sugarcane yield database. We also extend our thanks to the peer reviewers and editors for their valuable comments and constructive suggestions.

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