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MICROCLIMATE AND IRRIGATION AFFECT THE GROWTH DYNAMICS OF SUGARCANE IN A SEMIARID ENVIRONMENT

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KEYWORDS

path analysis, correlation, radiation interception, biomass.

ABSTRACT

The aim of this study was to assess how microclimate variables and irrigation affect the growth of sugarcane. The experiment was conducted using the VAT90-212 cultivar in the Semi-arid region of Brazil. The microclimate was monitored and by quantifying the irrigation depth. Nine campaigns were carried out in the field to collect morphological and biomass data. The data were subjected to descriptive statistics, so as to generate the mean values and/or sum between the campaigns. Using the correlation coefficient, the extent, sign and significance of the relationship between the response and explanatory variables were evaluated. The direct or indirect effects of the explanatory variables on the response variables were identified by path analysis. There was a significant correlation between microclimate variables and the morphological and biomass variables of the sugarcane, with a strong contribution from the intercepted fraction of the photosynthetically active radiation, the wind speed and soil temperature. The negative correlation with irrigation suggests that excess water impaired the growth dynamics of the crop. It is concluded that the growth of sugarcane is closely related to its capacity to intercept radiation, to the wind, thermal regime of the soil and irrigation management.

INTRODUCTION

Sugarcane is of great importance on the agricultural stage, crop accounting for nearly 80% of world sugar production (ISO, 2020; Dlamini & Zhou, 2022). The Brazil is one of the main global producers of this crop, the region north-east of Brazil also plays an important contribution, especially the coastal region of the states of Alagoas, Paraíba and Pernambuco (CONAB, 2019). Another important area of production in the region is the Lower-Middle São Francisco Valley, particularly the district of Juazeiro, Bahia, in the semi-arid region of Brazil, which, due to the use of irrigation linked to soil and climate conditions and to crop management, has excellent sugarcane production indicators (Silva et al., 2019).

A sugarcane is affected by a combination of factors during its growth, such as natural factors (soil, climate, botany, etc.) and anthropogenic factors (crop and economic management, etc.) (Qin et al., 2023). For exemplo abiotic factors that affect the sugarcane crop (Silva et al., 2011a). Research has been carried out in the semi-arid region of Brazil seeking to understand the interaction of sugarcane with the atmosphere, and the effects of irrigation depth on yield (Silva et al., 2011a, b; Silva et al., 2012a, b; Silva et al., 2014a, b; Carmo et al., 2018; Oliveira & Braga, 2019).

However, there is a gap in the knowledge of how abiotic factors (i.e. solar radiation, photoperiod, air and soil temperature, and wind) modify growth dynamics throughout the sugarcane cycle in this region. This information is crucial for defining management and adaptation strategies in the face of environmental change (Marin et al., 2020; Silva et al., 2012a, b).

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One way of verifying the cause and effect relationships between the growth dynamics of the crop and environmental and/or management factors is through the use of multivariate statistics, such as path analysis, which identifies the direct and indirect effects of explanatory variables on response variables. This technique has been successfully applied in several studies (Barbosa et al., 2017b; Barbosa et al., 2018a; Pinheiro et al., 2014). In this study, the aim was to assess how microclimate variables and irrigation affect the growth of sugarcane in a semi-arid environment, as an aid to adapting crop management in the region.

MATERIAL AND METHODS

The experiment sugarcane cultivar VAT 90-212 was conducted in an area of commercial sugarcane production (*Saccharum officinarum* spp.) (09º26' S, 40º19' W, 396 m) in the district of Juazeiro, Bahia, the Lower-Middle São Francisco Valley, in the Semi-arid region of Brazil. Planting was carried out in January 2013, using whole stalks with 12 buds on average per linear meter, in furrows 0.2 m deep arranged in double rows spaced at 1.3 x 1.0 m. The first harvest was performed after 18 months from planting and the second (ratoon), after 12 months, on June, 2015. Then this study was carry out from June 2015 to May 2016.

The VAT 90-212 variety was grown in a Vertisol, in double rows at a spacing of 1.3 x 1.0 m, irrigated during the third regrowth by subsurface drip. A micrometeorological tower, eight metres in height, was installed in the centre of the experimental area, equipped with electronic sensors to measure the global incident solar radiation (Rs) (CNR1 Net radiometer); air temperature (Ta) and relative humidity (RH); wind speed (WS); photosynthetically active radiation (PAR) above and below the canopy; soil temperature (Ts) and rainfall (R).

The photoperiod (N) was calculated based on the latitude and day of the year (Bergamaschi & Bergonci, 2017). The intercepted fraction of the photosynthetically active radiation (fPARi) was calculated from the PAR measured above and below the sugarcane canopy using [eq. (1)]:

$$\mathrm{fPARi} = 1 - \frac{\mathrm{PARbl}}{\mathrm{PARi}} \qquad (1)$$

Where:

PARbl = photosynthetically active radiation below the canopy (µmol . m^{-2} s^{-1}) and incident photosynthetically active radiation (µmol . m^{-2} s^{-1}).

Nine campaigns were carried out from 150 days after cutting the second regrowth (28/10/2015, 18/11/2015, 16/12/2015, 06/01/2016, 27/01/2016, 24/02/2016, 23/03/2016, 27/04/2016 and 26/05/2016) to record the following morphological variables: number of fully expanded leaves (NFEL), number of emerging leaves (NEL), number of live leaves (NLL), width (W+3) and length (L+3) of the +3 leaf, number of commercial stalks (NCS), stalk diameter (SD) and height (SH), and plant height (PH), following the methodology adopted by Silva et al. (2012b). On the same dates as the campaigns, ten representative plants were collected to evaluate dry biomass in the fully expanded leaves (DBFEL), emerging leaves (DBEL), live sheaths (DBLS) pseudostalks (DBPS), stalks (DBS) and shoots (DBSH), as per Silva et al. (2014b).

The data were classified into three groups: Group I and Group II, both of response variables, comprising the morphological and biomass data respectively; Group III (explanatory variables), consisting of microclimate variables and irrigation depth. The data were initially submitted to descriptive statistics in order to generate the mean values and/or sum between the campaigns. Pearson's correlation matrix was then applied to the mean values and/or sum.

Magnitude, sign (positive or negative) and significance were evaluated by means of the coefficient of correlation (r), using Student's t-test ($p < 0.01$ and $p < 0.05$). The magnitude of the Pearson correlation coefficients was interpreted as per Thomaz et al. (2012), using the following classification: 0 to 0.19 as 'very weak', 0.20 to 0.39 as 'weak', 0.40 to 0.69 as 'moderate', 0.70 to 0.89 as 'strong' and 0.90 to 1.00 as 'very strong'. The test for multicollinearity was applied to analyse the weak relationship between variables of the same group (Barbosa et al., 2017a; Barbosa et al., 2018a; Pinheiro et al., 2014).

The associations between the groups of variables were assessed by means of canonical analysis using the chi-square test, which refers to the correlations between linear combinations of variables, i.e. canonical variables, in such a way that the correlation between these combinations was greatest. When orthogonal, the variables were independent of each other (Barbosa et al., 2017b; Barbosa et al., 2018b). Finally, path analysis was carried out to identify the direct or indirect effects of the explanatory variables on the response variables. All the steps were performed using the GENES software (Cruz, 2006).

RESULTS AND DISCUSSION

Figure 1 shows mean and/or accumulated values for the microclimate variables over the nine time intervals considered during the sugarcane cycle. During the crop cycle, the main rainfall events were concentrated over just two months, reflecting the occurrence of the hot phase of the ENSO phenomenon (El Niño Southern Oscillation). Due to the low latitude (9º S), the photoperiod varies little throughout the year (Figure 1A).

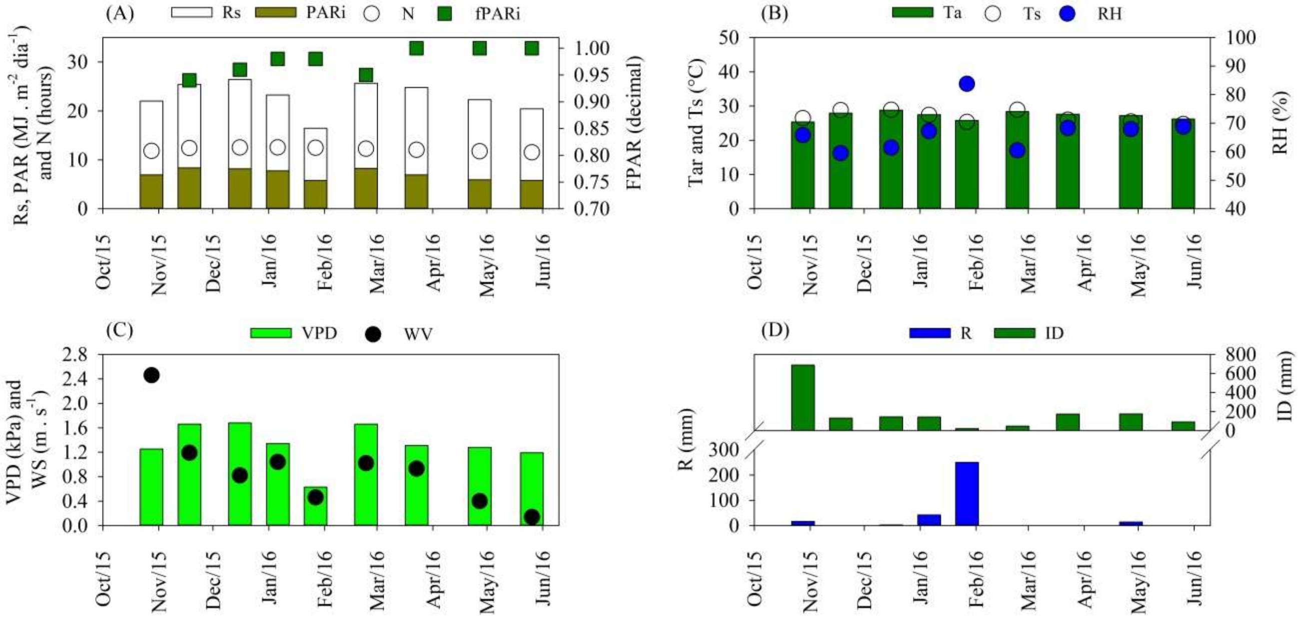

FIGURE 1. Microclimatic variables and irrigation depth over nine periods of the sugarcane cultivation cycle. District of Juazeiro, Bahia, in the semi-arid region of Brazil.

In Jan 2016 and Feb 2016, between the 8th and 9th months of the crop cycle, the incidence of radiation (Rs) and photosynthetically active radiation (PARi) is reduced (Figure 1A) due to greater cloudiness (Figure 1D), culminating in a slight decrease in T and an increase in RH, with a consequent reduction in VPD. WS was more intense during the first five months of the cycle (Jun 2015 to Oct 2015).

Because of the low R values, the irrigation depths (ID) were applied throughout the period. The irrigation depth accumulated over the first period under analysis (Jun-15 to Oct-15) is noteworthy, as it includes the total for the five months prior to collecting the morphological and biomass data (Figure 1D). The soil temperature (Ts) followed the same trend as Ta; whereas, the intercepted fraction of the photosynthetically active radiation (fPARi) increased up until the end of the cycle due to the growth of the crop (0.99).

The global incident solar radiation (Rs), air temperature (Ta), relative humidity (RH), water vapour-pressure deficit (VPD), wind speed (WS) and rainfall (R) showed differences in relation to the climate pattern of the region (Table 1), especially during the rainy season between Jan 2016 and May 2016.

TABLE 1. Climate data from the 1975 to 2015 data series. District of Juazeiro, Bahia, in the semi-arid region of Brazil.

Month	Rs (MJ m^{-2} day^{-1})	T (°C)	RH (%)	WS (m s^{-1})	VPD (kPa)	R (mm)
Jan	19.1	27.4	63.5	1.96	1.34	88
Feb	18.5	27.3	64.9	1.95	1.28	83
Mar	17.8	27.1	66.7	1.71	1.20	111
Apr	16.9	26.8	66.0	1.91	1.20	54
May	15.0	26.0	65.3	2.24	1.16	18
Jun	14.1	24.7	65.1	2.61	1.08	7
Jul	14.9	24.2	62.7	2.80	1.13	5
Aug	17.3	25.0	59.3	3.02	1.29	2
Sep	19.5	26.7	55.0	3.08	1.57	3
Oct	20.2	27.9	53.9	2.92	1.74	7
Nov	19.4	28.4	56.7	2.52	1.67	45
Dec	19.2	27.9	60.1	2.15	1.50	71
Yearly	17.7	26.6	61.5	2.42	1.34	499

Source: Embrapa Semiárido. http://www.cpatsa.embrapa.br:8080/servicos/dadosmet/cem-mes.html

Figures 2 and 3 show morphological and biomass data throughout the sugarcane cycle. The crop reached 24 stalks . m^{-2} (NCS) by the ninth month of the cycle (Figure 2A), with a maximum of 11 simultaneous expanded leaves (NFEL) between the 6th and 7th months (Figure 2B). Leaf emission (NEL) continued until harvest, with 3 units $plant^{-1}$ (Figure 2C), but the greatest number of live leaves (NLL, expanded plus emerging) occurred during the fourth month (Figure 2D).

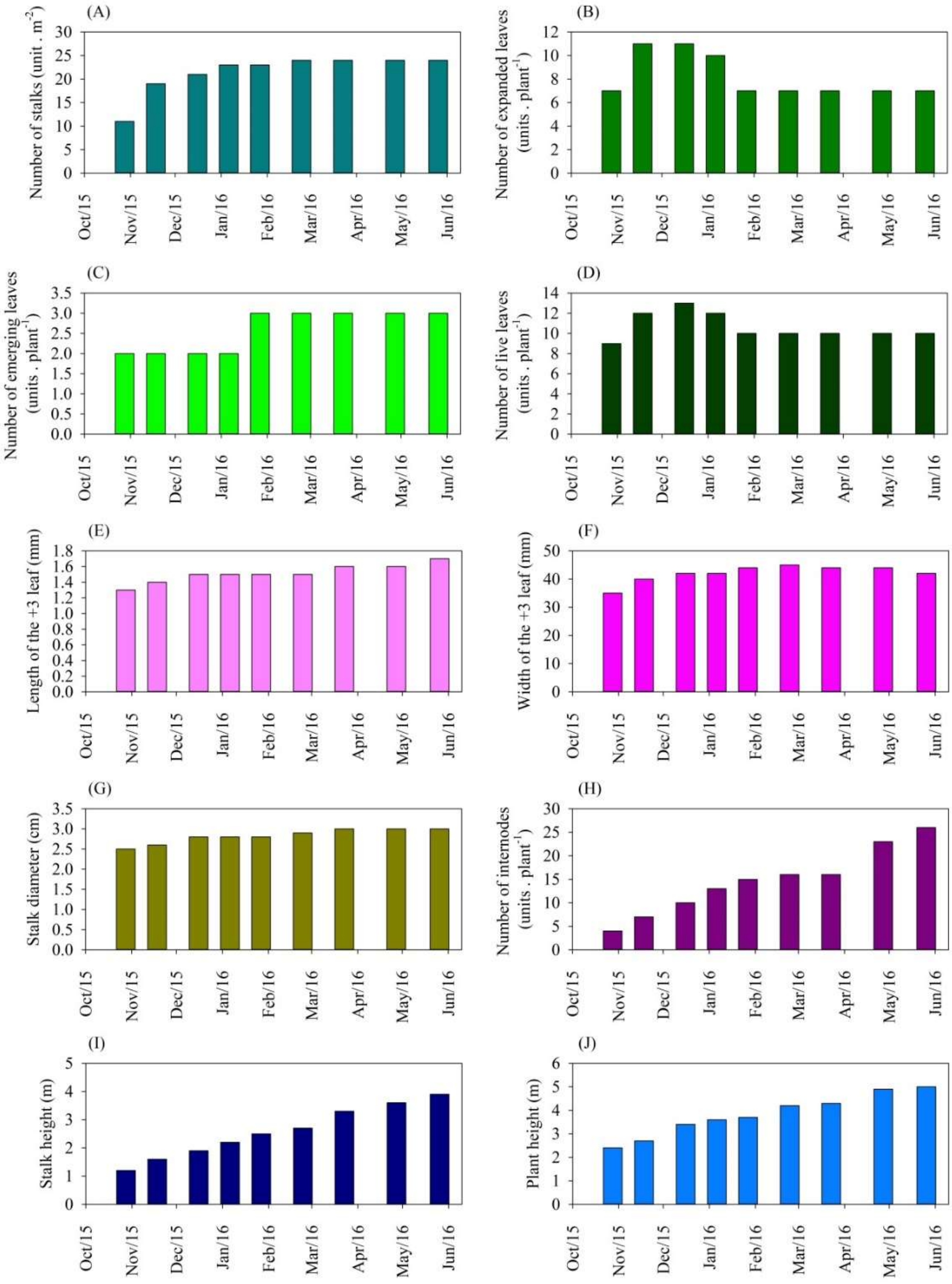

FIGURE 2. Morphological data during the sugarcane cycle. Grown in the district of Juazeiro, Bahia, in the semi-arid region of Brazil.

The greatest leaf width (W+3) was recorded during the 10th month (Figure 2F), while the greatest length (L+3) was only seen at the end of the cycle, during the 12th month (Figure 2E). The number of internodes (NIN) increased prior to harvesting, when it totalled 26 units . stalk^{-1}, with the mean stalk diameter (SD) increasing up to the fourth month (Figure 2G), resulting in a stalk height (SH) of 3.9 m (Figure 2H) and a plant height (PH) of 5.0 m (Figure 2I) when including the leaves.

Biomass (Figure 3) continued to increase until the end of the cycle, with the exception of pseudostalk dry biomass (DBPS) (Figure 3D), which decreased from the ninth month in favour of biomass partitioning to the stalks (DBS) (Figure 2E).

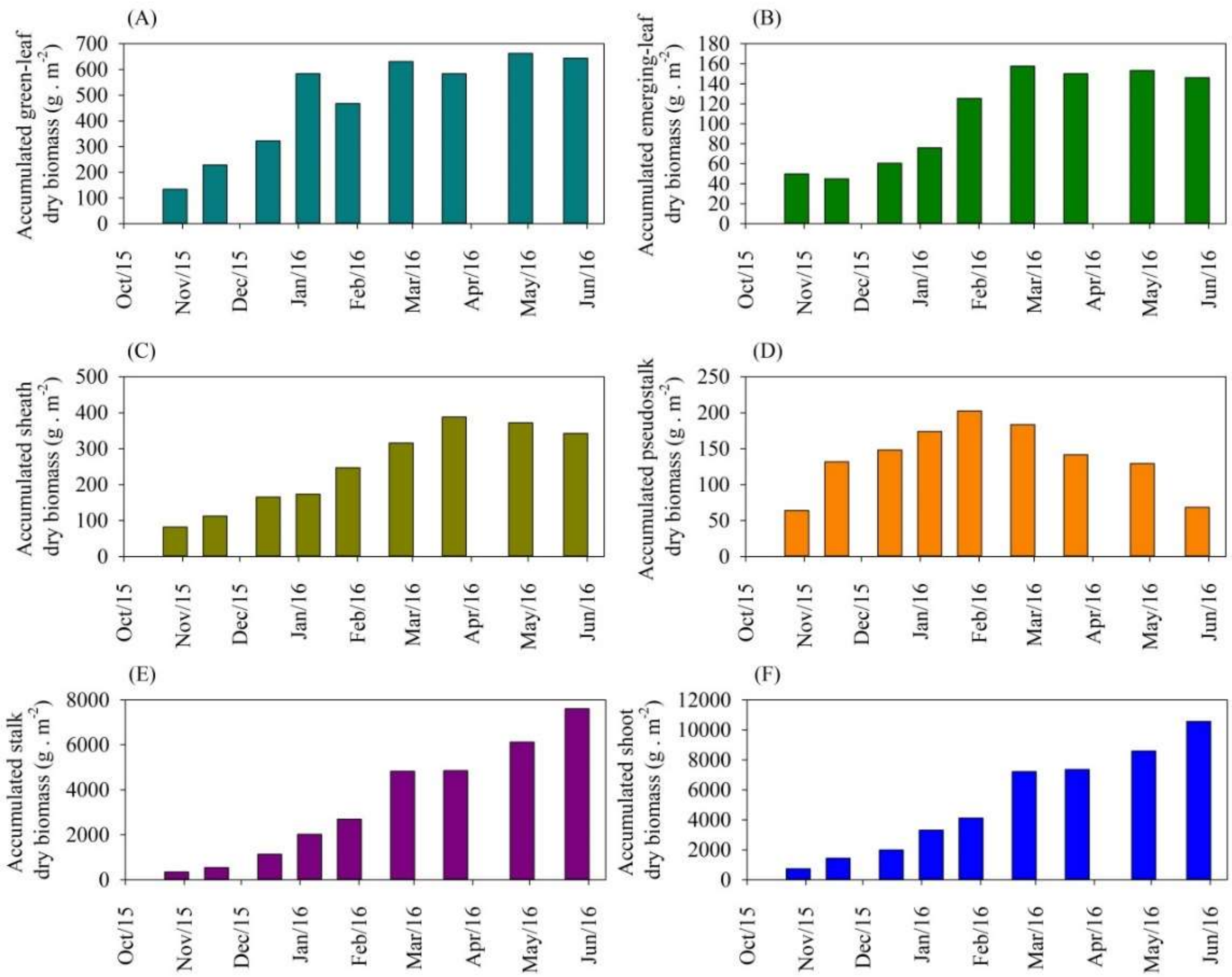

FIGURE 3. Accumulated biomass during the sugarcane cycle. Grown in the district of Juazeiro, Bahia, in the semi-arid region of Brazil.

Biomass accumulation in the expanded leaves (DBFEL), emerging leaves (DBEL) and sheaths (DBLS) follows the pattern found for their respective morphological variables (Figure 2). The dry biomass accumulated in the shoots reached 10,566 g . m^{-2}. The dynamics of sugarcane growth and production in this study corroborate those found by Silva et al. (2012a) and Silva et al. (2014b), Batista et al. (2015), Brunini & Turco (2016) and Oliveira & Braga (2019).

The microclimate variables that showed a correlation with the morphological variables and biomass of the crop are shown in Table 2. Using Pearson's correlation coefficient (r), it is possible to check the reliability of the relationship between the variables based on the degree of significance. PARi and Ts showed a positive and strong (0.70) significant correlation with NEL only. FPARi and WS showed a strong and very strong correlation with the following variables: NCS, NEL, NLL, SD, NCS, L+3, W+3, SH and PH. While ID showed a strong and negative correlation with NCP (-0.89) and with W+3 (-0.87).

TABLE 2. Pearson's correlation coefficient between microclimate variables (explanatory), and morphological variables and biomass accumulation (response) in sugarcane grown in the Semi-arid region of Brazil.

	Morphological variables							
	NCS	**NEL**	**DI**	**NIN**	**L+3**	**W+3**	**SH**	**PH**
PARi	0.15	0.70*	-0.09	-0.37	-0.20	0.20	-0.35	-0.25
fPARi	0.96**	0.06	0.81**	0.72*	0.83**	0.87**	0.72**	0.74**
WS	-0.88*	-0.62	-0.80**	-0.83**	-0.88**	-0.80**	-0.78*	-0.80**
Ts	-0.15	0.70*	0.64	-0.59	-0.49	-0.06	-0.60	-0.50
ID	-0.89**	-0.46	-0.62	-0.54	-0.62	-0.87**	-0.51	-0.55
N	-	-	-	-	-	-	-	-

	Biomass variables				
	DBLL	**DBLS**	**DBPS**	**DBS**	**DBSH**
PARi	-	-	-	-	-
fPARi	0.74*	0.68*	0.47	0.59	0.61
WS	-0.72*	-0.68*	-0.31	-0.69*	-0.69*
Ts	-	-	-	-	-
ID	-0.69*	-0.50	-0.65	-0.42	-0.45
N	-0.05	-0.45	0.79*	-0.64	-0.61

Explanatory variables: PARi - incident photosynthetically active radiation; fPARi - fraction of the incident photosynthetically active radiation; WS - wind speed; N - photoperiod; Ts - soil temperature; ID - irrigation depth. Responses variables: NCS - number of commercial stalks; NEL - number of expanded leaves; DI - internode diameter; NIN - number of internodes; L+3 - length of the +3 leaf; W+3 - width of the +3 leaf; SH - stalk height; PH - plant height; DBLL – live-leaf dry biomass; DBLS - sheath dry biomass; DBPS - pseudostalk dry biomass; DBS - stalk dry biomass; DBSH - total dry shoot biomass.

**, *Significant at 1 and 5% respectively by t-test.

The fPARi showed an intensely strong correlation with live-leaf dry biomass (DBLL) (0.74) and a moderate correlation with sheath dry biomass (DBLS) (0.68) (Table 2). WS had a strong negative correlation with live-leaf dry biomass (DBLL) (-0.72), and a moderate correlation with sheath dry biomass (DBLS) (-0.68), stalk dry biomass (-0. 69) and total shoot biomass (DBSH) (-0.69). Photoperiod (N) and irrigation were correlated with pseudostalk dry biomass (DBPS) (0.79) and with DBLL (-0.69). Irrigation was also found to have a strong and negative correlation with NCP (-0.89) and W+3 (-0.87).

The associations between groups of morphological variables and of biomass with the group of microclimate variables and irrigation were not significant by canonical analysis; as such, at the significance level of $p = 0.01$ and $p = 0.05$ by chi-square test, these groups were independent of each other, i.e. one or more individual variables affect the growth dynamics of sugarcane, as broken down in the path analysis.

A breakdown of 'r' between the microclimate, morphological and biomass variables is shown in Tables 3 and 4. From this analysis, it was found that Ts had a direct positive effect (0.40) and an indirect positive effect via PARi (0.36) on NEL; despite this, the residual effect was greater (0.70) than the coefficient of determination (r^2), showing that other factors are more important in issuing new leaves.

TABLE 3. Direct and indirect effect of microclimate variables and irrigation on the dynamics of morphological variables in sugarcane grown in the semi-arid region of Brazil.

Variable	Growth variables			
	Effect		**r partial**	**r total**
PARi	direct on	NEL	0.34	0.70
	indirect via	Ts	0.36	
Ts	direct on	NEL	0.40	0.70
	indirect via	PARi	0.30	
	Coefficient of determination			0.50
	Residual effect			0.70
fPARi	direct on	L+3	0.17	0.83
	indirect via	WS	0.66	
WS	direct on	L+3	0.72	-0.88
	indirect via	fPARi	0.16	
	Coefficient of determination			0.77
	Residual effect			0.48
fPARi	direct on	W+3	0.60	0.87
	indirect via	WS	-0.12	
	indirect via	ID	0.40	
WS	direct on	W+3	0.13	-0.79
	indirect via	fPARi	-0.55	
	indirect via	ID	-0.37	
ID	direct on	W+3	-0.44	-0.87
	indirect via	fPARi	-0.54	
	indirect via	WS	0.11	
	Coefficient of determination			0.81
	Residual effect			0.44
fPARi	direct on	NIN	-0.33	0.72
	indirect via	WS	1.05	
WS	direct on	NIN	-1.14	-0.83
	indirect via	fPARi	0.30	
	Coefficient of determination			0.71
	Residual effect			0.54

Explanatory variables: PARi - incident photosynthetically active radiation; fPARi - fraction of photosynthetically active radiation; WS - wind speed; N - photoperiod; ID - irrigation depth, Ts - soil temperature. Response variables: NEL - number of expanded leaves; DI - internode diameter; NIN - number of internodes; L+3 - length of the +3 leaf; W+3 - width of the +3 leaf.

TABLE 4. Direct and indirect effect of microclimate variables and irrigation on biomass accumulation in sugarcane grown in the semi-arid region of Brazil.

fPARi	direct on	DBLL	0.45	0.74
	indirect via	WS	0.25	
	indirect via	ID	0.09	
WS	direct on	DBLL	-0.22	-0.72
	indirect via	fPARi	-0.41	
	indirect via	ID	-0.83	
ID	direct on	DBLL	-0.10	-0.69
	indirect via	fPARi	-0.40	
	indirect via	WS	-0.19	
	Coefficient of determination			0.56
	Residual effect			0.67
fPARi	direct on	DBLS	0.33	0.68
	indirect via	WS	0.37	
WS	direct on	DBLS	-0.38	-0.68
	indirect via	fPARi	-0.31	
	Coefficient of determination			0.49
	Residual effect			0.72
N	direct on	DBPS	0.79	0.79
	Coefficient of determination			0.62
	Residual effect			0.62

Explanatory variables: fPARi - fraction of photosynthetically active radiation; WS - wind speed; N - photoperiod; ID - irrigation depth, Ts - soil temperature. Variable responses: DBLL – live-leaf dry biomass; DBLS - sheath dry biomass; DBPS – pseudostalk dry biomass.

In turn, in the path analysis for the morphological variables L+3, W+3 and NIN, r^2 was greater than the residual (0.77 versus 0.48, 0.81 versus 0.44, and 0.71 versus 0.54 respectively), showing that fPARi, WS and ID were important to the dynamics of these growth variables. For L+3, WS had a direct positive effect (0.72) and an indirect positive effect via fPARi (0.66), while for W+3, fPARi was more important, with a direct positive effect (0.60) and indirect negative effect via WS (-0.55) and ID (-0.54).

For NIN, WS was important, with a direct negative effect (-1.14) and indirect positive effect via fPARi (1.05) respectively. Despite the effects of fPARi, WS, ID and N being found on the biomass variables DBLS, DBLL and DBPS, it can be seen that the values of r^2 were less than or equal to the residual coefficients (0.56 versus 0.67, 0.72 versus 0.49, and 0.62 versus 0.62 respectively), so other factors are more decisive for biomass accumulation in these plant structures (Table 4).

PARi is an important variable for plant growth, as it acts as a driving force in the physiological processes (Marchiori et al., 2014; and Li et al., 2014). This result agrees with Silva et al. (2014a), who, evaluating morphophysiological indices, biomass and radiation usage in sugarcane, found it was possible to increase photosynthetic efficiency by altering the start of the cycle. The ability of sugarcane to intercept radiation, i.e. fPARi, varies according to the variety (Almeida Neto et al., 2020) due to the influence of the leaf area index (Ferreira Júnior et al., 2014; Elli et al., 2016) and is essential for increasing crop yield (Brunini & Turco, 2016). In the present study, fPARi had a strong influence on the growth dynamics of the crop.

Wind speed, another important variable in this study, showed a negative correlation with the growth dynamics of the crop. In sugarcane, wind speed can cause stalks to topple prior to harvesting (Marin et al., 2009; Bergamaschi & Bergonci, 2017), which is frequently seen in areas of high production. In addition, intense wind reduces gas exchange between the plants and the atmosphere, affecting transpiration, carbon assimilation and other metabolic activities (Marin et al., 2009).

The positive effect of soil temperature on the growth of sugarcane may be related to its influence on water uptake by the roots (Marin et al., 2009; Awe et al., 2015), in addition to its effect on growth, the allocation and translocation of nutrients (Dong et al., 2001), and crop production (Sawan, 2017). Carvalho et al. (2018) state that soil temperature even influences evapotranspiration in sugarcane.

The strong negative correlation of irrigation with the morphological variables and biomass of the sugarcane shows that excess water reduced crop growth. In this research, the total volume of water applied was 1984 mm (403 mm via rainfall), over a 12-month cycle. A deficit or excess of irrigation can cause losses in the number of shoots and tillers and, consequently, impair production (Batista et al., 2015; Brunini & Turco, 2018). Adequate irrigation management is a major factor in the productive response of sugarcane (Silva et al., 2011b, Silva et al., 2012a).

CONCLUSIONS

Understanding the effects of climate factors on growth dynamics and biomass accumulation in sugarcane can add important information for crop management. In this study, a significant correlation was found between microclimate, morphological and biomass variables, with a strong contribution from the intercepted fraction of photosynthetically active radiation, wind speed and soil temperature. The negative correlation with irrigation suggests that excess water impaired the growth dynamics of the crop. The growth of sugarcane is therefore closely related to its ability to intercept radiation, to the wind, thermal regime of the soil and irrigation management.

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