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Tolerance of sugarcane varieties to different levels of water depletion on soil

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Sugarcane is one of the most important crops for Brazilian agribusiness, despite water stress being one of the main limiting factors of growth and productivity. Thus, the objective was to verify if there is variation in the tolerance to water deficit among sugarcane varieties in the soil and climate conditions of Quirinópolis-GO (State of Goiás). The trial was conducted on a Red Latosol, with sugarcane planted in Mar/2019, with 15 buds m^{-1} in an environment with water deficit of 532 mm during the period from May to September. It used randomized blocks, with four repetitions, in a factorial scheme (3x8), with three varieties: CTC4, RB966928 and RB867515, and eight f factors (soil water depletion factor): 0.36, 0.41, 0.46, 0.55, 0.60, 0.72, 0.84, and 0.87. The data were subjected to mean comparison test and quadratic regression. It was observed that the varieties statistically differed when subjected to the same f factor, regarding stomatal conductance-Gs, leaf transpiration-E, and liquid photosynthesis-Lp, reflecting in a penalty on the productivity of culm and sugar, total recoverable sugar content, juice purity, sucrose content in the culm, fiber and culm moisture. The f factor identified for avoiding water stress was 0.50 for RB867515, 0.49 for RB966928 and 0.47 for CTC4.

Key words: Water balance, *Saccharum officinarum*, depletion, water stress index.

INTRODUCTION

Sugarcane stands out in the efficient use of light and water in its biomass production process. Besides being destined for the generation of renewable energy that complements and substitutes petroleum derivatives, it is also food for animals and humans (Anjos et al., 2020). Brazil is the world's largest producer of sugarcane, with 10.04 million hectares (ha), culm average productivity of 76.13 Mg ha^{-1}, 39.35 million tons of sugar and 2.70 billion liters of alcohol. And the state of Goiás is the second largest national producer with an area of 11.33% and 79.80 Mg ha^{-1}, losing in area to São Paulo (50.64% of the area and 79.63 Mg ha^{-1}), and in productivity to Minas Gerais (9.80% of the area and 83.72 Mg ha^{-1}), in the 2019/2020 harvest (Conab, 2020). In the state of Goiás,

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although sugarcane is adapted to temperature and radiation conditions (Casaroli et al., 2019; Anjos et al., 2020), sugarcane fields suffer strong reductions of growth and yield, for soil water depletion, caused by prolonged dry spells and droughts of up to six months - fall and winter (Marin and Nassif, 2013). However, water stress can be avoided or mitigated with the adoption of soil and water conservation practices, genetic improvement, root growth stimulators, hydrogel, production scenario prediction models, and with the use of irrigation. Being the f factor (soil water depletion factor) used in any of these managements, whether in the choice of a variety, the soil water balance or in the prediction of production scenarios (Doorenbos and Kassam, 1994; Vieira et al., 2015). Thus, more specific studies on the soil water depletion factor are needed. Based on climate, crop, and soil data, it is possible to predict the water balance, simulate production scenarios, and define the right time to plant, estimate productivity, and design irrigation systems that are efficient in supplying water to the crop in the long and short term (Doorenbos and Kassam, 1994; Battisti et al., 2012; Marin and Nassif, 2013). However, for greater certainty in the water balance of a cropping system, it is necessary to know to what extent it can reduce soil moisture without compromising the growth, development, and productivity of the evaluated crop. For this, the f factor is used, which indicates the moment to replace soil water without promoting water stress to the crop, that is, it indicates the fraction of water in the soil readily available to the crop (Bernardo et al., 2009; Trentin et al., 2011).

In the soil and climate conditions of the cerrado of Goiás, it is common for sugarcane producers to use the f factor equal to 0.70, that is, soil moisture is replenished when it reduces to 70% of the available soil water capacity (AWC), in the water balance in the system. Others use the f factor based on the recommendation of Doorenbos and Kassan (1994), who define the f factor as a function of crop groups according to their sensitivity to water stress and the maximum evapotranspiration occurring in the crop cycle. Nowadays, Vieira et al. (2015), recommend an f factor between 0.5 and 0.70 for the RB867515 grown in the soil and climate conditions of Jaíba - MG (State of Minas Gerais). Due to these variations in the f factor values for the same crop and the lack of distinction between varieties, there is a need to investigate this factor for the most grown varieties in the region. Machado et al. (2009) observed significant differences in stomatal conductance, leaf transpiration and liquid photosynthesis between two sugarcane varieties and within the same variety when grown without and with water deficit, as reflected in the biometry and dry mass of the culm. Anjos et al. (2020) observed that sugarcane varieties vary according to their water use efficiency for biomass production and industrial yield. Taiz and Zeiger (2013) reported that tolerance to water stress is related to morphological, physiological, biochemical, and metabolic factors. Thicker cuticles prevent water loss by transpiration (Castro et al., 2009). Increase in proline synthesis, superoxide dismutase, catalase, peroxidase, and abscisic acid act as messengers in response pathways in perceiving and acting on growth pathways in situations of water stress and other environmental stressors (Sharma et al., 2011). It is observed that even though there are different tolerance mechanisms to water stress within the same species, there is still no work in the literature that defines an f factor for each variety. With technological advances, the f factor can be determined by relating physiological changes and industrial yield of sugarcane to soil moisture for each variety and cultivation conditions. Therefore, the objective was to assess if there is variation in tolerance to water stress among sugarcane varieties in the soil and climate conditions of Quirinópolis - GO.

MATERIALS AND METHODS

Location and climatic characteristics of the study site

The study was conducted in the experimental field of Usina Boa Vista located in the municipality of Quirinópolis, Goiás (18°34'01" S and 50°26'44" W; and 446 m altitude), respectively, in the 2019/2020 crop year. According to the Koppen classification (Alvares et al., 2013), the local climate is Aw, tropical savanna (dry winter and rainy summer).

Statistical design and treatments

The outlining was in randomized blocks, with four repetitions, in a factorial scheme (3x8), being three varieties of sugar cane (*Saccharum officinarum*): CTC4; RB966928 and RB867515; eight soil water depletion factors (f factor): 0.36; 0.41; 0.46; 0.55; 0.66; 0.72; 0.84; and 0.87. With the combination of the factor levels, 24 treatments were obtained. Each plot was composed of seven seven-meter rows, with two meters between them, totalizing 98 m^2.

Soil identification, corrections, fertilization and physical-hydric analysis

The soil was classified according to the Brazilian Soil Classification System (Santos et al., 2018), as typical Dystrophic RED LATOSOLS (LVd). The correction of acidity, toxic elements, and soil fertility was carried out by the plant. The soil was subsoiled to 0.50 m, and crushed with a toothed roller. Shortly after, 2000 kg ha^{-1} of dolomitic limestone was applied on the surface, raising the base saturation to 50%, and 1000 kg ha^{-1} of agricultural plaster, besides 100 kg ha^{-1} of P_2O_5 in the form of natural phosphate (aiming at correcting phosphate, acidity, and toxic elements), and then incorporated by plowing and harrowing. At planting, 280 to 315 kg ha^{-1} of mineral phosphate fertilizer (MAP) was applied in the area, together with a mixture composed of biozyme (0.250 L), sodium molybdate (0.306 kg) and regent (0.100 g). At the bottom of the planting furrow, 400 kg ha^{-1} of the formulation 08-25-25 (N-P-K) was added. The results of the chemical analysis of the soil was interpreted by the concentration ranges according to criteria proposed by Souza and Lobato (2004) and only for the micronutrient and Fe the criteria proposed by the Goiás Soil Fertility Commission were adopted. For the physical-hydric soil analyses,

Table 1. Soil grain size, particle density (Dp), and soil density (Ds), total porosity (PT), moisture at field capacity (θcc), and at permanent wilting point (θpmp), and the S index (S), along the soil profile. Quirinópolis, 2019.

Layer	Clay	Silt	Sand	Dp	Ds	PT	θcc	θpmp	S
m		g kg^{-1}			g cm^{-3}	%	m^3 m^{-3}		kPa
0.00 - 0.20	707	175	118	2.42	1.08	54.25	0.43	0.28	9.98
0.20 - 0.40	747	133	120	2.91	1.10	52.09	0.41	0.25	6.61
0.40 - 0.60	757	132	111	2.83	1.18	55.11	0.42	0.25	7.13
0.60 - 0.80	737	189	74	2.79	1.09				

Source: Anjos (2022)

deformed and undeformed samples were collected, and the results are presented in Table 1. In which the grain size, particle density, and total porosity were determined (Embrapa 2017). The undeformed samples, collected at depths of 0.00 - 0.20 m; 0.20 - 0.40 m; 0.40 - 0.60 m and 0.60 - 0.80 m, with the aid of volumetric rings of 4.8 cm in diameter and 3.0 cm in height were used for the determination of the density of particles and the water retention curve, at 0; 6; 10; 30; 100; 300; 500 and 1500 kPa tensions, in the laboratory of soil physics at Embrapa Meio-Norte. For this, Richards' pressure chamber with porous plate (Richards 1965) was used. The water retention curves were adjusted based on the mathematical model proposed by Van Genuchten (1980) using the software Soil Water Retention Curve - SWRC, Beta 3.0 version (Dourado-Neto et al., 2000). Immediately afterwards, the moisture at field capacity was determined, corresponding to the inversion point of the curve (S index), and the moisture content at the permanent wilting point at a tension of 1500 kPa.

Installation of monitoring and meteorological elements

Sugarcane varieties planting was on March 11, 2019, using three stems with five vegetative buds, a total of 15 buds per linear meter, in furrows 0.30 m deep. The rows were spaced two meters apart, aiming at facilitating biometric and physiological evaluations throughout the crop cycle, which occurred in the central row of each plot. The harvest occurred on May 21, 2020 (437-day cycle). As the crop was rainfed, the soil water balance considered precipitation as input and crop evapotranspiration as output. To estimate reference evapotranspiration (ETo), Penman-Monteith was used, according to the methodology proposed by Allen et al. (1998). The input data for the model were obtained from an automatic weather station installed about 1 (one) km from the experimental area in both municipalities, which recorded during the tests the average air temperature (Tmed, °C); maximum (Tmax, °C), and minimum (Tmin, °C); relative humidity (RH, %); wind speed (v, m s^{-1}); precipitation (P, mm), and global solar radiation (Rs, MJ m^{-2} day^{-1}).
The crop evapotranspiration (ETc) was obtained by the product of ETc and the crop coefficient (Kc) (Allen et al., 1998). Being the Kc in the regrowth and establishment phase (from zero to 40 days after planting - DAP), was 0.45; in the tillering phase (from 40 to 120 DAP), varying from 0.4 to 1.25; in the full growth phase (from 121 to 305 DAP), 1.25; and in the ripening phase (from 306 to 381 DAP), 0.75, where, from 365 DAP onward, it considered constant and equal to 0.75.

Daily soil moisture recording and determination of factors f

From the 84 DAP, volumetric humidity (θ, m^3 m^{-3}) of the soil profile stratified in layers from 0.20 to 0.20m to 1 (one) m depth was recorded, by EC-5 sensor, every 60 minutes, stored and controlled by a datalogger (Emb50, Decagon), calibrated (Pereira et al.,, 2018). The daily factors f for sugarcane varieties were estimated according to the drying and moistening cycles of the soil throughout the growth and development of the crop. For this purpose, the Equation (Eq.) was used. (4) which was deducted from the Eqs. (1), (2) and (3). Water is easily available (WEA) in mm.

$$\mathrm{WEA} = \mathrm{AWC} * \mathrm{f}$$

So:

$$\mathrm{WEA} = (\theta\mathrm{fc} - \theta\mathrm{crit}) * \mathrm{f}$$

Eqs equaling. (4) and (5) one has:

$$\mathrm{AWC} * \mathrm{f} = (\theta\mathrm{fc} - \theta\mathrm{crit}) * \mathrm{Z}$$

So:

$$\mathrm{f} = \frac{((\theta\mathrm{fc} - \theta\mathrm{crit}) * \mathrm{Z})}{\mathrm{AWC}}$$

Being, θfc the humidity in the field capacity (m^3 m^{-3}); θcrit critical humidity, or humidity recorded by EC5 during the crop cycle (m^3 m^{-3}); and Z the effective depth of the root system (mm); AWC available water capacity (mm); and f the supposed factor of water availability in the soil being tested for sugarcane, dimensional.

The available water capacity in the soil – (AWC, mm) was defined by Equation (5) using the data in Table 3, em que θpwp is the water content in the permanent wilting point. With effective depth of the initial root system of 0.30m and final of 0.60m (Sousa et al.,, 2013; Rossi-Neto et al., 2018). It considered daily root growth, up to 305 DAP, of 0.98 mm day^{-1}.

$$\mathrm{AWC} = (\theta\mathrm{fc} - \theta\mathrm{pwp}) * \mathrm{f}$$

Record of sugarcane water stress indicators

In the analyses of the variables, the reading of liquid photosynthesis (Lp), in μmol CO_2 m^{-2} s^{-1}; stomatal conductance (Gs), in mol m^{-2} s^{-1}; leaf temperature (Tf), in °C; leaf transpiration (E), in mmol H_2O m^{-2} s^{-1}, both in the middle third of the leaf lamina of leaves 1+ (Kuijper 1915), was performed, on 12 tillers and three readings per tiller, totalizing 36 readings in each plot, always between 8 and 12 am. For such, it was used a portable infrared gas analyzer, IRGA (LI-COR), model LI-6400 XT with photosynthetically active radiation (PAR) of 2000 μmol m^{-2} s^{-1}, defined in the field from the light curve. The physiological readings were taken at all stages of growth and development of the crop, being, in tillering: at 84 DAP; in full growth at 124, 164, 201, 247 and 249 DAP; and in maturity at 327 and 375 DAP. The atmosphere leaf temperature gradient (GTFA), in °C, was obtained from the difference between leaf temperature (°C) and air temperature (°C).

Post-harvest analysis

In the post-harvest analyses, at 437 DAP, the plants were harvested from the plots, weighed and the mass in kg m^{-2} determined, from which the productivity per hectare - TCH (Mg ha^{-1}) was stipulated. From these, 10 culms per plot were randomly chosen and taken to the UBV analysis laboratory for the following technological evaluations: sucrose content - POL (%); juice purity - PZA (%); fiber (%); moisture (%); total recoverable sugars - ATR (kg ha^{-1}); and ton of POL per hectare - TPH (Mg ha^{-1}): obtained by multiplying the value of POL by the actual productivity.

Statistical analysis

The data were submitted to variance analysis, using the “F” test, to diagnose significant effects and the qualitative treatments were compared to each other using the Tukey test ($p \leq 0.05$) to assess significant differences. As to the quantitative treatments, they were analyzed using quadratic regression analysis as recommended by Ferreira (2000). The analysis used the software Sisvar 5.7 Build 91 (Ferreira, 2011).

RESULTS AND DISCUSSION

Meteorological conditions of the study site

It is observed that the meteorological conditions recorded during the conduction of the field experiment are favorable for the growth and development of sugarcane (Table 2) (Cardozo and Sentelhas, 2013; Caetano and Casaroli, 2017). With an average air temperature of 24.85°C during the cycle, with an oscillation between 32.54°C and 18.43°C (keeping within the temperature range favorable to the crop, which is 18 to 32°C), global radiation of 7357.36 MJ m^{-2} well distributed throughout the year of cultivation, besides an average relative humidity of 71.42% with lower rates in the months of September, October and November (variation between 59.46 and 48.15%). Furthermore, wind velocity does not exceed 2 m s^{-2}, thus, and relatively, reducing lodging and water loss of the system. Figure 1 shows the relationship between the meteorological components and their interference in the f factor. It can be observed that during the cycle of the sugarcane varieties there was a precipitation of 1838 mm, although sufficient to meet the reference hydric demand of the study environment (1736 mm), it was poorly distributed, concentrated almost exclusively in the months of October/2019 to April/2020 (Figure 1a). Furthermore, during the rainy season (spring and summer), prolonged dry spells of up to 16 days were observed (Figures 1a and 1b). Therefore, the water deficit is evident in both the dry and rainy periods, as can be seen in Figure 1b. For such, it is necessary to know the f factor in order to predict and quantify the losses in sugarcane productivity due to water stress and to evaluate the economic viability of adopting an irrigation system and/or delaying or advancing the planting season of sugarcane, considering that the maturation phase of the crop is favored by water stress. It was observed that the irregularity in precipitation distribution and frequency caused a soil water deficit of 791 mm and an excess of 897 mm throughout the cycle of sugarcane varieties, the dry spells having a deficit of 532 mm (Figure 1b). In this scenario, during the dry spells the restriction in crop evapotranspiration reached a level of 60% (Ks = 0.60), and f factor of 0.87 (Figure 1c). Moreover, there was an inversely proportional relationship between Ks and the f factor, i.e., the lower the AWC level, the greater the restriction in crop evapotranspiration (ETa/ETc). However, to what extent can the f factor increase the restriction in ETc without harming plant growth and development? This response can be found by evaluating the physiological alterations as a function of the f factors and their effects on the biometry, productivity and industrial yield of the crop, which in this case, for sugarcane, will be discussed later on. It is interesting to note that the f factor observed in Figure 1c, on a daily scale and beginning at 85 DAP, and allows for its correlation with the response variables of the sugarcane varieties at the same time, space and soil and climate conditions under study. With this, it was possible to create a model that made it possible to identify the exact moment when the plant started to be penalized by the water stress caused by the reduction of the water storage capacity in the soil - AWC.

Effect of the f factor on physiology

During the cycle of cane varieties it was verified that the f factor influenced the behavior of physiological variables. In which stomatal conductance - Gs (Figure 2c), liquid photosynthesis - Lp (Figure 2c) and leaf transpiration - E (Figure 2b), are the most sensitive to soil water depletion (Figure 2), and which showed significant differences among themselves ($P<0.5$) by the mean comparison test (Tukey). This result is related to the interactions of these variables among themselves and with the other metabolic pathways that rule crop maintenance, growth, and production (Machado et al., 2009; Zarco-Tejada et al., 2012; Taiz and Zeiger, 2013). It was verified that the atmosphere leaf temperature gradient - GTFA, the intrinsic water use efficiency - EUA_I and the water use efficiency - EUA of the varieties: RB966928, RB867515 and CTC4 did not differ statistically by the mean comparison test (Tukey, $p<0.05$), among themselves when submitted to the same f factor (Figure 2a, 2e and 2f). The similarities in responses among the sugarcane varieties are related to the common characteristics among them, such as the high sensitivity of Gs and E to soil water depletion (being $EUA_I = Lp/Gs$ and $EUA = Lp/E$), and the enzyme complex such as Rubisco

Table 2. Maximum temperature (Tmax), mean (Tmed), minimum (Tmin), global radiation (Rs), mean relative humidity (Ur), and wind speed (V), during the sugarcane crop cycle. Quirinópolis - GO, Brazil, 2019/2020 crop.

Month	Tmax (°C)	Tmed (°C)	Tmin (°C)	Rs (MJ m^{-2})	Ur (%)	V (m s^{-1})
March	33.08	26.02	21.46	616.08	83.31	0.34
April	32.34	25.43	21.64	506.51	85.98	0.33
May	32.19	25.38	20.43	351.00	79.78	0.97
June	31.96	24.91	19.57	438.40	78.90	0.74
July	30.56	23.11	16.41	427.50	76.50	1.21
August	30.11	21.43	12.69	408.90	68.24	1.26
September	29.84	20.93	11.52	428.00	59.46	1.47
October	32.37	23.88	14.75	483.50	53.25	1.80
November	37.22	28.00	19.01	533.80	48.15	1.92
December	35.58	27.50	20.59	577.60	60.38	2.00
January	34.30	26.57	20.91	533.72	72.01	1.43
February	32.28	25.48	20.67	593.10	82.76	0.34
March	33.38	26.12	20.96	618.11	76.54	0.27
April	31.69	24.94	19.71	511.04	76.54	0.25
May	30.46	22.48	16.32	330.20	73.38	0.17
Cycle	32.54	24.85	18.43	7357.46	71.42	0.99

Source: Anjos (2022)

Table 3. Mathematical-physiological model for predicting the penalty in the physiological variables promoted by the water availability factor in the soil, and equation indicating the moment when the losses by water deficit begin (f factor), of three sugarcane varieties (Var). Quirinópolis - GO, Brazil, 2019/2020 crop.

Var	Equation	R^2	$f = -b/(2*a)$	CV %
RB 966928	$GTFA = 50.829f^2 - 53.248f + 14.869$	0.85*	0.52	22.51
	$E = -10.196f^2 + 11.151f$	0.85*	0.55	8.78
	$Gs = -1.137f^2 + 1.0526f$	0.68*	0.46	4.93
	$Lp = -123.86f^2 + 122.04f$	0.89*	0.50	3.48
	$EUA_I = -409.8f^2 + 672.92f - 102.74$	0.86*	0.82	3.15
	$EUA = -33.136f^2 + 36.388f$	0.73*	0.55	6.69
RB 867515	$GTFA = 46.847f^2 - 49.091f + 14.212$	0.79*	0.52	21.33
	$E = -10.975f^2 + 11.835f$	0.80*	0.54	6.95
	$Gs = -1.1624f^2 + 1.0707f$	0.76*	0.46	3.20
	$Lp = -116.03f^2 + 115.99f$	0.77*	0.49	5.18
	$EUA_I = -423.79f^2 + 689.44f - 105.96$	0.92*	0.81	5.31
	$EUA = -34.144f^2 + 36.849f$	0.70*	0.54	8.16
CTC 4	$GTFA = 48.315f^2 - 49.697f + 14.257$	0.91*	0.51	22.11
	$E = -14.112f^2 + 14.199f$	0.72*	0.50	9.23
	$Gs = -1.4715f^2 + 1.3208f$	0.75*	0.45	4.22
	$Lp = -155.67f^2 + 147.7f$	0.85*	0.47	7.12
	$EUA_I = -701.23f^2 + 1041.2f - 211.54$	0.85*	0.74	5.37
	$EUA = -35.318f^2 + 38.105f$	0.70*	0.54	11.28

R^2 = Coefficient of determination; f = water availability factor in the soil, a and b are the coefficients of the equations; temperature gradient leaf atmosphere - GTFA (°C), leaf transpiration - E (mmol H_2O m^{-2} s^{-1}), stomatic conductance - Gs (mol H_2O m^{-2} s^{-1}), liquid photosynthesis - Lp (μmol CO_2 m^{-2} s^{-1}), intrinsic efficiency in water use - EUA_I (μmol mol^{-2}), and efficiency in water use - EUA (mmol mol^{-2} s^{-1}); CV = percentage margin of error of the values estimated by the equations (coefficient of variation).
Source: Anjos (2022)

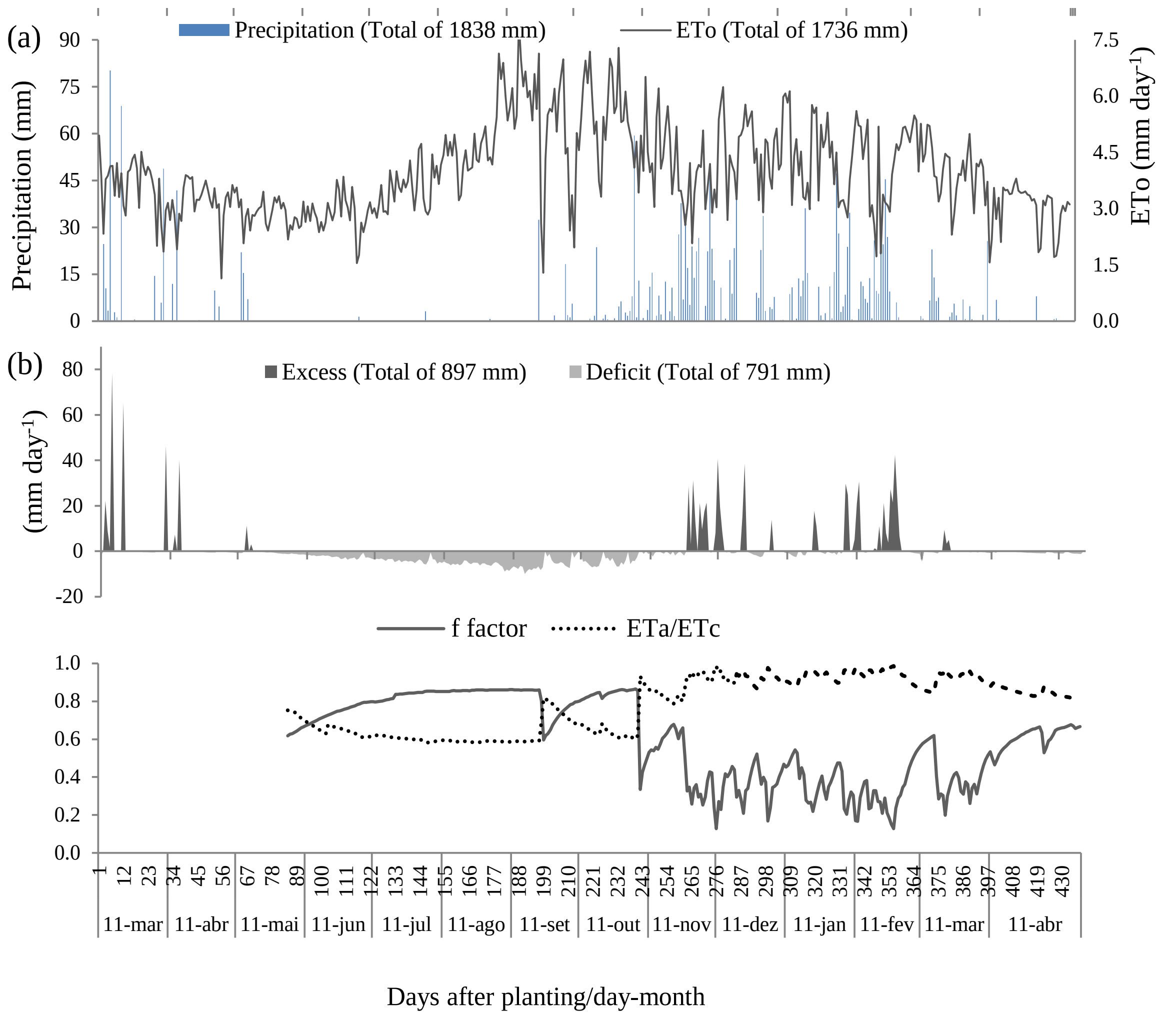

Figure 1. Relationship between water input and output, excess and deficit, and the soil water availability factor and soil moisture coefficient - Ks (ETa/ETc), during the sugarcane crop cycle. Quirinópolis - GO, Brazil, 2019/2020 crop. Source: Anjos (2022)

(ribulose-1,5-bisphosphate carboxylase) and PEPcase (phosphoenolpyruvate carboxylase) have the same limitations at high temperature - GTGA (Figure 2b and 2c), GTFA is related to its effect on enzymes common among varieties, as well as EUA_I (Lp/Gs) the high sensitivity of Gs to water deficit (Figure 2c), and EUA (Lp/E) which relates Lp to Gs. This result corroborates with Machado et al. (2009), who evaluated the EUA_I of IACSP 94-2094 and IACSP 96-2042 submitted to conditions without and with soil water deficit, and found no significant difference between them at 115 DAP. When evaluating the statistical unfolding of the variables of each variety within the same f factor it was found that Gs, E and Lp differed statistically among themselves ($p<0.05$), when submitted to the same f factor, and that the CTC4 is the most sensitive to the variation of soil dryness (Figure 2). These results explain those found by Campos et al. (2014), and Anjos et al. (2020) that verified significant difference between RB966928, RB867515 and CTC4, under water restriction condition, in the variables EUA, productivity and industrial yield. These results, unlike the GTAF, EUA_I and EUA, point to the need to identify an f factor for each of the sugarcane varieties under study. Something that will be done soon after evaluating the behavior of sugarcane (average of the values of the varieties) against the variation of the f factors (Figure 3). Figure 3 shows the mathematical-physiological model; the f factor that indicates the point of inversion of the curve, that is, the true f factor for sugarcane, which is the moment when the plant initiates water stress; the observed data and their respective standard deviations; and also the trend line that describes the behavior of each of the responding variables to the f factors. It was found that Gs are the most sensitive, and that f factors above 0.46 started to limit the plant's gas exchange. However, the reduction in

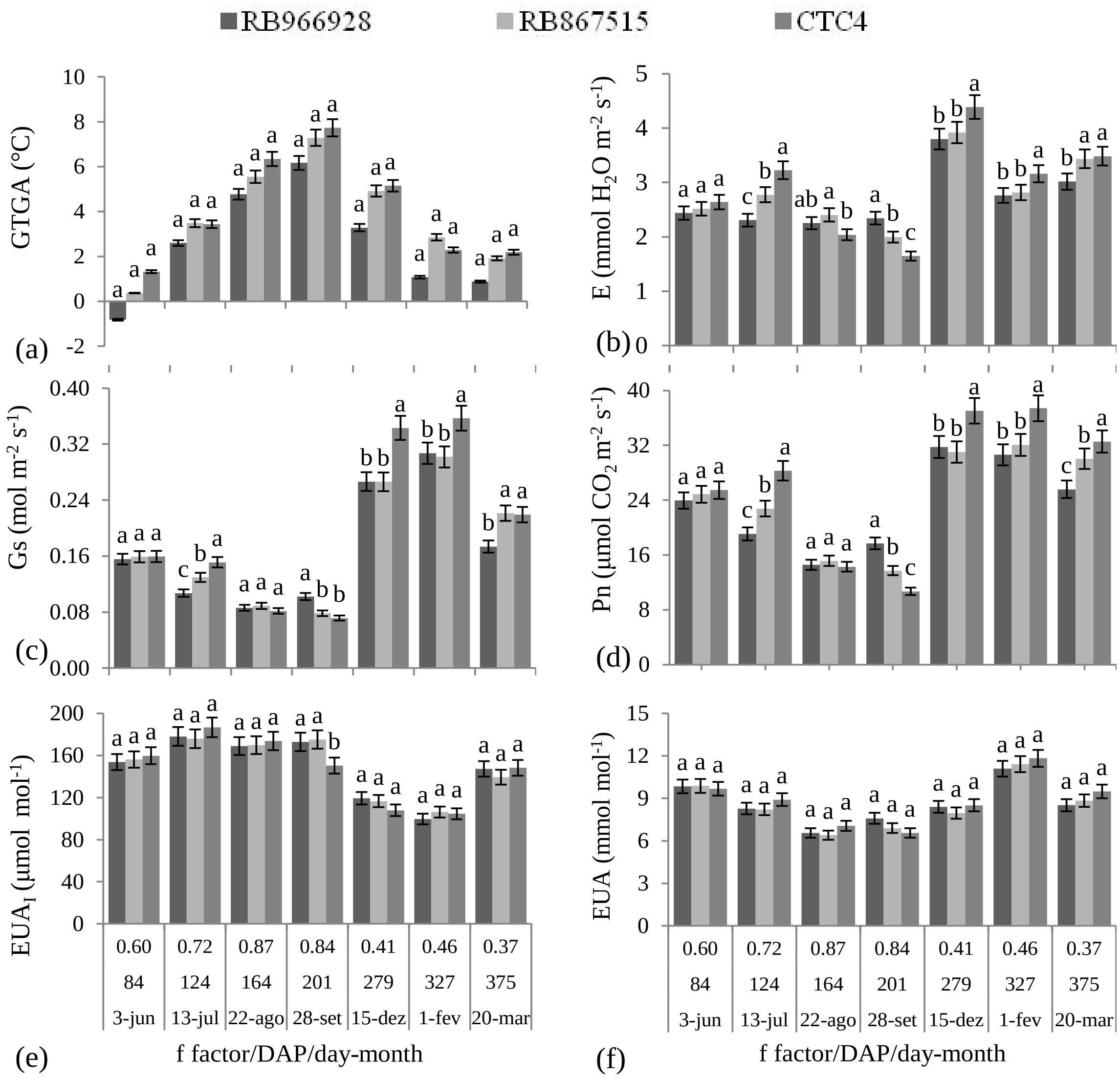

Figure 2. Atmosphere leaf temperature gradient - GTFA, leaf transpiration - E, stomatal conductance - Gs, liquid photosynthesis - Lp, intrinsic water use efficiency - EUA_I, and water use efficiency - EUA (respectively in Figure a, b, c, d, e and f), from three sugarcane varieties as a function of different soil water depletion factors (f factor) and days after planting (DAP). Quirinópolis - GO, Brazil, 2019/2020 crop. Bars, with their respective standard errors, in the same factor and with the same letters do not differ statistically ($p < 0.05$) from each other by Tukey's test. Source: Anjos (2022)

Gs only began to affect Lp when the f factor reached a magnitude of 0.49. At this moment the Lp starts to suffer limitation, and, with it, a reduction of photo-assimilates for growth, development and productivity of the crop. Gonçalves el al. (2010) evaluated, in a greenhouse, the responses of four varieties of sugarcane (SP79-1011, RB72454, RB98710 and RB92579) subjected to water deficiency during the initial stage of vegetative growth, and observed that water stress reduced stomatal conductance in some varieties without altering the liquid photosynthesis rate of sugarcane varieties.

In Figure 3, it was verified that GTFA and EUA_I are directly proportional to the f factor, while the other physiological variables decrease with the increase of f factor. Being that the increase in GTFA is due to the reduction of stomatal opening caused by water stress, and consequent limitation of Gs and E, and with it, of heat dissipation by the plant. According to García-Tejero et al. (2011) and Zarco-Tejada et al. (2012) the main response of plants to the depletion of soil water is the closure of stomata and the reduction of leaf transpiration, a fact that conditions the gradual increase of leaf temperature. It was found that when the f factor reaches 0.52 the GTFA starts to increase significantly, and, with this, it starts to add to the limitation of Gs in the punishment of Lp (Figure 3a). If soil moisture is not

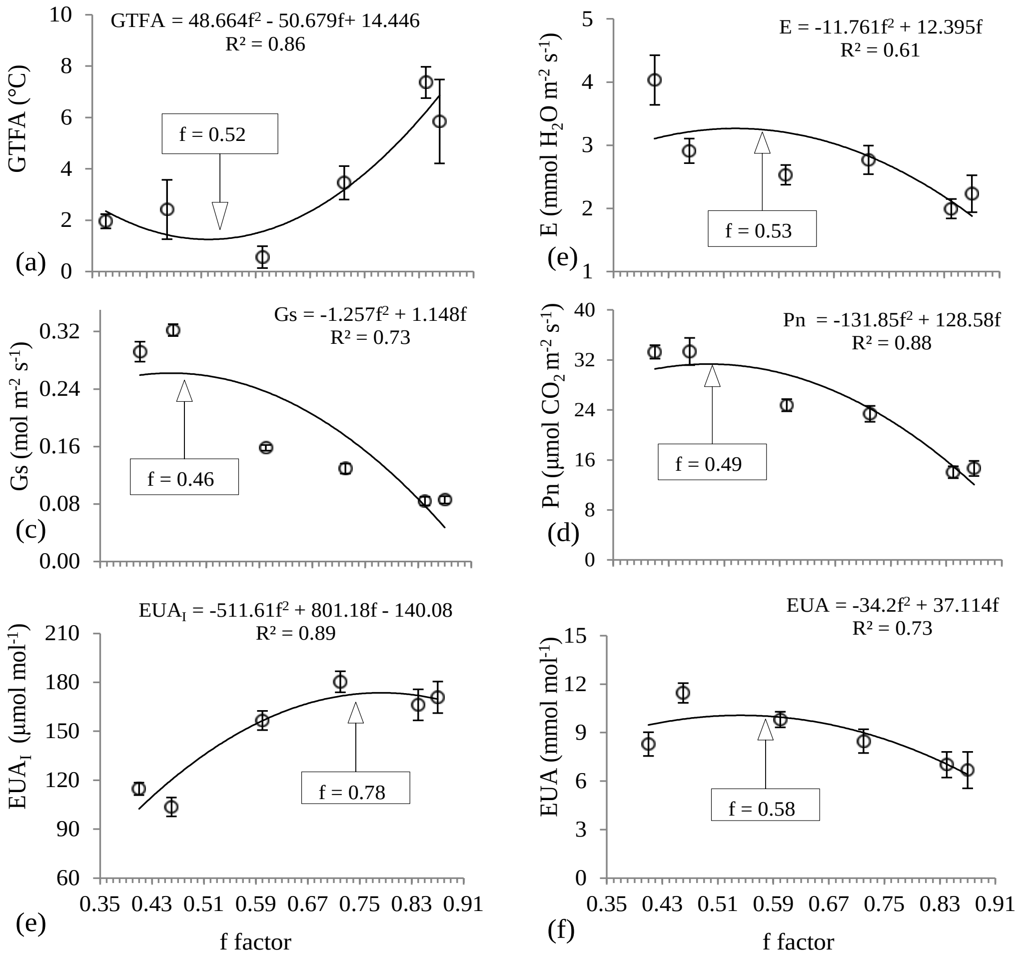

Figure 3. Atmosphere leaf temperature gradient - GTFA, leaf transpiration - E, stomatal conductance - Gs, liquid photosynthesis - Lp, intrinsic water use efficiency - EUA_I, and water use efficiency - EUA (respectively in Figure a, b, c, d, e and f), from three sugarcane varieties as a function of different soil water depletion factors (f factor). Quirinópolis - GO, Brazil, 2019/2020 crop.
Source: Anjos (2022)

restored, AWC will reach 53% (f 0.53), limiting E, and at 58% (f 0.58), EUA, and last and least sensitive the stomatal conduction efficiency (EUA_I), when AWC reduces to 78% (f 0.78) (Figure 3b, 3f and 3e). Furthermore, it is observed that, as the f factor increases, the joint effect of the other physiological variables in limiting the photosynthetic process intensifies and adds up, due to the fact that the sensitivity to water stress is different among them, a fact verified by the different f factors observed for each physiological variable evaluated. It was observed that, in Figure 3, an average f factor of the varieties was presented, aiming to elucidate their behavior in sugarcane physiology without distinction between varieties. However, in Figure 2, it was found that the varieties differed statistically within the same f factor, making it necessary to define an f factor for each variety and not a single one for all, as presented in Figure 3. Table 3 shows an f factor for each sugarcane variety, the mathematical-physiological models for estimating the f factor penalty, the model's precision (R^2), and the average percent error margin (CV). Being the quadratic model the best fit for all variables studied, with precision ranging from 0.68 to 0.68; and relative standard deviation around the mean ranging from 22.51 to 3.15%. Still, Table 3 shows that CTC4 was more sensitive to soil moisture depletion in all the variables analyzed, when compared to RB966928 and RB867515. This result indicates that CTC4 needs more frequent soil water replenishment, since Gs began its reduction with an factor of 0.45 and soon began to affect Lp (f factor of 0.47). The other sugarcane varieties only began to suffer limitations in their photosynthesis when the f factor was 0.49 for RB867515 and 0.50 for RB966928.

Table 4 shows the applicability of the f factor determined in this study for the three most widely cultivated sugarcane varieties in Brazil, according to varietal sense (RIDESA, 2018). In this simulation it was found that as the f factor increases the combined effect of

Table 4. Applicability of the mathematical-physiological models determined for three sugarcane varieties. Quirinópolis - GO, Brazil, 2019/2020 crop.

Var	Equação	F	Penalizing	Lp	PLp	PLpr
			Physiological variables	µmol CO_2 m^{-2} s^{-1}		%
RB 867515	$Lp = -116.03f^2 + 115.99f$	0.50	Gs = Lp	28.99±1.5	0	0
		0.52	Gs+GTFA	28.94±1.5	0.05	0.16
		0.55	Gs+GTFA+E	28.70±1.5	0.29	1.01
		0.55	Gs+GTFA+E+EUA	28.70±1.5	0.29	1.01
		0.58	Gs+GTFA+E+EUA	28.24±1.5	0.75	2.57
		0.60	Gs+GTFA+E+EUA	27.82±1.4	1.16	4.02
		0.70	Gs+GTFA+E+EUA	24.34±1.3	4.65	16.04
		0.82	Gs+GTFA+E+EUA+EUA_I	17.09±0.9	11.89	41.03
RB 966928	$Lp = -123.86f^2 + 122.04f$	0.49	Gs = Lp	30.06±1.0	0	0
		0.52	Gs+GTFA	29.97±1.0	0.09	0.31
		0.54	Gs+GTFA+E	29.78±1.0	0.28	0.92
		0.54	Gs+GTFA+E+EUA	29.78±1.0	0.28	0.92
		0.58	Gs+GTFA+E+EUA	29.12±1.0	0.94	3.14
		0.60	Gs+GTFA+E+EUA	28.63±1.0	1.43	4.75
		0.70	Gs+GTFA+E+EUA	24.74±0.9	5.32	17.71
		0.82	Gs+GTFA+E+EUA+EUA_I	16.79±0.6	13.27	44.15
CTC 4	$Lp = -155.67f^2 + 147.7f$	0.47	Gs = Lp	35.03±2.5	0	0
		0.50	Gs+E	34.93±2.5	0.10	0.28
		0.51	Gs+E+GTFA	34.84±2.5	0.19	0.55
		0.54	Gs+E+GTFA+EUA	34.36±2.4	0.67	1.90
		0.58	Gs+GTFA+E+EUA	33.30±2.4	1.73	4.95
		0.60	Gs+GTFA+E+EUA	32.58±2.3	2.45	7.00
		0.70	Gs+GTFA+E+EUA	27.11±1.9	7.92	22.61
		0.82	Gs+GTFA+E+EUA+EUA_I	16.44±1.0	18.59	53.07

Water availability factor in soil - f; temperature gradient leaf atmosphere - GTFA; leaf sweating - E; stomatic conductance - Gs; liquid photosynthesis - Lp and its respective standard deviation; intrinsic efficiency in water use - EUA_I; efficiency in water use - EUA; absolute photosynthesis loss - PLp; relative liquid photosynthesis loss - Lpr.
Source: Anjos (2022)

physiological variables on Lp penalty increases. Also, the absolute (PLp) and relative (PLpr) penalty of Lp is presented, and the Lp with their respective standard deviations obtained by the product between the value of Lp estimated by the equation and the coefficient of variation (CV) (Table 3). Table 4 shows that although RB867515 presents a higher tolerance to soil water depletion, observed by the fact that it starts losing Lp with a f factor higher than the other varieties (f factor 0.50), thus, as a lower loss with the increase of f factors when simulated with the same values, it presented a lower potential in Lp production. Furthermore, in the simulation with the f factors 0.60; 0.70; and 0.82, common for the three sugarcane varieties, the maximum penalty in Lp was 41.03% in RB867515. In RB966928 and CTC4, the maximum penalties were 44.15 and 53.07%, respectively. These results place CTC4 as the variety with the highest Lp rate (35.03±2.5 µmol CO_2 m^{-2} s^{-1}), when grown without water stress, however, it was the most sensitive to water depletion in the soil. Table 4 shows that due to the fact that CTC4 presented the highest Lp at the lowest f factors when cultivated without water stress, it tended to present higher productivity than the other varieties. However, as the f factor increases its Lp rate tends to reduce in greater proportion than RB966928 and RB867515, achieving penalty of Lp in f factor 0.82; of 8.92 and 12.04% higher than RB966928 and RB867515, respectively. Table 4 observed that instead of adopting the f factor 0.47 for CTC4 and opting for f 0.60 the penalty on Lp productivity will be only 7%. In the most water deficit tolerant variety (RB867515), when adopting f 0.60 instead of f 0.50 the PLpr will be only 4.02%. However, quantifying the impact on productivity and industrial yield of the crop is needed, something that will be done later on.

Throughout the study, it was observed that as the f factor increases the crop evapotranspiration reduces and the production of photo-assimilates. However, for project

Table 5. Ton of culm per hectare (TCH), ton of POL per hectare (TPH), total recoverable sugars (ATR), juice purity (PZA), sucrose content (POL), fiber and culm moisture of three sugarcane varieties. Quirinópolis - GO, Brazil, 2019/2020 crop.

Variety	TCH	TPH	ATR	PZA	POL	Fibre	Moisture
	Mg ha^{-1}		kg Mg^{-1}	%			
RB867515	153.7^{a}	24.8^{a}	136.6^{a}	85.1^{a}	16.2^{a}	12.3^{a}	71.8^{a}
RB966928	142.7^{ab}	21.5^{a}	130.4^{a}	82.9^{a}	15.0^{b}	11.9^{b}	72.7^{b}
CTC4	116.2^{b}	16.1^{b}	118.2^{b}	81.6^{b}	13.8c	11.7^{c}	73.9^{c}
Average	137.5	20.8	128.4	83.2	15.0	12.0	72.8
DMS	27.3	5.1	9.5	1.7	1.0	0.1	0.9
CV %	9.2	11.3	3.4	2.2	3.3	1.6	2.6

Lines with the same lowercase letter do not differ statistically ($p < 0.05$), among themselves by Tukey's test. DMS-V = significant minimum difference; CV = coefficient of variation.
Source: Anjos (2022)

designers and irrigators the following question arises: which f factor provides the best cost-benefit? If an f factor higher than that indicated for the variety is used, there will be a saving in total water consumption, due to the restriction in evapotranspiration. However, it will be necessary to increase the blade per irrigation, and, with it, the flow rate of the system and the power of the motor pump, or to increase the irrigation time (lower AWC), increasing the consumption of electrical energy and the initial cost of the irrigation project. Vieira et al. (2015), investigated the effect of the f factor on sugarcane grown in the soil and climate conditions of Jaíba - MG, and observed that if the irrigation management opts for the f factor of 0.70 instead of 0.50 (reference value), there would be a 17% reduction in water consumption, and if the option is to use the f value of 0.9, the reduction would be 40%.

Reflex of the f factor in the industrial yield of the varieties

Table 5 shows the contrast between the culm productivity - TCH, and the industrial yield of RB966928, RB867515 and CTC4 in response to the soil and climate conditions in which they were grown. There was a significant difference between varieties observed by the Tukey test ($p<0.05$), in all analyzed variables. The TCH of RB867515 was 153.7 Mg ha^{-1}, and even though it was statistically equal to RB966928 (142.7 Mg ha^{-1}), it was higher than CTC4 (116.2 Mg ha^{-1}) (Table 5). The TPH and ATR of RB867515, however, were higher than those from CTC4, but statistically equal to RB966928. These results corroborate the simulations of liquid photosynthesis productivity using the physiological equations presented in Table 4. Considering that the cultivars were subjected to about five months of water stress, a fact verified by observing the depletion of water in the soil presented in Figure 1 and the f factor determined in this research and observed in Figure 3 and Table 3. Campos et al. (2014), evaluated the TCH, in irrigated cultivation with replacement of 50% of the crop water requirement, and observed that RB867515 (154.98 Mg ha^{-1}), was superior to CTC4 (140.68 Mg ha^{-1}) and RB966928 (130.26 Mg ha^{-1}). The same authors observed similar behavior for TPH (variation from 18 to 16 Mg ha^{-1}) and ATR (from 128 to 118 kg Mg^{-1}). As for PZA, they found a variation of 85.1 to 81.6%. Being RB867515 statistically equal to RB966928 and higher than CTC4. As for the POL (from 16 to 13.9%), and fiber (from 12.3 to 11.7%), it was observed that RB867515 had the best performance, RB966928 was intermediate and CTC4 had the worst performance, however, with moisture (from 71.8 to 73.9%), higher than the other varieties. It is important to report on the importance of further studies to evaluate the variation of the f factor between the different phenological phases of the crop. This study was limited to the phase of full growth and final tillering (84 to 327 DAP), which coincided with the entire dry spells and the beginning of the rainy season. However, these were the Crop phases and period of the year when sugarcane demanded water replacement the most (Figure 1a and 1b).

Conclusion

Sugarcane fields suffer strong penalties for soil water depletion, caused by prolonged dry spells and droughts of up to six months - fall and winter. Sugarcane varieties present different levels of tolerance to soil water depletion. Additionally, when subjected to the same soil water depletion, they respond differently in terms of physiology and industrial yield. Thus, the soil water depletion factors to avoid water stress were: 0.50, 0.49 and 0.47, for RB867515, RB966928 and CTC4, respectively.

CONFLICT OF INTERESTS

The authors have not declared any conflict of interests.

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