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How agrometeorological and water deficit variations influence the growth and yield of sugarcane

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Abstract

Edaphoclimatic variables play a crucial role in shaping both the growth and yield of sugarcane. This study aimed to evaluate the intricate relationships among plant variables, agrometeorological factors, and water stress conditions in three successive crop cycles of sugarcane (cane plant, ratoon 1, and ratoon 2). The investigated plant variables included stem height, stalk diameter, number of tillers, leaf area, leaf area index, and stalk fresh yield, alongside growth rates (growth/time). Concurrently, climate variables, such as air temperature, humidity, rainfall, wind speed, solar and net radiation, reference evapotranspiration, and degree-days, were monitored. Additionally, water stress parameters, including water deficit and water surplus, were quantified. Statistical models were skillfully fitted ($r^2 > 0.90$) to the biometric data, employing thermal time as a critical determinant. Surprisingly, no adverse agrometeorological or soil moisture conditions, as indicated in the literature, were detected when growth rates started to decline. This suggests that other unmeasured stress factors may have influenced the plants during that period. The analysis of the ratio between actual and maximum crop evapotranspiration (ETa/ETc) revealed the most pronounced sensitivity to water deficit during the vegetative growth phase (phase III). Moreover, the study identified that growth achieved satisfactory levels when at least 60% of the maximum crop evapotranspiration was met during the initial phases. A comprehensive cluster analysis encompassing height, leaf area, leaf area index, relative air humidity, soil moisture, and actual evapotranspiration rates provided valuable insights into the interrelated dynamics of these variables. Furthermore, a significant exponential reduction in yield was observed as the number of harvests increased. This decline in yield was attributed to the combined effects of 50% of biometric variables, 63% of agrometeorological variables, and 50% of water stress variables, all of which exhibited negative correlations with yield. Approximately 82%, 63%, and 71% of the correlations among biometric, agrometeorological, and water stress variables, respectively, were strong or very strong ($r \geq 0.70$). As a result, this study highlights that: i) estimating sugarcane growth and tracking its developmental stages can be accomplished by employing appropriate models based on thermal time; ii) most biometric measurements exhibit correlations of $r < 0.70$ with agrometeorological variables; iii) an integrated understanding of biometric, agrometeorological, and water stress variables can effectively explain the observed reductions in sugarcane yield.

Keywords: *Saccharum* spp., biometric, water balance, yield decline, crop management.

Abbreviations: DAP_days after planting; DAC_days after cutting (or harvest); H_stem height; D_stalk diameter; T_number of tillers; LA_leaf area; LAI_leaf area index (LAI, $m^2\ m^{-2}$); Y_yield; Tmax, Tmin and Ta_maximum, minimum, and average air temperatures; R_rainfall; RH_relative air humidity; u_wind speed at 2 m height; Rs_solar radiation; Rn_net radiation; ETo_reference evapotranspiration; ETc_crop evapotranspiration; ETa_Actual evapotranspiration; Kc_crop coefficient; DD_degree-days; Tb_lower basal temperature; TB_upper basal temperature; ∑DD_thermal time; AC_average climate, which is the average of at least 30 years of observations; TAW_total available water; RAW_readily available water; WS_water surplus; WD_water deficit; θ_l_water content limited.

Introduction

Sugarcane, cultivated in over a hundred countries worldwide, holds significant importance due to its versatile products. These products encompass sugar, a vital food energy source, as well as renewable energy sources like ethanol (biofuel) and biomass (used for electricity and biogas production) (Bressanin et al., 2021; Hughes et al., 2020; Soto et al., 2021). In 2020, Brazil (757.1 million Mg), India (370.5 million Mg), and China (108.6 million Mg) were the largest sugarcane producers. However, they ranked lower in yield, with Brazil in 24th place (75.6 Mg ha^{-1}), India in 21st place (77.3 Mg ha^{-1}), and China in 19th place (79.4 Mg ha^{-1}). In contrast, Peru (123.7 Mg ha^{-1}), Senegal (114.2 Mg ha^{-1}), and Guatemala (112.9 Mg ha^{-1}) achieved the highest averages, with the global average being 73 Mg ha^{-1} (FAO, 2021). Within Brazil, São Paulo State emerges as the primary producer (4.3 million ha and 342,614.3 Mg), followed by Goiás State (943.3 thousand ha and 75,273.7 Mg). São Paulo boasts a higher average yield (75.8 ± 6.7 Mg ha^{-1}) compared to Goiás (70.9 ± 11.7 Mg ha^{-1}) (IBGE 2021). Despite its leading production, Brazil's yield significantly lags behind the top-ranking countries, warranting investigation into the limiting factors affecting crop growth and yield in the Brazilian Savanna biome, which includes Goiás State (Durigan and Ratter, 2016).

Various factors influence sugarcane yield, such as climatic conditions, planting methods, row spacing, and farm management practices (Chiluwal et al., 2018; Flack-Prain et al., 2021). Being a crop that thrives in hot and humid climates, sugarcane requires an average air temperature between 19°C and 32°C and well-distributed rainfall throughout its growth cycle, with a water demand exceeding 1000 mm $year^{-1}$ (Marin and Nassif, 2013). Dry periods can hinder sugarcane development (Elsayed-Farag et al., 2018), leading to yield losses of up to 60% depending on the severity and duration of water deficits. To overcome this, irrigation and locally adapted varieties are highly recommended (Liu et al., 2016). Some varieties cultivated in Brazil demand an average of 8.3 and 7.6 L $plant^{-1}$ day^{-1} for the cane and ratoon cycles, respectively (Antunes et al., 2021). Additionally, a dry period before harvesting, known as "drying-off," enhances industrial production efficiency by increasing sugar content (Cardozo et al., 2015).

Another crucial agrometeorological aspect affecting sugarcane's industrial yield is the number of negative degree-days, as low temperatures tend to elevate the stalk sucrose content (Araújo et al., 2016). Goiás State experiences considerable variation in climatic conditions and soil water availability across different regions (Jardim et al., 2023), thereby influencing sugarcane's biochemical, physiological, and morphological characteristics, consequently affecting growth and yield during both cane-plant and ratoon cycles (Paixão et al., 2020; Menezes et al., 2022). Therefore, studying crop growth behavior in the field, addressing each phenological phase and crop cycle, becomes essential in devising strategies that optimize growth and yield in accordance with surrounding environmental conditions (*e.g*., agrometeorological variables and water availability). This knowledge can provide society with accurate and transparent forecasts, offering early warnings in case of unfavorable conditions, and thereby mitigating price volatility that often impacts major food commodities (OECD and FAO, 2015). The present study aims to evaluate and quantify the impacts of agrometeorological variables and water stress on sugarcane growth and yield, considering different phenological phases and crop cycles.

Results

Agrometeorological relationships for sugarcane development

The mean maximum air temperature (Tmax: 29.6 °C) and average air temperature (Ta: 23.9 °C) remained within the lower (Tb = 20 °C) and upper (TB = 35°C) basal temperature range for sugarcane throughout the three cultivation cycles (cane plant, ratoon 1, and ratoon 2). However, the mean minimum temperature values (Tmin: 18.1 °C) fell below Tb, except for sprouting (ratoons 1 and 2) and tillering (ratoon 2) phases, where temperatures exceeded Tb (Figure 1A). Additionally, the average air temperature during the experiment was higher than the average climate (≥30 years) for all three cultivation cycles (cane plant: 3.1%; ratoon 1: 4.3%; ratoon 2: 6.3%), with an average overestimate of 0.05 °C per °C. The mean relative humidity (RH) ranged between 60% to 65% for all three cycles (Figure 1A). The average solar radiation for the cane plant, ratoon 1, and ratoon 2 cycles was 17.5, 16.4, and 15.9 MJ m^{-2} day^{-1}, respectively (Figure 1B). Accumulated rainfall (R) values were 1923.6, 1390.2, and 1168.0 mm, respectively, for the cane plant, ratoon 1, and ratoon 2 cycles (Figure 1B), resulting in daily averages of 4.01, 4.34-, and 3.65-mm day^{-1}. Rainfall depths varied with the phenological phase in each cultivation cycle. The cane plant showed higher R rates in phase IV (2.27 mm day^{-1}), while ratoon cycles 1 and 2 had the highest R rates in phase III, with values of 2.88- and 2.01-mm day^{-1}, respectively. Rainfall was on average 9.2% higher than CN for the cane plant cycle, but it was 12.9% and 29.9% lower than CN for ratoon cycles 1 and 2, respectively, with an overestimate of 0.12 mm per mm^{-1} (cane plant), and underestimates of 0.08 and 0.2 mm per mm^{-1} (ratoon 1 and ratoon 2, respectively).

Another important variable studied was thermal time, which accumulated to 2148.4 °C day (rate: 4.48 °C day day^{-1}), 1616.4 °C day (rate: 5.05 °C day day^{-1}), and 1621.1 °C day (rate: 5.07 °C day day^{-1}) during the cane plant, ratoon 1, and ratoon 2 cycles, respectively (Figure 1C).

The average wind speed did not show significant differences between cycles or phases, with average values ranging from 0.8 to 2.2 m s^{-1}.

Sugarcane water balance exhibited periods of daily water deficit and surplus within the crop cycles and phases (Figure 2A). The water requirement as a function of ETc for the cane plant, ratoon 1, and ratoon 2 cycles was 1906.05, 1326.73, and 1054.96 mm, respectively. Daily water requirement rates were observed as 3.48, 3.48-, and 3.01-mm day^{-1}, respectively, for the cane plant, ratoon 1, and ratoon 2 cycles. These values allowed us to determine the ETa/ETc ratio, which showed little numerical difference between their means (cane plant: 0.58; ratoon 1: 0.56; ratoon 2: 0.57), but with greater differences between phenological phases within the same cycle, as well as for the same phase between cycles (Figure 2A). Notably, the ETa/ETc ratio was < 0.5 during approximately 43% of the time for all three cultivation cycles, indicating that the soil moisture only met 50% of the water demand. When evaluating the phases, for the cane plant cycle, phases III and IV had ETa/ETc < 0.5 for 55% and 46% of the time, respectively. For the ratoon 1 cycle, the phases with the highest percentages were phase I (83%) and IV (97%). The ratoon 2 cycle obtained the highest percentage of ETa/ETc < 0.5 in phase IV (95%), followed by phase III (42%). Additionally, some values of volumetric soil water content were lower than the limiting water content (θ_l: 0.2956 m^3 m^{-3}) (Figure 2B), with percentage times of $\theta < \theta_l$ equal to 39%, 44%, and 46% in the cane plant, ratoon 1, and ratoon 2 cycles, respectively (Figure 2C).

Within each phase, the cane plant cycle showed higher percentages of $\theta < \theta_l$ within phases III (48%) and IV (44%), while ratoon 1 had higher percentages (100% of the time) within phases I and IV. For ratoon 2, the highest percentages occurred within phase IV (96%), followed by phase III (37%) (Figure 2B). The accumulated values of water surplus (WS) for the cane plant, ratoon 1, and ratoon 2 cycles were 916.8, 792.1, and 642.9 mm, respectively, with rates of 1.67, 2.08-, and 1.84-mm day^{-1}, respectively (Figure 2). Water deficit (WD) values were equal to 816.8, 721.4, and 537.72 mm, with rates of 1.49, 1.89-, and 1.54-mm day^{-1}, respectively. Notably, the ratoon 1 cycle had the highest rates of both WS and WD (Figure 2A). Furthermore, for the cane plant, ratoon 1, and ratoon 2 cycles, the highest accumulated values of

WD occurred in phase IV (417.3, 537.0, and 304.4 mm, respectively), followed by phase III (374.2, 120.9, and 203.9 mm, respectively). This same sequence occurred for the cane plant cycle regarding the accumulated values of WS (phase IV: 549.7 mm; phase III: 231.2 mm). However, in the ratoon 1 and ratoon 2 cycles, the highest accumulated WS occurred in phases III (ratoon 1: 548.8 mm; ratoon 2: 437.0 mm) and II (ratoon 1: 243.4 mm; ratoon 2: 179.1 mm). When comparing cycles and phases, the highest WS rates occurred in phases I (3.22 mm day^{-1}) for the cane plant, and in phase II for ratoon 1 (4.87 mm day^{-1}) and ratoon 2 (3.58 mm day^{-1}). On the other hand, the highest WD rates occurred in phase III for the cane plant (2.1 mm day^{-1}), and in phase IV for ratoon 1 (4.44 mm day^{-1}) and ratoon 2 (3.38 mm day^{-1}).

Biometric variables were evaluated as a function of the thermal time within each phase and cycle and from their growth rates (Figure 3). All variables, in all cycles, had their values adjusted to mathematical models of the sigmoid or exponential type ($r^2 > 0.90$ and significant parameters with $p > 0.0001$).

The cane plant cycle had the maximum height (H = 4.1 m) and diameter (D = 0.0336 m) values. The highest growth rates for both height and diameter occurred in the ratoon 1 cycle (H_R = 0.005 m day^{-1}; $D_R = 4.98 \cdot 10^{-5}$ m day^{-1}). The highest average values in the three cycles occurred within phase III (cane plant: H_R = 0.0025 m day^{-1}; $D_R = 1.32 \cdot 10^{-5}$ m day^{-1}; ratoon 1: H_R = 0.0067 m day^{-1}; $D_R = 3.07 \cdot 10^{-5}$ m day^{-1}; ratoon 2: $D_R = 1.14 \cdot 10^{-5}$ m day^{-1}), except for height rates of the ratoon 2 cycle, which were higher in phase II (H_R = 0.0038 m day^{-1}) (Figure 3A and B).

The number of tillers per linear meter (T) tended to decrease throughout the cycle, with its highest values occurring in the initial phases (Figure 3C). The ratoon 1 cycle had the highest tillering values (T = 25.0 tillers m^{-1}), followed by the cane plant (T = 23.2 tillers m^{-1}) and ratoon 2 cycles (T = 18.3 tillers m^{-1}). The highest rates of decrease occurred in the ratoon 2 cycle (0.009 tillers m^{-1} day^{-1}) (Figure 3C). The maximum values of leaf area (LA) and leaf area index (LAI) occurred in ratoon 1, with values of 11.5 m^{-2} m^{-1} and 7.7, respectively. The ratoon 2 cycle had intermediate values for these variables (LA = 11.2 m^{-2} m^{-1}; LAI = 7.4), and the cane plant cycle had the lowest averages (LA = 8.2 m^{-2} m^{-1}; LAI = 5.5) (Figure 3C). Growth rates for both variables followed the same trend (ratoon 1: LA_R = 0.0171, LAI_R = 0.0113; ratoon 2: LA_R = 0.0104, LAI_R = 0.0069; cane plant: LA_R = 0.0025, LAI_R = 0.0017) (Figure 3C).

The agrometeorological and biometric results provided insights into the surrounding conditions affecting sugarcane growth. The moment when growth rates started to decrease after reaching their maximum value was also identified. For both the cane plant and ratoon cycles, the rates started to decrease in phase III, except for the number of tillers, which decreased in rates within phase I (Figure 4).

Principal component analysis (PCA) showed no significant difference between cultivation cycles (cane plant, ratoon 1, and ratoon 2) (Figure 5A). The first two dimensions or PCAs explained 50.83% of those relationships (Figure 5B). Biometric variables such as height, leaf area, and leaf area index, and the agrometeorological variable relative humidity (RH) showed the highest values for the two dimensions. Conversely, agrometeorological variables (WDac, Tamp, Tmax, Rs) exhibited negative values for both dimensions, indicating that while one group of variables increased, the other decreased and vice versa (Figure 5B). Cluster analysis for these variables formed groups consisting of either biometric variables or agrometeorological and soil moisture variables (Figure 5C). An exception was the group formed by the variables height (Hr), leaf area (LAr), leaf area index (LAIr), relative air humidity (RH), ETa/ETc, soil moisture (θ), and ETa (Figure 5C).

Sugarcane yield

We found an overestimation of the yield data obtained in the experimental plots compared to the data obtained by the sugarcane mill. This comparison was made using a 1:1 line, and despite the overestimation, the statistical indices indicated a suitable relationship (Figure 6A). The average yield for the three cultivation cycles in the experimental plots (Yo = 85.7 Mg ha^{-1}) was higher than the average values for the mill (Yr = 77.3 Mg ha^{-1}), Santo Antônio de Goiás city (SA = 78.6 ± 1.5 Mg ha^{-1}), and Goiás State (GO = 70.9 ± 11.7 Mg ha^{-1}) (Figure 6B). The mill data fell within the variability (±σ) for both SA and GO (Figure 6C). On average, Yo was 9.8%, 8.3%, and 17.2% higher than the mill, SA, and GO yields, respectively (Figure 6D).

The yields of the cane plant, ratoon 1, and ratoon 2 cycles showed positive correlations with 50% of the biometric and water stress variables and 36.4% of the agrometeorological variables (63.6% of negative correlations). Furthermore, 81.8% of the positive or negative correlations of yield with biometric variables were strong or very strong, with $r \geq 0.70$ (Figure 7A).

The correlation between sugarcane yields and agrometeorological variables revealed that 65% of the positive values and 62.9% of the negative values had $r \geq 0.70$ (Figure 7B). Regarding the correlations between yields and water stress variables, 81.2% of the positive values and 71.4% of the negative values showed $r \geq 0.70$ (Figure 7C).

Discussion

Physiological processes in sugarcane vary over time and are influenced by the phenological phases, including sprouting, tillering, growth, maturation, and sometimes flowering. The duration of each phase primarily depends on the crop cycle, either one-year or one-and-a-half-year sugarcane. Sprouting typically lasts from 30 to 60 days, tillering from 60 to 90 days, growth from 180 to 210 days, and maturation from 60 to 90 days (Dinardo-Miranda et al., 2010; Jadoski et al., 2011). These findings are consistent with the field results of the present study (Figure 3). While literature reports a sigmoidal behavior of sugarcane growth, particularly in height, as a function of days after harvests (Segato and Carvalho, 2018), the present study observed this behavior concerning thermal time (Figure 3).

Identifying patterns of stalk growth is crucial as this variable exhibits a strong positive correlation with sugarcane yield (Carlin et al., 2008). Previous research on Brazilian sugarcane varieties (SP79-1011, RB93509, and RB931530) during the cane plant and ratoon cycles revealed distinct height rates during specific phenological phases: phase I (establishment, from 0 to 160 DAP) with rates between 0.2 and 0.9 cm day^{-1}, phase II (linear growth, from 160 to 270 DAP) with rates > 0.9 cm day^{-1}, and phase III (maturation, from 270 to 365 DAP) with rates < 0.2 cm day^{-1} (Almeida et al. 2008). Furthermore, other studies on RB varieties (Oliveira et al., 2005) reported an average stalk elongation rate of approximately 1.8 cm day^{-1} during the period of high growth of the cane plant. The authors attributed the decline in elongation rate to increased self-shading during maturation,

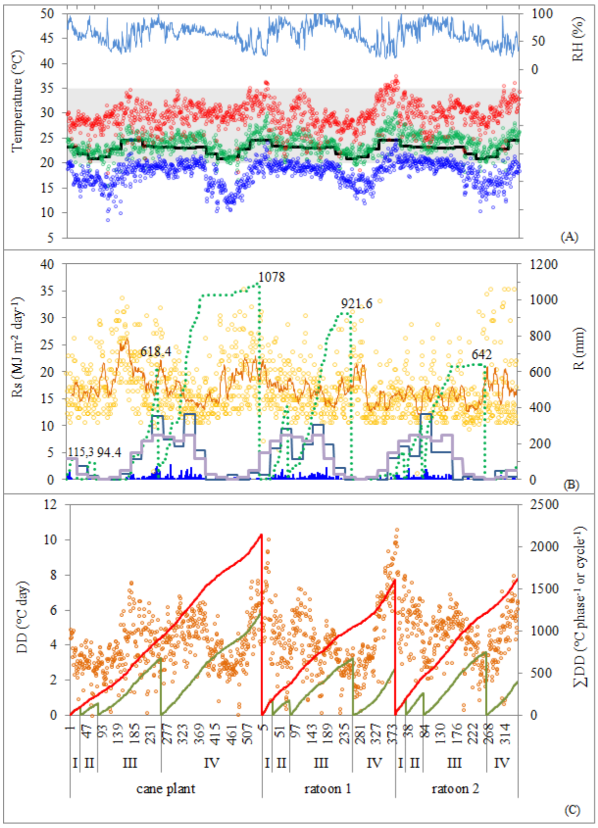


Figure 1. Maximum (red circle), minimum (blue circle), and average (green circle) air temperature, average climate of monthly air temperature (black solid line), and relative humidity (RH, %) (blue solid line). The gray band represents the extreme values of lower (Tb = 20 °C) and higher (TB = 35 °C; Pereira et al., 2015a) basal temperature for sugarcane (A). Solar radiation (Rs; yellow circle), weighted average of Rs for 15 days (orange solid line), daily rainfall (blue column), accumulated rainfall per sugarcane phase (green dotted line), accumulated rainfall per month (solid dark blue line), average climate of monthly rainfall (solid light blue line) (B). Degree-days (DD; orange circles), thermal time per sugarcane phase (green solid line) and per sugarcane cycle (red solid line) (C). The arrows indicate the maximum accumulated values per phase (I: sprouting; II: tillering; III: vegetative growth; IV: ripening; Allen et al. (1998)) and per cycle.

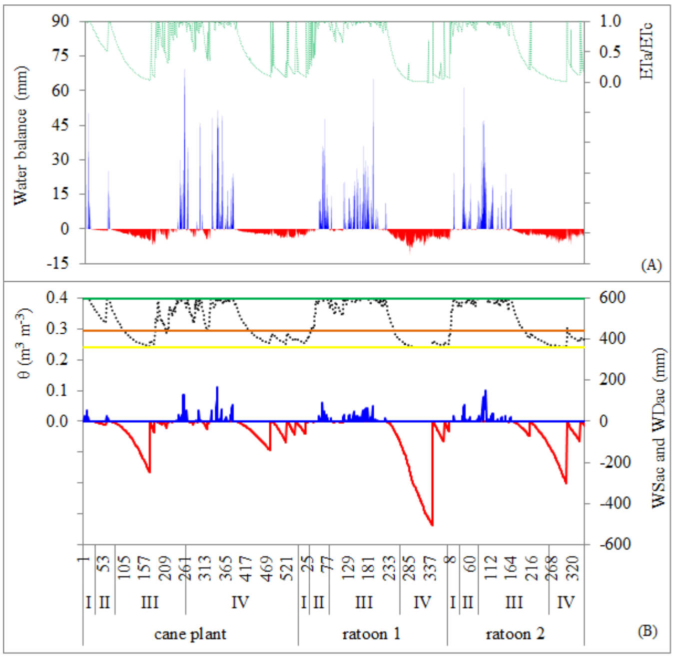


Figure 2. The sugarcane water balance shows the water surplus [blue area] and water deficit [red area] depth per day (mm day^{-1}), as well as the ratio between the actual and maximum crop evapotranspiration (ETa/ETc) [green dotted line] (A). Also, the variation in soil water content (θ, m^3 m^{-3}) [black dotted line] and the accumulated water deficit (WDac, mm) [red solid line] and water surplus (WSac, mm) [blue solid line], from the last value of water deficit or surplus equal to zero. Green-, orange-, and yellow-filled lines represent water content at field capacity (0.399 m^3 m^{-3}), at the limiting point (0.2956 m^3 m^{-3}), and at the permanent wilting point (0.24 m^3 m^{-3}), respectively (B). All variables depend on the cycle, phenological phase, and days after planting.

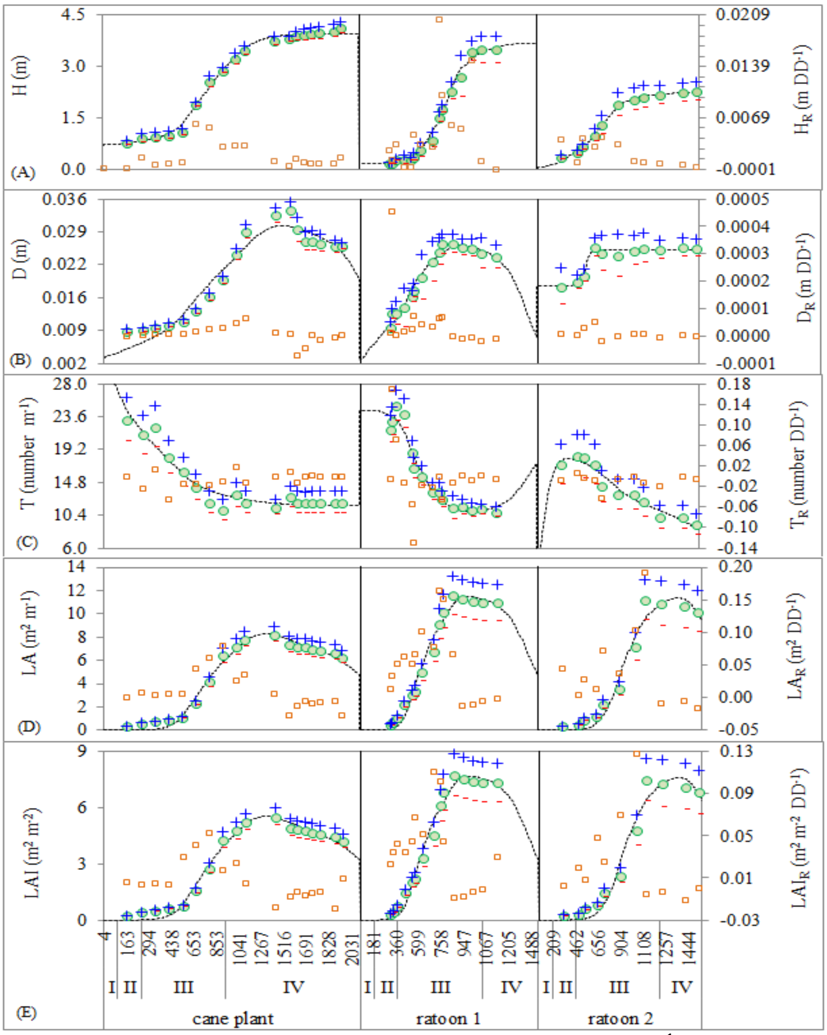
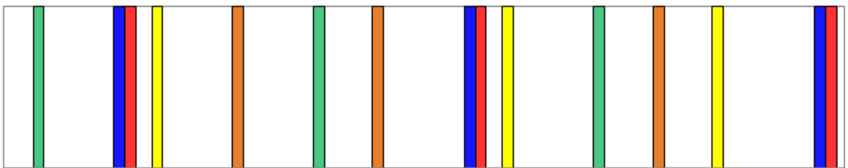


Figure 3. Height (H, m) (A) and diameter (D, m) (B) of stalks, number of tillers (T, number m^{-1}) (C), leaf area (LA, m^2 m^{-1}) (D), and leaf area index II, m^2 m^{-2}) (E) [green circles] as a function of the cycle, phenological phase (I: sprouting; II: tillering; III: growth; IV: ripening (Allen et al. 1998), and thermal time (∑DD, °C day) for the sugarcane crop, as well as their respective standard deviations for plus (**+**) and for less (**-**) and the daily growth rates [orange square], where the same acronyms were used plus the subscript "R", representing the "rate". Estimates for each of the variables [black dotted line] were obtained from equations adjusted as a function of thermal time ($r^2 > 0.9$; significant parameters with $p > 0.001$).



WDac	0.0	0.0	1.4	4.1	19.3	3.5	0.1	0.0	0.0	0.1	0.0	21.0
θ	0.3990	0.2895	0.3568	0.3463	0.2627	0.3586	0.3929	0.3990	0.2859	0.3921	0.3832	0.3155
S_0	95.4	29.7	70.1	63.8	13.6	71.2	91.8	95.4	27.5	91.3	85.9	45.3
Rac	0	360.4	434.6	434.6	0	511.2	668	1143.2	28	786.6	930.2	1088.2
∑DD	4.4	751.5	787.1	797.2	18.8	509.8	637.0	821.4	62.6	556.1	681.7	950.8
DAP	1	215	225	227	3	107	136	189	7	107	133	185
Date	4/1/13	11/1/13	11/11/13	11/13/13	10/3/14	1/15/15	2/13/15	4/7/15	10/23/15	1/31/16	2/26/16	4/18/16
Phase	I	III			I	III			I	III		
Cycle	cane plant				ratoon 1				ratoon 2			

Figure 4. Moments when the inflection points occurred in the growth functions, in which the rates started to decrease after reaching their maximum values, for the biometric variables: height (yellow column) and diameter (orange column) of stalks, tillers (green columns), leaf area (blue columns), and leaf area index (red columns). The analysis considered the following boundary conditions at each inflection point: cycle, development phase, date (month/day/year), days after planting (DAP), thermal time accumulated so far (∑DD, °C day), rainfall accumulated so far (Rac, mm), water storage at the moment (S_0, mm), volumetric water content at the moment (θ, m^3 m^{-3}), and accumulated water deficit so far, from the last value equal to zero (WDac, mm).

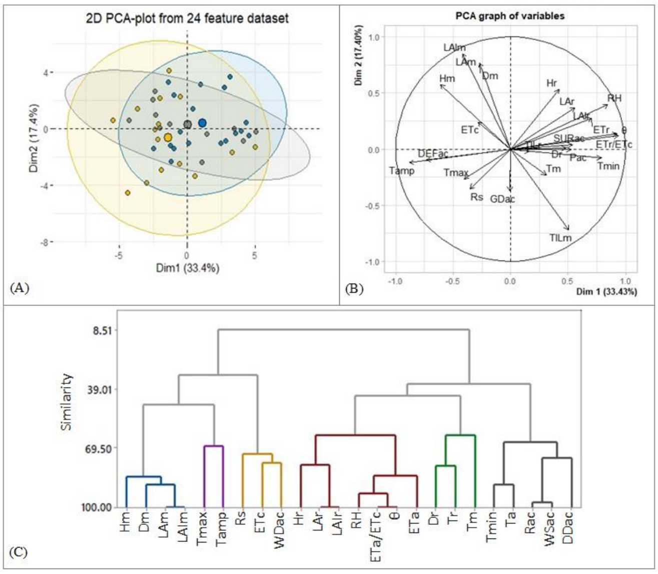


Figure 5. Principal component analysis (PCA) for the biometric variables of mean height (Hm) and its rate (Hr), mean diameter (Dm) and its rate (Dr), mean nIr of tillers (Tm) and its rate (Tr), mean leaf area (LAm) and its rate (LAr), mean leaf area index (LAIm) and its rate (LAIr); and agrometeorological variables of maximum, minimum, and average air temperature (Tmax, Tmin, Ta, respectively), thermal amplitude (Tamp), accumulated rainfall (Rac), solar radiation (Rs), relative humidity (RH), degree-days accumulated (DDac), crop evapotranspiration (ETc), actual evapotranspiration (ETa) and ETa/ETc ratio, accumulated water deficit and surplus (WDac and WSac, respectively), and soil volumetric moisture (θ) for the three sugarcane cycles (cane plant [●], ratoon 1 [●], and ratoon 2 [●]). Analysis of the two main components for the crop cycles (A). Principal Component Analysis (PCA) graph of the variables under study (B). Dendrogram of variables with greater similarity 50% (C).

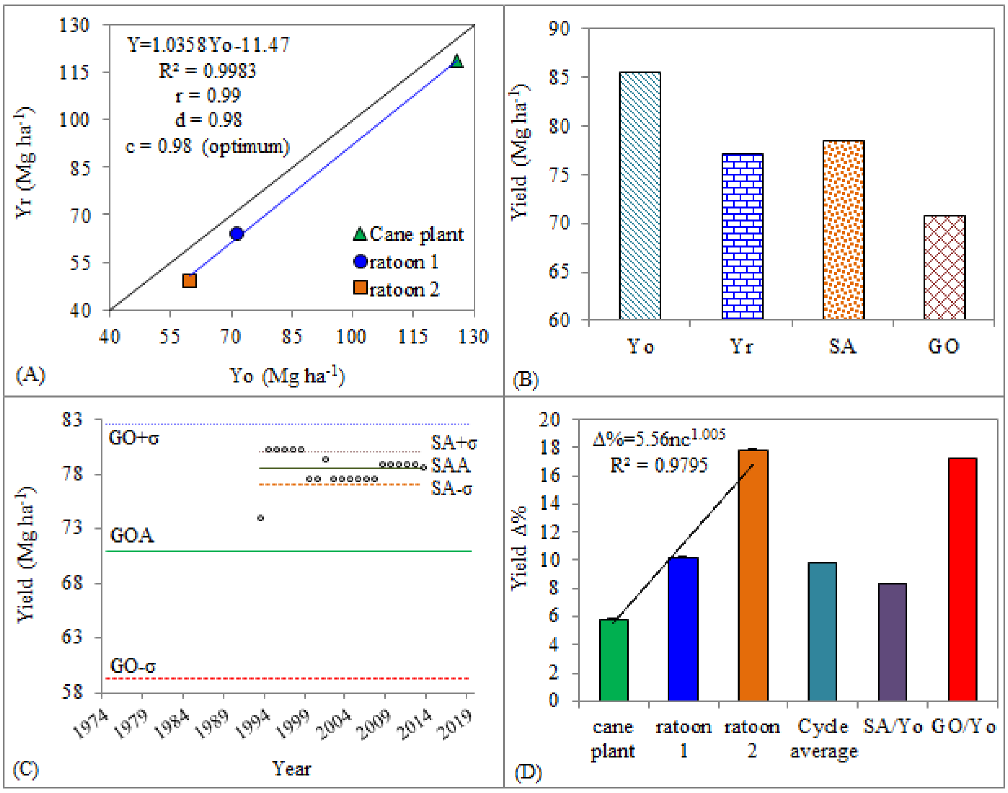


Figure 6. Regression analysis, determination I) and correlation (r) coefficients, Wilmott index (d) and "c" index, between the actual yield (Yr; sugarcane mill average) and the yield obtained in the experiment (Yo) for the cane plant, ratoon 1, and ratoon 2 cycles (A). Average yield from the three cultivation cycles obtained in the experiment (Yo) and in the sugarcane mill (Yr), as well as the yield averages for Santo Antônio de Goiás city (SA) and Goiás State (GO) (B). Average yield for Goiás State (GOA) and their respective standard deviations for plus (GO +σ) and for less (GO -σ), and average yield for Santo Antônio de Goiás city, from the historical series 1993-2013 (○), as well as its mean (SAA) and standard deviations for plus (SA +σ) and for lesss (SA -σ) (C). Percentage differences between Yo and Yr for the cane plant, ratoon 1, and ratoon 2 cycles (green, blue, and orange bars); between Yo and Yr averages of the cycles (cycle average, dark green); SA and Yo (purple bar); GO and Yo (red bar) (C). *nc = number of cuts. Source: Average yield data for Santo Antônio de Goiás city and Goiás State, Brazil (IBGE 2021).

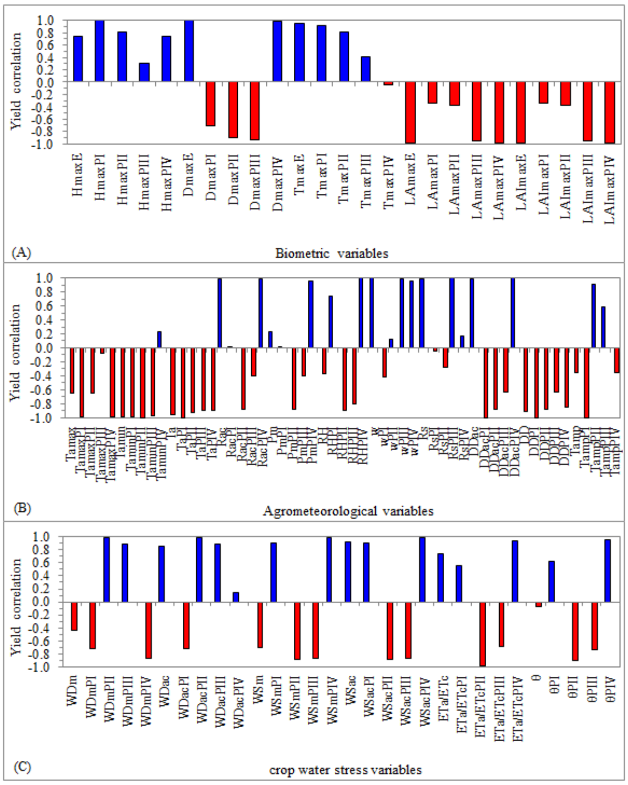


Figure 7. Pearson's "r" correlation analysis between the yield of the three cultivation cycles (cane plant, ratoon 1, and ratoon 2) and biometric variables (E: estimated by the models described in Table S4; see Supplementary Material), agrometeorological variables (averages per cycle; ac: accumulated per cycle or per phase; m: daily average), and plant water stress variables (averages per cycle; ac: accumulated per cycle or per phase; m: daily average); obtained both by cycle and by phenological phases (Phase I: PI; Phase II: PII; Phase III: PIII; Phase IV: PIV). Hmax: maximum stalk height; Dmax: maximum stalk diameter; Tmax: maximum number of tillers; LAmax: maximum leaf area; LAI: maximum leaf area index; Tamax, Tamin, and Ta: maximum, minimum, and average air temperature, respectively; Rac: accumulated rainfall; w: average wind speed; Rs: average solar radiation; DDac: accumulated degree-days; Tamp: thermal amplitude.

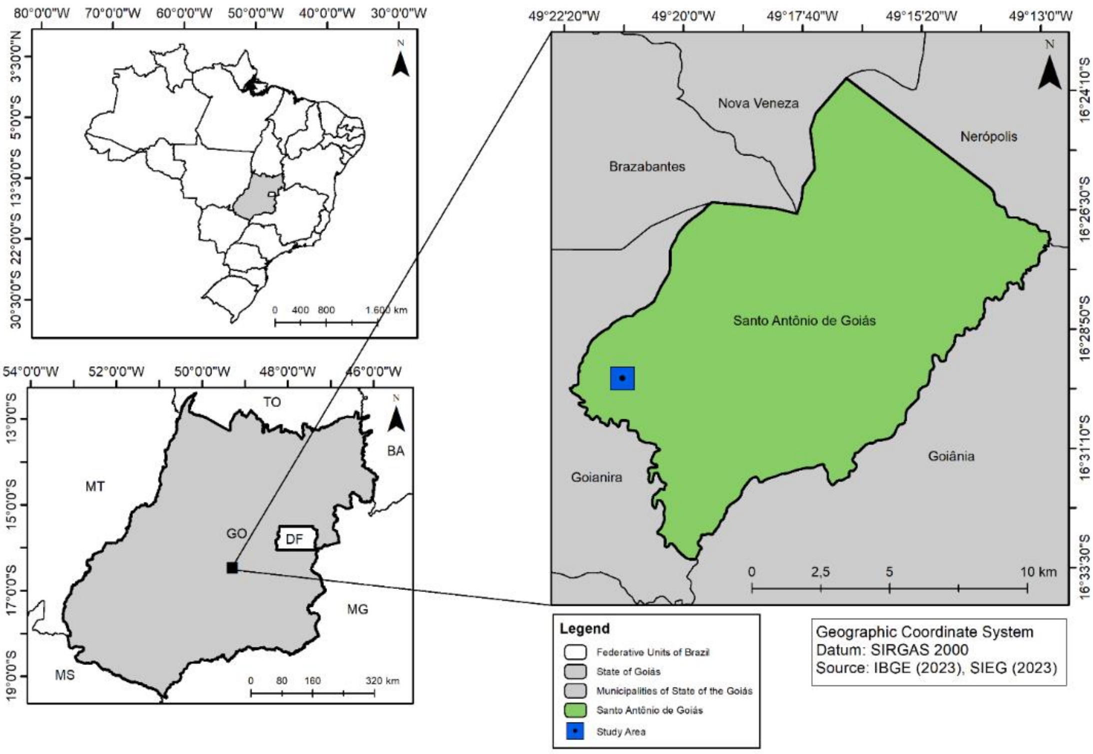


Figure 8. Location of the study area within the municipality of Santo Antônio de Goiás, in the state of Goiás (GO), Brazil.

leading to a decrease in the average photosynthetic rate of the entire leaf area. In our study, these rates were calculated based on thermal time, and when converted to days after planting or harvest, the mean values of daily height rates were comparable to those reported in the literature, but with higher values in phase III, across all cycles. Additionally, both stem diameter (Oliveira et al., 2010) and leaf area index (Santos et al., 2009) demonstrated rapid growth between 60-90 DAC, stabilizing after 120 DAC. These results are in line with the present study, where the highest stem diameter growth rates were observed within phase III (Figure 3). This decline in growth rates could be attributed to the accumulation of water deficit during phase III, with depths exceeding 65 mm (Figure 2), which was sufficient to hinder sugarcane growth (Inman-Bamber, 1994, 2004; Inmam-Bamber and Smith, 2005).

Research in Goiás State, Brazil, conducted cluster analysis based on rainfall, maximum and minimum air temperatures, dividing the territory into four homogeneous regions. The study classified Santo Antônio de Goiás with the lowest rainfall depth (1431 mm) and the second highest averages of minimum (18.4 °C) and maximum temperature (30.1 °C) (Paixão et al., 2020). This combination of factors could lead to increased water deficit, resulting in decreased transpiration (gas exchange) and ultimately contributing to yield losses (Caetano and Casaroli, 2017; Dias and Sentelhas, 2018; Anjos et al., 2020). This could explain why Santo Antônio de Goiás city is grouped among cities with intermediate yield, ranking 4th (46.4 ± 10.8 Mg ha^{-1}) among a total of eight groups (Paixão et al., 2020).

Studies have highlighted the strong correlation between thermal time and the accumulation of negative degree-days with the yield of different sugarcane cycles (Casaroli et al., 2019). For complete establishment, the sugarcane crop requires approximately 200 °C day, with the thermal time until the end of the vegetative phase (phase III) being equal to 1000 °C day, marking the start of the maturation phase (Scarpari, 2004). These values align with those observed in the present study.

Some studies have investigated the relationship between thermal time and the appearance of tillers, noting divergences between cane plant cycles (> tillering: 800 °C day; stabilization: 1600 °C day) and ratoon cycles (> tillering: 350 °C day; stabilization: 600 °C day) (Almeida et al., 2008). In the present study, the highest number of tillers occurred at thermal times of 166.3, 371.8, and 488.7 °C day, stabilizing after 797, 779, and 897 °C day for the cane plant, ratoon 1, and ratoon 2 cycles, respectively (Figure 3).

Adequate water availability during establishment and vegetative growth is essential for achieving high sugarcane yields in terms of both biomass (35% reduction) and sucrose yield (25% reduction in soluble solids) (Inman-Bamber and Smith, 2005; Machado et al., 2009). Water deficit during the vegetative period can lead to reductions in stalk elongation by 60%, stem diameter by 55 to 75% (Ecco et al., 2014), and leaf area index by 50% (Santos, 2018).

Paixão et al. (2020) categorized Goiás State, Brazil, into five groups based on total water availability (TAW), ranging from 0-50 mm to 150-250 mm, with higher depths associated with higher yields. However, one exception was Santo Antônio de Goiás city (the location of the present study), which, despite being classified within the highest TAW range (Group 5: 150-250 mm), did not exhibit the highest yields (46.4 ± 10.8 Mg ha^{-1}), falling below the Brazilian average of 74.7 Mg ha^{-1} (FAO 2021). The present study (TAW = 95.4 mm) recorded an average ETa/ETc ratio of 0.57 between the three cultivation cycles, with an average yield of 85.7 Mg ha^{-1} in the experimental plots (Figure 6B). Inman-Bamber (2004) established that a water deficit exceeding 120 mm affects stalk biomass accumulation, while a deficit surpassing 145 mm affects sucrose accumulation. In our study, the accumulated soil water deficit during the vegetative growth phases (I, II, and III) for the three cycles was below 145 mm, which likely contributed to similar plant growth results across different cycles (Figure 3). However, the varying yields can be attributed to the common observation that sugarcane yield tends to decline with successive harvests (Bernardes et al., 2008; Casaroli et al., 2019).

Irrigation presents a viable option to achieve higher sugarcane yields, even when meeting only 50% of the water needs of the plants, with certain varieties exhibiting higher water use efficiency (Anjos et al., 2020). Economic indicators reveal that full irrigation of sugarcane is more profitable than irrigation meeting 50% of the water requirement (30% less profitable) and rescue irrigation (80 mm during sprouting) (50% less profitable) (Pereira et al., 2015b).

A study by Araújo et al. (2016) on the same variety (CTC-04) in the same region as our study (Goiás State) reported average yields of 170 Mg ha^{-1} during the cane plant cycle when irrigation met 50% of the water demand of the plants. It is worth noting that the rainfall during our experimental period also fulfilled, on average, 50% of the water requirements for all three cycles evaluated, with an ETa/ETc ratio of approximately 0.57 (Figure 2). Studies conducted with Brazilian varieties from the RB group (RIDESA: https://www.ridesa.com.br/) did not show significant differences in stalk fresh yield (SFY, Mg ha^{-1}) during the cane plant cycle, with values ranging between 76 and 102 Mg ha^{-1}. However, SFY values were significantly lower (65-95 Mg ha^{-1}) during the ratoon cycle (2nd cut or harvest). The authors attributed this yield decrease to greater water deficit (544 mm at 210 DAP), with a substantial portion of the deficit (181 mm) occurring within 80 days before the harvest of the first crop. This situation adversely affected ratoon sprouting, and the remaining deficit (363 mm) occurred during the initial 130 days of crop development (Abreu et al., 2013). Our study also revealed yield reductions between the cane plant and ratoon 1 cycles (from 125.8 to 71.5 Mg ha^{-1}), with the largest accumulated water deficits observed in phases III and IV (374.2 and 417.3, respectively), in the cane plant cycle (Figure 6).

Planting date has been found to significantly influence sugarcane yield (Paixão et al., 2021). In our study, sugarcane planting occurred on April 01, falling within the period recommended by the agricultural zoning of climate risk of the Ministry of Agriculture, Livestock, and Supply of Brazil (ZARC-MAPA: http://indicadores.agricultura.gov.br/zarc/index.htm).

Recent studies utilizing the FAO Agroecological Zone model to simulate sugarcane planting dates (12-month cycle) indicated that the optimal planting window for the central region of Goiás State is from May 16 to August 01, resulting in yield averages (limited by water deficit) of Yw = 119 Mg ha^{-1} (Paixão et al., 2021).

Another significant factor contributing to yield losses is the number of harvests. Under conditions in central Brazil, the production of whole fresh sugarcane per cut ranges from 60 to 120 Mg ha^{-1} for a period of up to five years, with higher yields in the first year (Thiago and Vieira, 2002; Dias and

Sentelhas, 2017). Sugarcane can resprout after harvesting, leading to successive harvests (usually every 11-16 months). Despite the lack of a physiological explanation, empirical evidence demonstrates a decline in yield as a function of the number of harvests in commercial fields (Bernardes et al., 2008; McGlinchey and Dell, 2010). This decline is attributed to substandard management practices, including high pressure from pests, diseases, and weeds; reduced soil fertility; soil compaction; and physical damage caused to the crop by mechanical harvesting (Jackson, 1992; Dinardo-Miranda et al., 2002; Christoffoleti et al., 2006; Srivastava and Chauhan, 2006; Vitti et al., 2007; Flores et al., 2020).

In a study involving nine sugarcane mills in six states in the center-south of Brazil, with data covering three to five years (different harvest cycles), Marin et al. (2019) concluded that stalk fresh mass yield (SFY, Mg ha^{-1}) declined at different rates depending on the environment, with a greater decline observed in poor soils. Moreover, within a given environment (climate-soil), the authors observed substantial variation in SFY for any number of cuts, implying that management plays a crucial role in explaining the variation in production. Thus, the authors proposed that the decline in yield is a consequence of management practices rather than an inherent physiological attribute of the crop. For Brazilian cultivars, the exponential decrease in yield seems to be a reasonable estimate (Bernardes et al., 2008; Dias and Sentelhas, 2017). While Dias and Sentelhas (2017) obtained k_{dec} = 0.21 for Bom Jesus de Goiás city (Goiás State, Brazil), the k_{dec} values in our study were 0.81 and 0.69 for the yields obtained by the sugarcane mill (Yr) and in the experiment (Yo). Other authors reported k_{dec} values ranging from 0.10, representing good crop management, to 0.40, indicating inadequate management practices (Bernardes et al., 2008).

Regarding varietal differences, with CTC varieties, the results showed distinct yields as a function of the sugarcane cycle (one-year sugarcane: 79; one-and-a-half-year sugarcane: 110; ratoon 1: 89; ratoon 2: 78; ratoon 3: 71; ratoon 4: 68 Mg ha-^{1}), with decreases relative to the one-and-a-half-year cane plant cycle of 28.2% (one-year cane plant), 19.1% (ratoon 1), 29.1% (ratoon 2), 35.4% (ratoon 3), and 38.2% (ratoon 4) (CTC 2004). These percentage values are lower than those found in our study (Figure 6).

Material and methods

Experimental site

The experiment was conducted at Fazenda Louzandira, located in Santo Antônio de Goiás city, Goiás State, Brazil (16° 28′ 12.11″ S; 49° 21′ 9.47″ W; 780 m) (Figure 8). The experimental site covers an area of 106.45 ha and belongs to the CentroAlcool® mill. According to the Köppen climate classification, the climate was classified as Aw (Alvares et al., 2013). The region experiences a well-defined rainfall regime, with a rainy season (October-April) and a dry season (May-September), with an annual average of 1,531 mm (Silva et al., 2014).

Sugarcane planting was conducted in April 2013 using a semi-mechanized approach with pre-sprouted seedlings and 1.5 m spacing. The CTC-4 variety was used for the experiment. The evaluations included the cane plant cycle (2013/2014), ratoon 1 (2014/2015), and ratoon 2 (2015/2016), all under rainfed cultivation.

The soil in the study area was a dystrophic Red-Yellow Latosol (EMBRAPA 2018), corresponding to Ferralsols (WRB/FAO) or Oxisols (Soil Taxonomy), with a medium texture: 27% clay, 13% silt, and 60% sand. It is worth noting that the climate and soil conditions in the municipality of Santo Antônio de Goiás were considered typical of the Brazilian Savanna biome (EMBRAPA 2020).

After soil chemical analysis, the soil was corrected by applying limestone (4.0 Mg ha^{-1}) and gypsum (2.0 Mg ha^{-1}). Additionally, 120 kg ha^{-1} of P_2O_5 were applied for fertilization, and 380 kg ha^{-1} of the formulated 18-00-27 (NPK) were applied as topdressing, with the latter applications repeated in ratoon cycles 1 and 2. Weed control was carried out with herbicides applied according to the manufacturer's recommendations. Both fertilization and herbicide application were conducted by the CentroAlcool® mill.

Five sampling points were demarcated in the cultivation area, approximately 190 m apart, except for points 4 and 5, which were 450 m apart. Each point consisted of three plots, with each plot formed by five crop rows (1.5 m spacing), measuring 10 linear meters in length (75 m^2). The plots at each sampling point were placed 10 crop rows apart, side by side.

Plant growth and yield

Biometric assessments were conducted, including nine plants per plot (three in each crop row), using the three central rows of the plot. In the cane plant cycle (2013/2014), evaluations started on 05/20/2013 (50 DAP). In the ratoon 1 (2014/2015) and ratoon 2 (2015/2016) harvests, evaluations started at 66 and 53 days after cutting/harvest (DAC), respectively. The assessments were performed at varying intervals, ranging from 15 to 50 days, to ensure favorable field conditions for data collection.

Plant growth and yield evaluations followed the methodologies described in the literature (Antunes Júnior et al., 2021; Casaroli et al., 2019; Machado et al., 2009; Marin et al., 2019) for the variables stem height (H, m), stalk diameter (D, m), number of tillers (T), leaf area (LA, m^2), leaf area index (LAI, m^2 m-^{2}), and stalk fresh yield (SFY, Mg m-^{2} day-^{1}). For each biometric assessment, growth rates were determined, representing the increase in growth in each interval between assessments, using degree-day units. Additionally, rates were determined by time unit (days) for discussion and comparison of results.

Agrometeorological data and water stress

Agrometeorological data were collected from an automatic weather station installed 7 km from the experimental area, on a daily scale during the experimental period. The data included maximum, minimum, and average air temperatures (°C), rainfall (mm), relative air humidity (%), wind speed at 2 m height (m s^{-1}), solar radiation, and net radiation (MJ m^{-2} day^{-1}). The authors estimated reference evapotranspiration (ETo, mm day^{-1}) using the standard FAO Penman-Monteith method (Allen et al., 1998).

Degree-days (DD, °C day) throughout the sugarcane cycles were determined using Eq.[1] (Arnold 1959):

$$DD = Ta - Tb$$

where Ta is the average air temperature, and Tb is the lower basal temperature (Tb = 20 °C) (Barbieri and Villa Nova 1977). The thermal time (∑DD; °C day) was calculated by summing the degree-days during the phenological phases and for the cultivation cycles.

Water stress due to both water deficit and water surplus was determined using the sugarcane water balance (Thornthwaite and Mather 1955), calculated on a daily scale from planting to harvesting the second-cut ratoon cane. Total available water (TAW, mm) and readily available water (RAW, mm) were determined following the literature (Costa Neto et al., 2021; Allen et al., 1998). The main water input into the system was rainfall, while water output was governed by crop evapotranspiration (ETc, mm day^{-1}), calculated as the product of ETo and crop coefficient values (Kc) for each phase of sugarcane development and for the different cultivation cycles (Doorenbos and Kassam, 1979).

Statiscal analysis

The differences in biometric variables within each cycle and between phenological phases were identified using a heatmap, presenting a color scale between the highest and lowest values, including their percentiles. Sigmoidal (H, D, LA, LAI) and exponential (T) models were fitted to verify the biometric behavior as a function of the thermal time within each phenological phase and cultivation cycle (cane plant, ratoon 1, and ratoon 2).

For assessing the interrelationships between biometric and agrometeorological variables, a Principal Component Analysis (PCA) was performed, a multivariate analysis technique. The differences between cultivation cycles (cane plant, ratoon 1, and ratoon 2) were evaluated, followed by a perceptual map analysis to visualize the relationships between the components and the variables. Additionally, a cluster analysis was conducted to show the similarity between variables.

Conclusions

The biometric variables exhibited similar patterns both between cycles and within the phenological phases of each cycle, with an accelerated growth observed up to 222 and 143 days after planting for the cane plant and ratoon cycles, respectively. The average thermal time for these specific periods was calculated as 778, 656, and 729 degree-days (DD, °C day) for the cane plant, ratoon 1, and ratoon 2 cycles, respectively. Subsequently, growth rates started to decrease until they stabilized and then abruptly dropped. The exception was the variable number of tillers, which initially showed the highest values but decreased as a function of the days after planting or harvests. By fitting appropriate models, it became possible to monitor both growth (mass increase) and development (phenological phase changes) as a function of thermal time.

This study did not identify strong correlations between biometric variables and agrometeorological or soil moisture variables, except for leaf area and leaf area index, which exhibited a negative correlation with the ETa/ETc ratio and soil moisture. The vegetative growth phase III was found to be particularly sensitive to water deficit, and satisfactory growth was observed when at least 60% of the maximum crop evapotranspiration (Etc) was met during the initial phases.

Interestingly, the average sugarcane yield showed a decline as a function of the number of harvests. However, biometric, agrometeorological, and water stress variables alone cannot always fully explain yield variations based on established ecophysiological concepts. In this study, the increase in leaf area, leaf area index, and stalk diameter did not correspond to an increase in yield. Furthermore, the average temperatures, despite falling within the crop's climate demand range, exhibited a strong negative correlation with yield. Similarly, degree-days also demonstrated a negative correlation with this yield variable.

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