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Environmental effects on sugarcane growth from on-farm data in the Brazilian Midwest

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Climate and soil water availability are factors that influence the growth and yield of sugarcane. These factors can also serve as valuable indicators for predicting maturity and biometric changes in sugarcane, and also enhanced productivity. The aim of this study was to determine the biometric and sucrose accumulation responses of surgarcane as a function of agrometeorological data and soil water storage. The study was conducted in Santo Antônio de Goiás, Brazil. The CTC-4 sugarcane variety was assessed across harvests 2013/2014 (cane plant), 2014/2015 (ratoon 1), and 2015/2016 (ratoon 2). Agrometeorological data were collected from a weather station, to calculate degree days (DD), potential evapotranspiration (PETP), and soil water storage (SWS). Parameters including height (H), leaf area index (LAI), dry matter (DM), number of nodes (Nn), and soluble solids content (°Brix) were measured bi-weekly. Growth rates exhibited decline when SWS was below the threshold (191.61 mm). The highest confidence indices (c>0.85) were determined in H, Nn and °Brix estimates, as a function of PET and SWS. However, these equations are recommended to estimate sugarcane growth under the climate conditions of South-Central Brazil. Predicting biometric variables and sugarcane maturity through models proves valuable, enabling crop monitoring and reducing maturity determination costs.

Key words: *Saccharum* spp., biometric variables, growth analysis, Brazilian Cerrado climate.

INTRODUCTION

Brazil is the largest sugarcane producer in the world and second largest in ethanol, accounting for 27% of the global total (RFA, 2021; Vidal, 2022). Ethanol is the second most important energy source and the main renewable source in the country (Carvalho et al., 2013; Coleti and Oliveira, 2019; BEN, 2022). São Paulo state is the largest producer, while Goiás ranks 2nd and 3rd respectively in ethanol and sugar production, where 88% of the planted area lies in the South-Central region of Brazil (CONAB, 2023). The current demand for sugarcane-derived products has prompted studies on the growth and development of the crop under different growing environments, in order to optimize the management of each phenological stage and maximize the available resources (Cardozo et al., 2015).

The main stages of sugarcane growth are sprouting

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(germination), tillering, stem elongation, and ripening (Kirubakaran et al., 2013; Khan et al., 2022). The duration of these stages is influenced by the crop cycle and climate conditions (Perecin, 2008; Jadoski et al., 2010; Silva et al., 2014). Environmental factors play a crucial role in determining both the quantitative and qualitative yield, as each phenological stage requires specific climate conditions (Cintra et al., 2008; Silva and Barbosa, 2021). Factors such as air temperature and soil moisture can significantly impact sugarcane growth and the accumulation of sucrose (Cintra et al., 2008; Perecin, 2008). Temperature is an important factor that influences photosynthesis and cell growth in the crop (Sanghera, 2020), with temperatures between 30 and 35°C favoring maximum plant growth and development (Barbieri and Villa Nova, 1977; Kirubakaran et al., 2013).

Temperatures below 18 to 20°C or above 38-40°C can reduce sucrose synthesis, limit photosynthesis and inhibit stomatal opening and CO_2 exchange (Barbieri and Villa Nova, 1977; Cardozo and Sentelhas, 2013; Marin et al., 2014).

Soil water content can influence germination, number of tillers; phytomass accumulation (Marin et al., 2009) and sucrose yield (Machado et al., 2009). Thus, the intensity and duration of soil water deficit may compromise these processes (André et al., 2010; Mauri et al., 2017), by stunting shoot growth by up to 83% (Ecco et al., 2014), or have a beneficial effect, increasing sucrose content by at least 10% (Machado et al., 2009). The CTC 4 sugarcane variety, known for its drought tolerance, is one of the most cultivated types in the Cerrado region, exhibiting medium to late ripening, vigorous development, an upright final growth habit, medium to long stalks, fine to medium diameter, easy leaf removal, and good tillering (CTC, 2013; Antunes et al., 2021; Braga et al., 2023).

Thus, forecasting variables that represent the growth, development, and maturation of sugarcane across different cycles through models, based on agrometeorological and soil moisture variables, is a useful tool, as it reduces costs in their determination, aids in crop monitoring, enables yield estimation, and provides crucial information for crop management and strategic decision-making throughout the harvests (Scarpari and Beauclair, 2009; Cardozo et al., 2015).

As such, the aim of the present study was to determine the soil water level that reduces or paralyzes growth and sucrose accumulation in sugarcane exposed to the environmental conditions in south-central Goias state and use mathematical models to quantify plant growth and development as a function of agroclimatic variables and soil water level.

MATERIALS AND METHODS

The study was conducted in the municipality of Santo Antônio de Goiás (16°29'08" S; 49°20'36" W; 780 m), Brazil, in a productive area (≈280 ha) of the Centro Álcool® sugarcane mill. According to the Köppen classification, climate in the region is Aw (tropical savanna) with dry winters (May-October) and rainy summers (September-April). This municipality has an average rainfall of around 1525 mm per year (Jardim et al., 2023).

The cultivated sugarcane variety was CTC 4, recommended by the mill, which exhibits drought tolerance (CTC, 2013) and was produced in the experimental area over subsequent harvests.

A semi-mechanized planting system was used, with furrowing, plowing and grading of the area, and pre-germinated seedlings (spacing: 0.30 m x 1.5 m). The study monitored the harvests that occurred in September 2014 (plant cane), October 2015 (ratoon 1) and October 2016 (ratoon 2). The experiment was carried out in dystrophic Red-Yellow Latosol, with sandy-clay-loam texture (27% clay, 13% silt and 60% sand) (Embrapa, 2013). For soil correction, 2.0 t ha^{-1} of agricultural gypsum and 4.0 t ha of lime were applied. At planting, 120 kg ha^{-1} of P_2O_5 was applied as base dressing and 380 kg ha^{-1} of 18-00-27 (N-P-K) as topdressing. Weeds were controlled following the mill's recommendations.

Data were collected at four sampling points along 15 m of five crop rows. A completely randomized design (homogeneous area), with five repetitions was used. Biometric measures (height, leaf area, leaf area index, stem, leaf and total dry matter) were taken of five plants at each sampling point every two weeks, in line with literature methodologies (Machado et al., 2009; Marafon, 2012; Nassif et al., 2012; Pereira et al., 2016; Andrade et al., 2022).

Soluble solids content (°Brix) was determined using a digital refractometer, making it possible to estimate the maturity index (green sugarcane: MI ≤ 0.60; in maturation: 0.60 < MI ≤ 0.85; mature: 0.85 < MI ≤ 1.00; declining sucrose: MI > 1.00) of the sugarcane (Fernandes and Benda, 1985; Marafon, 2012).

Agrometeorological variables were obtained from a weather station (≈7 km from the area). The climatic water balance was calculated monthly and crop water balance daily (Thornthwaite and Mather, 1955), with total available water (TAW, mm) of 95.14 mm, and effective root system of Ze = 0.60 m (Costa Neto et al., 2021). Potential evapotranspiration (PET, mm) was determined using the Penman-Monteith method (Allen et al., 2006).

Water content at field capacity (θ_{CC} = 0.399 m^3 m^{-3}) and the permanent wilting point (θ_{PMP} = 0.240 m^3 m^{-3}) were determined according to the methodology described by Casaroli et al. (2010). To obtain the critical soil water level, maximum sugarcane evapotranspiration of 7 mm day^{-1} and water availability factor of f=0.5 were considered (Doorenbos and Kassam, 1979). Thus, the readily available water (RAW) level was 47.57 mm, corresponding to soil water storage (SWS_l) of 191.61 mm.

Degree days (DD, °C) were determined based on the methodology described by Villa Nova et al. (1972), using a maximum daily temperature (TM, °C) below 38°C (Fauconier and Bassereau, 1975); minimum daily temperature (Tm, °C) above 7°C (Waldron et al., 1967); minimum basal temperature (Tb, °C) of 20 °C (Barbieri and Villa Nova, 1977) and maximum basal temperature (TB, °C) of 35°C (Pereira et al., 2015). The regression equations were fitted by the free SciDAVis software (http://scidavis.sourceforge.net/index.html) to data on height (H, m), leaf area index (LAI m^{-2} m^{-2}), shoot dry matter (SDM, kg), number of nodes (Nn, nodes) and soluble solids content (°Brix) as a function of days after planting/harvest (DAH), degree days (DD, °C dayu), potential evapotranspiration (PET, mm) and water deficit (WD, mm). The equations used in the fittings were sigmoidal (Equation 1) and second-order polynomial (Equation 2).

$$y = \frac{a}{1 + \exp^{-\frac{(x - x_0)}{b}}} \qquad (1)$$

$$y = x_0 + a \cdot x + b \cdot x^2 \qquad (2)$$

Model fits were assessed based on the standard error of estimate (SEE), mean standard error (MSE), root mean square error

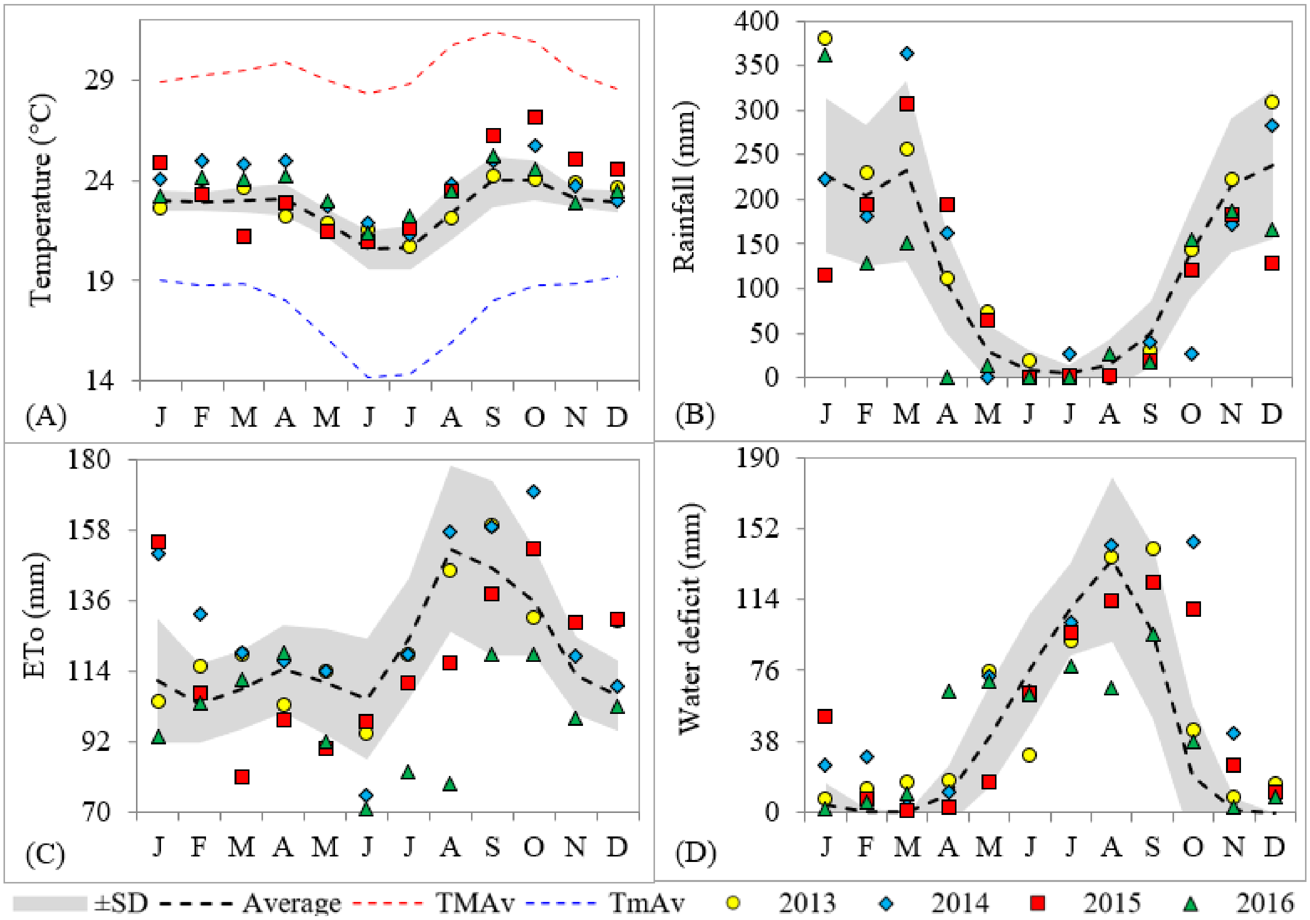

Figure 1. Air temperature (A), rainfall (B), potential evapotranspiration (C) and water deficit depth (D) (averages from 1983 to 2004) for sugarcane growing seasons (from 2013 to 2016). ±SD: standard deviation of Santo Antônio de Goiás, GO, Brazil.

(RMSE), mean absolute error (MAE), coefficient of determination (R^2), agreement index "d" (Willmott et al., 1985) and the confidence index (c), classified as "excellent" (> 0.85), "very good" (0.76-0.85), "good" (0.66-0.75), "median" (0.61-0.65), "tolerable" (0.51-0.60), "poor" (0.41-0.50) and "very poor" (< 0.40) (Camargo and Sentelhas, 1997).

RESULTS AND DISCUSSION

Agrometeorological data and water deficit

The agrometeorological and water deficit variables obtained in the 2013-2016 growing seasons exhibited values above or below the standard deviation of the mean (1983-2004) (Figure 1). It is important to note that the average temperatures in the growing seasons were generally above the mean, especially in 2015 (Figure 1A). Total rainfall (R) of the municipality was 1481.3 mm, 93% of which occurred between October and April. The highest and lowest water level of R occurred in December (239.2 mm) and July (4.7 mm), respectively. The average monthly R values from 2014 to 2016 were sometimes higher and sometimes lower than the standard deviation of the mean (1983-2004) (Figure 1B).

These characteristics meet crop requirements for commercial production, with a hot and humid environment in the tillering phase and crop growth (Ta: between $21°C \leq Ta \leq 35°C$; $R \geq 1000$ mm) (Barbieri and Villa Nova, 1977; Manzatto et al., 2010; Capone et al., 2011; Marin and Nassif, 2013; Araújo et al., 2016; Amaral et al., 2019). In areas where temperature does not limit growth ($Ta \geq Tb$), sugarcane maturation is induced primarily by the occurrence of soil water deficit (Humbert, 1968; Tianco and Escober, 1970; Alexander, 1973; André et al., 2010; Cardozo and Sentelhas, 2013).

Average maximum potential evapotranspiration (PET) occurred in August (152.1 mm), different from 2013 (Sept.), 2014 (Oct.), 2015 (Oct.) and 2016 (Sep.). Average water deficit (WD) obtained the highest values in July (108.9 mm), August (135.7 mm) and September (96.8 mm) (Figure 1D), simultaneously with low R and PET values (Figures 1B and 1C). WD values in 2014 (145.2 mm) and 2015 (109.2 mm) were also high in October (Figure 1D), a period of a sharp decline in WD

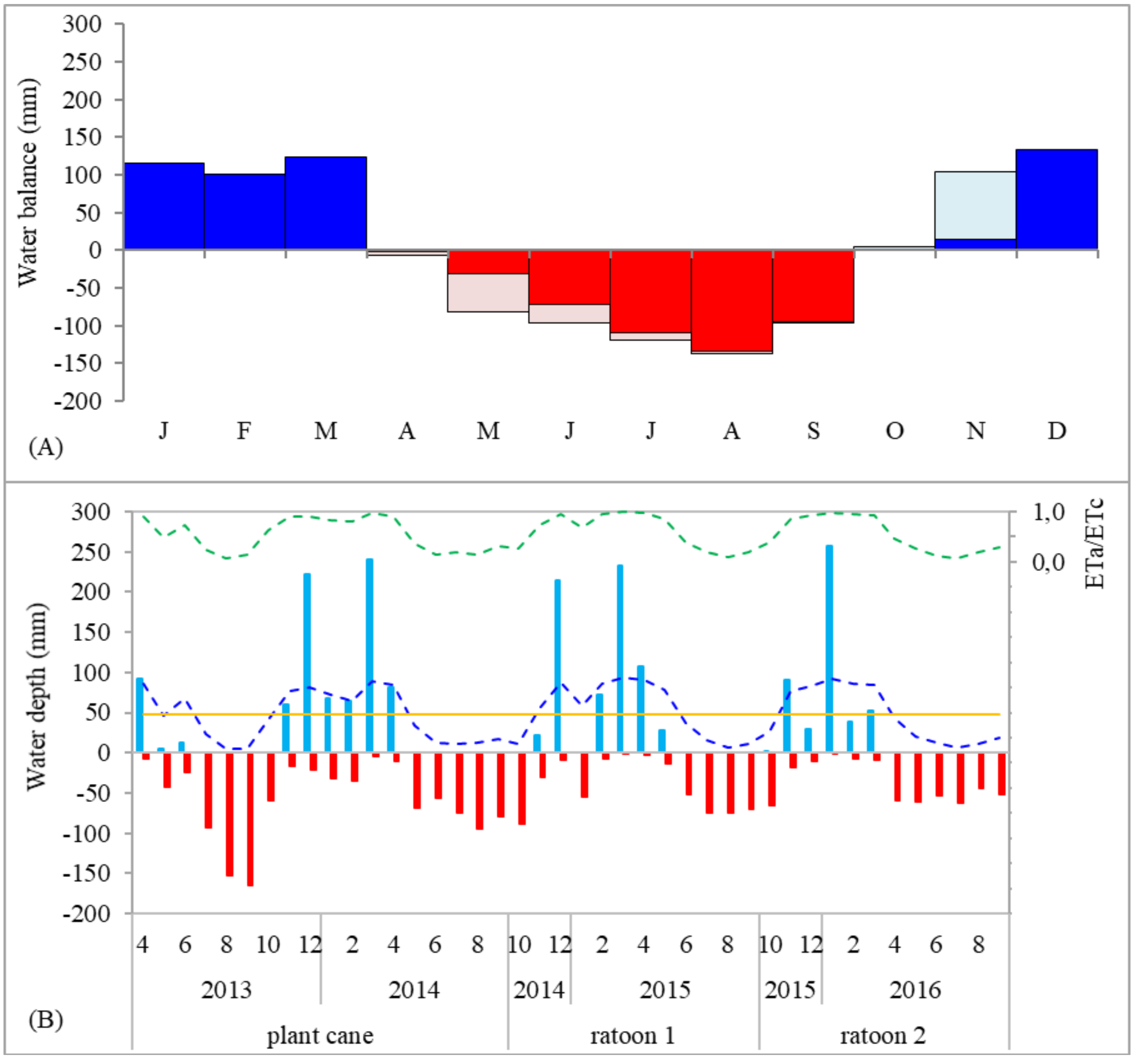

Figure 2. Average water balance (from 1983 to 2004): water surplus [blue bars], water deficit [red bars], replenishment [light blue bars] and withdrawal [light red bars] of water from the soil (A). Water balance to the sugarcane crop: water surplus [blue bars], water deficit [red bars], soil water storage [blue dotted line], soil water limit [orange line] (B) of Santo Antônio de Goiás, GO, Brazil.

(average: 19.6±37 mm) due to the occurrence of rain, which was below average in these months (Figure 1B).

Average climatological water balance showed water surplus (WS) and water deficit (WD) levels of 486.12 and 442.95 mm, respectively, with average WS values of ≈100 mm (Jan., Feb., Mar. and Dec.) and WD≈88 mm (from Mar. to Sept.) (Figure 2A). The water balance of the crop showed higher WS and WD values in some months of the growing season, such as Aug./2013 (WD: 153 mm), Sept./2013 (WD: 164 mm), Dec./2013 (WS: 221), and Mar./2014 (WS: 240 mm) (Figure 2B). These WD values reduced actual sugarcane evapotranspiration (ETa) to null values at some moments of the cycle, as detected when ETa/ETc=0 (Figure 2B). Soil water storage (SWS) below the water level limit promotes ETa/ETc<1, which was also observed in the three crop cycles (Figure 2B). Since accentuated water deficit can cause yield losses, knowing when it occurs may guide producers in their planting/harvest planning (Paixão et al., 2021). In addition, estimates show that WD≥130 mm in the months preceding harvest may negatively influence sucrose accumulation in the stems (Scarpari & Beauclair, 2004). Inman-Bamber (2004) found that WD≥120 mm affects biomass accumulation in the stem, while WD≥145 mm reduces sucrose accumulation.

Characterization of sugarcane growth

Plant height (H) declined as a function of the number of cuts (Figure 3A). Height rates (H_R) were negatively influenced by soil moisture content below the storage limit (SWS_l = 191.61 mm) of the crop (Figure 3A). Ratoon 1 showed a 55% decline in average H_R when WD=236.5 mm (280 DAH). In this crop, SWS <191.61 mm was recorded in the first week of June (Figure 2B).

In the next growing season (ratoon 2), $SWS<SWS_l$ was obtained in the third week of April, while average H_R decreased to around 205 DAH (WD=131 mm; SWS=172.43 mm). Average H_R in ratoon 1 was 40.2% higher than in ratoon 2. H_R at the end of the plant cane cycle was around 89 and 38% lower than in the 2014/15 (ratoon 1) and 2015/16 (ratoon 2) growing seasons, respectively, since $SWS<SWS_l$ from the second week of May/2014 onwards (Figure 2B).

Despite the behavior observed for average H_R, maximum H from 280 DAH onwards was on average 3.72, 2.73 and 2.03 m in plant cane, ratoon 1 and 2, respectively. On average, H_R declined by more than 40% when $SWS<SWS_l$, for WD>130 mm. These results were similar to those reported by Hemaprabha et al. (2004), who found an average reduction of 48.79% in H in 97 sugarcane varieties in WD, decreasing mass accumulation of the crop by 64.16%. Ecco et al. (2014) observed an average decline in H of 60% and stem diameter of 65% in the RB855536 and RB867515 varieties, with WD (20 to 40% of θ_{CC}).

The leaf area index (LAI) also varied as a function of SWS (Figure 3B), due to water stress caused by WD, thereby reducing photosynthesis rates, carbohydrate synthesis, leaf expansion and internode elongation (Taiz and Zeiger, 2013; Bianchi et al., 2016). For ratoon 1 (Figure 3B), maximum LAI was 5.38 m^2 m^{-2} at 242 DAH (May). At this time, SWS of 203.17 mm, WD=156.43 mm and accumulated degree days (DD) of 979.21°C day were recorded. The average leaf area index rate (LAI_R) was 0.019 m^2 m^{-2} day^{-1}, declining at 150 and 280 DAH. In ratoon 2 (Figure 3B), the maximum LAI observed was 3.62 m^2 m^{-2} at 205 DAH, with SWS = 172.43 mm, WD = 130.27 mm and DD = 1044.61 °C day, later exhibiting successive decreases in average LAI_R (Figure 3B and 2B).

For the ratoon 1 and 2 cycles, the CB 47-355 variety grown in an irrigated system, Teruel et al. (1997) obtained maximum LAI of more than 4 m^2 m^{-2} for DD between 650 and 900°C. Almeida et al. (2008) assessed four different varieties in an irrigated system and found a maximum LAI of around 4.5 m^2 m^{-2} for ratoon 1, between 600 and 950 DD.

These results differ from those obtained here, since the effect of WD on LAI is not linear, but variable as a function of WD level and the phenological stage of the crop (Teruel et al., 1997). In the maturation period, all the crops exhibited a decline in LAI, obtaining average values of 2.26 m^2 m^{-2} for plant cane, 2.71 m^2 m^{-2} for ratoon 1 and 1.81 m^2 m^{-2} for ratoon 2 (Figure 3B). In the different growing seasons, DD until the onset of maturation (466 DAH in plant cane and 280 DAH in ratoons) was 1650.39; 1074.98 and 1304.48 °C. Teruel et al. (1997) found no significant difference in LAI between ratoon cycles and obtained values below 3.5 m^2 m^{-2} at the end of the cycle, when it reached around 1100°C day, characterizing the onset of maturation.

In the first 150 DAH, the LAI_R of ratoon 2 was 58% higher when compared to ratoon 1. It is important to note that WD (77.6 mm) was lower in the ratoon 2 cycle, when compared to the WD (146.5 mm) of ratoon 1 (for the same period), which may have influenced leaf growth. Barbosa et al. (2015) observed that WD promotes a decline in photosynthetic rate, greater stomatal limitation and young leaf photorespiration (until ≈150 DAH), when compared to mature and senescent leaves. These authors found a 64% decrease in sugarcane leaf area (LA) when submitted to WD of 20% of θ_{CC}.

The behavior of H and LAI as a function of SWS was reflected in the shoot dry matter (DM) values (Figure 3C and 2B).

In the ratoon 1 cycle, decreases in H_R (Figure 3A) and LAI_R (Figure 3B) at 280 DAH resulted in average dry matter rates (DM_R) of 0.077 kg day^{-1}, with a subsequent decline to 0.053 kg day^{-1} (SWS=182.50 mm) (Figure 2B). Ecco et al. (2014) studied the biometric responses of sugarcane exposed to WD (20 to 40% of θ_{CC}) and found an average DM decrease of 83% when compared to optimal water availability. Barbosa et al. (2015) assessed the RB86-7515 variety and found that DM was 3.6 times lower under WD (20% da θ_{CC}). For CP 01-2390 and CP 80-1743, Zhao et al. (2013) observed that WD (from 55 DAH onwards) reduced green leaf and stem phytomass by 70 and 45%, respectively.

According to Silva et al. (2012), DM declines as a response to interrupted stem growth and a decrease in sugarcane LAI. Average DM_R (ratoon 2) was 0.009 kg day^{-1} up to 280 DAH (WD= 259.94 mm), thereafter reaching 0.055 kg day^{-1} (Figure 3C). This 84% rise in DM_R occurred due to the increase in the number of leaves from 280 DAH onwards. The increase in the photosynthetic apparatus of the sugarcane contributed to photoassimilate accumulation, thereby optimizing solar radiation, raising biomass and consequently, DM by up to 47% (Almeida et al., 2008).

For number of nodes (Nn), in all the nodes, an initial (until 150 DAH) slow growth stage was observed, followed by a rise in the rate (Nn_R) and stabilization at 280 DAH (Figure 3D). In ratoon 1, no internodes were formed until 118 DAH (WD=146.24 mm) (Figure 2B), showing Nn_R = 0.007 nodes day^{-1}. Thereafter (DD=546.64°C day) and until 280 DAH, $SWS\geq SWS_l$ during the entire period, with a significant increase in Nn (Nn_R = 0.153 nodes day^{-1}). A decline in Nn_R (0.005 nodes day^{-1}) was observed when $SWS<SWS_l$.

In the first 150 days of the ratoon 2 cycle, Nn_R=0.011 nodes day^{-1}, forming internodes from 156 DAH onwards (WD=77.58 mm; DD=792.07 °C day) (Figure 3D and 2B), which was higher when compared to the previous growing season (same period), since soil water availability was

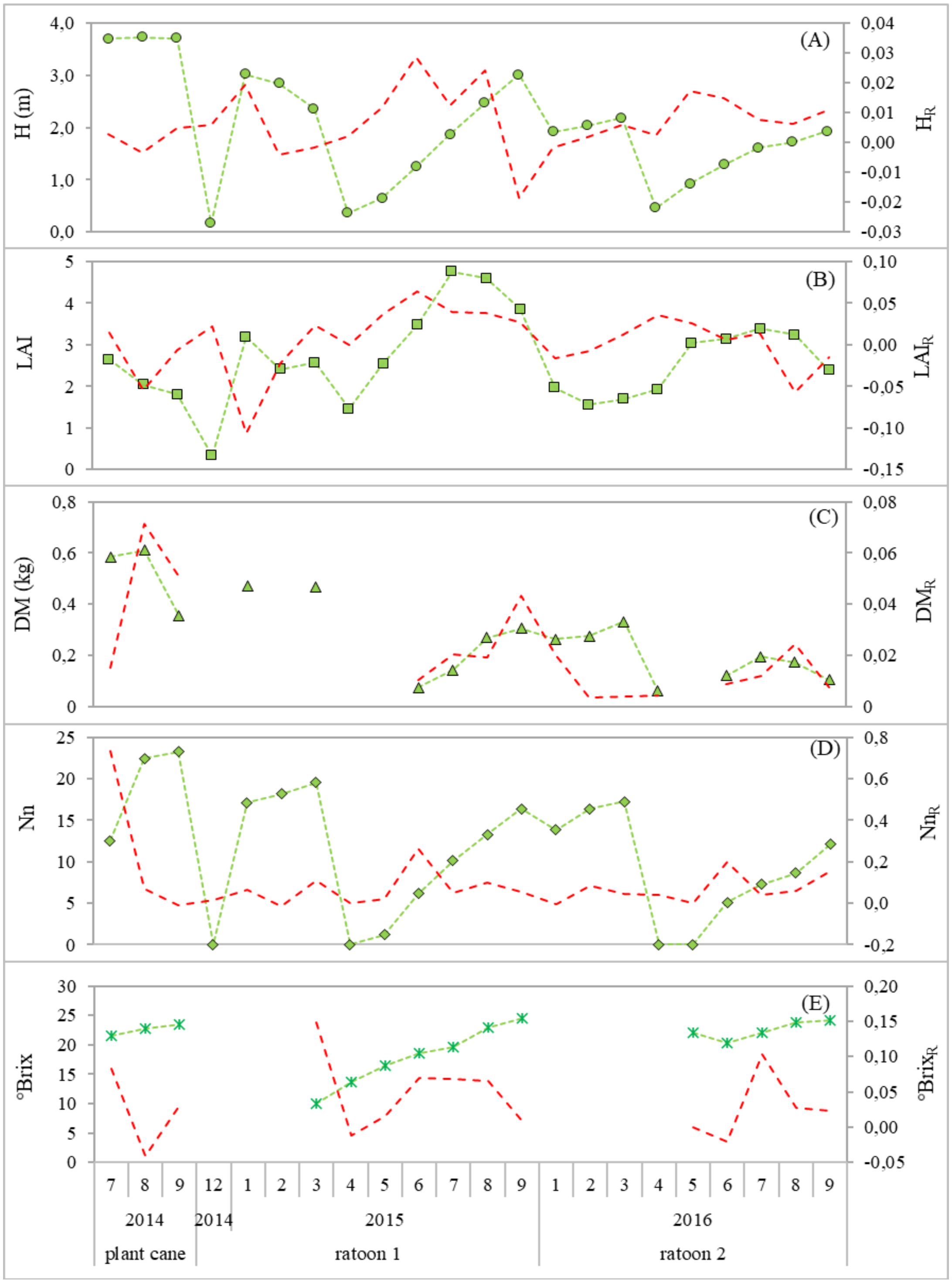

Figure 3. Plant height (H, m), leaf area index (LAI), dry matter (DM, kg), number of nodes (Nn) and soluble solids content (°Brix), as well as their respective rates (red dotted lines and subscripts "R") as a function of the months, years, and crop cycles of Santo Antônio de Goiás, GO, Brazil.

greater.

The highest average Nn_R (0.049 nodes day^{-1}) was obtained in the maturation phase of the plant cane cycle in the maturation phase, even with SWS=146.47 mm, similar to the other crops. Zhao et al. (2013) studied the effects of WD (at 55 DAH) on the growth of two varieties

(CP 01-2390 and CP 80-1743) and observed a Nn decline of between 23 and 62% in the two ratoon cycles. According to Inman-Bamber et al. (2008), WD compromised stem growth and development due to decreased cell division.

The soluble solids content (°Brix) behaved differently between the crops (Figure 3E). In plant cane, the average °Brix rate (°Brix$_R$) was 0.031 °Brix day^{-1} from 458 DAH onwards (maturation: MI=0.78). Accumulated WD was 658 mm (SWS=150.89 mm; 63% of θ_{CC}) (Figure 2B). The rise in °Brix was accompanied by an increase in temperature (5.14 °C of thermal amplitude; r=0.7).

In the vegetative growth stage (up to 280 DAH; WD = 48.7 mm), the ratoon 1 cycle obtained a rate of 0.055 °Brix day^{-1} (Figures 3E and 2B) and ratoon 2 -0.021 °Brix day^{-1} (WD=395.3 mm) (Figures 3E and 2B). For ratoon cycles 1 (r=0.4) and 2 (r=0.2) the lower temperature did not affect sucrose asccumulation.

In general, it is recommended that sucrose accumulation in sugarcane stems be observed four months before harvest. In the plant cane cycle, three months before harvest, °Brix=21.6, with accumulated WD of 77.9 mm, where four months before it was 134.4 mm. In the ratoon cycles, (four months before, °Brix and WD were 18.5 °Brix and 12.2 mm (ratoon 1), and 20.3 °Brix and 31.5 mm (ratoon 2) respectively (Figures 2B and 3E). At harvest (end of September) these values were respectively, 23.4 °Brix and 15.2 mm (plant cane), 24.5 °Brix and 2.1 mm (ratoon 1), and 24.2 °Brix and 13.5 mm (ratoon 2) (Figures 2B and 3E). According to Scarpari and Beauclair (2004), WD>130 mm accumulated four months before harvest affects stem sucrose accumulation. Inman-Bamber (2004) concluded that sucrose accumulation declines by 34% with WD above 145 mm. Machado et al. (2009) found that WD (40% of θ_{CC}) decreases stem sucrose accumulation by 25% when it occurs in the vegetative period. An optimal SWS for sugarcane maturation could maintain plant phytomass, favor stem sucrose concentration and allow sucrose synthesis to continue. However, this varies as a function of the variety studied and climate and soil conditions of the crop environment (Cardozo and Sentelhas, 2013; Araújo et al., 2016).

The °Brix values at harvest were higher in the ratoon cycles (>24 °Brix) in relation to plant cane (23.7 °Brix) (Figure 3E). This result corroborates those of the literature (Batta et al., 2011; Simões et al., 2015), which were attributed to environmental conditions and decreased rainfall. Muraro et al. (2009) reported that WS is a diluting factor of sucrose in the stems, compromising accumulation since it stimulates plant growth and development.

Fitting models to sugarcane growth

A sigmoidal equation was fit to the plant height (H) data as a function of days after planting/harvest (DAH), degree days (DD), potential evapotranspiration (PET) and water déficit (WD) (Figures 4A, B, C and D), as observed by other authors (Machado et al., 1982; Atique-Ur-Rehman et al., 2013). H values were similar for ratoon 1 and 2, where 22% of H occurred by 150 DAH (germination and tillering phases), 59% by 280 DAH (accelerated growth phase) and 19% by the harvest (maturation phase) (Figure 4A). According to Machado et al. (1982), sugarcane growth and dry matter (DM) accumulation can be divided into three phases: i) initial slow growth phase (until 200 DAH); ii) rapid growth with 75% of total DM accumulation (200 to 400 DAH); and iii) final phase, also slow (>400 DAH), corresponding to 11% of accumulated DM, corroborating the results of the present study. The onset of the rapid vegetative growth stage (150 DAH) for the ratoon cycles occurred from 749.26 DD and 656.34 mm of PET, with a decline in height rates (H$_R$) at 280 DAH (WD=159 mm; DD=1189.73°C day). At that time, PET was 1000.64 mm (Figures 4B, C and D).

Similar DD values were observed by Almeida et al. (2008) for SP79-1011, RB92579, RB93509 and RB931530 varieties. For plant cane and ratoon cane, respectively, the 1st phase exhibited 750 and 600 DD, the 2nd 1500 and 950 DD and the final accumulated 2015 and 1800 DD. The ratoon H models, as a function of DAH, showed excellent performance (c > 0.85) and good accuracy (r = 0.91; SEE = 0.37; MAE = 0.26) (Table 1). However, the fit for the plant cane cycle was not adequate (Table 1). On the other hand, the fit for the three cycles studied exhibited excellent performance (c = 0.92) and satisfactory accuracy (r = 0.92; SEE = 0.44; MAE = 0.34) (Table 1).

Second-order polynomial equations were fit to LAI, where the maximum points (plant cane and ratoon: ≈230 DAH; DD≈1000 °C day; PET≈900 mm; WD=160 mm) can be observed in Figures 4E, F, G and H. This LAI behavior as a function of DAH can also be found in the literature (Oliveira et al., 2007; Cabral et al., 2012; Atique-Ur-Rehman et al., 2013). It is important to note that the crop obtained higher DD values to reach maximum LAI when compared to other studies (Teruel et al., 1997, Scarpari and Beauclair, 2008). According to Teruel et al. (1997), the difference between LAI values may be due to the variations in tillering between the varieties, cycles, chemical properties and soil compaction. The LAI models showed very good performance in terms of DAH and DD, and good for PET. However, performance was considered very poor for WD (Table 1). Subestimates were observed for maximum LAI in ratoon 1 (Figures 4E, F, G and H). Other authors fit quadratic equations to LAI as a function of DAH, obtaining coefficients of determination (R^2) of 0.90 (RB72454), 0.83 (RB855113) and 0.82 (RB855536) (Oliveira et al., 2007). Teruel et al. (1997) fit LAI to DD, observing satisfactory results for plant cane (R^2 = 0.58), ratoon 1 (R^2 = 0.88) and 2 (R^2 = 0.80).

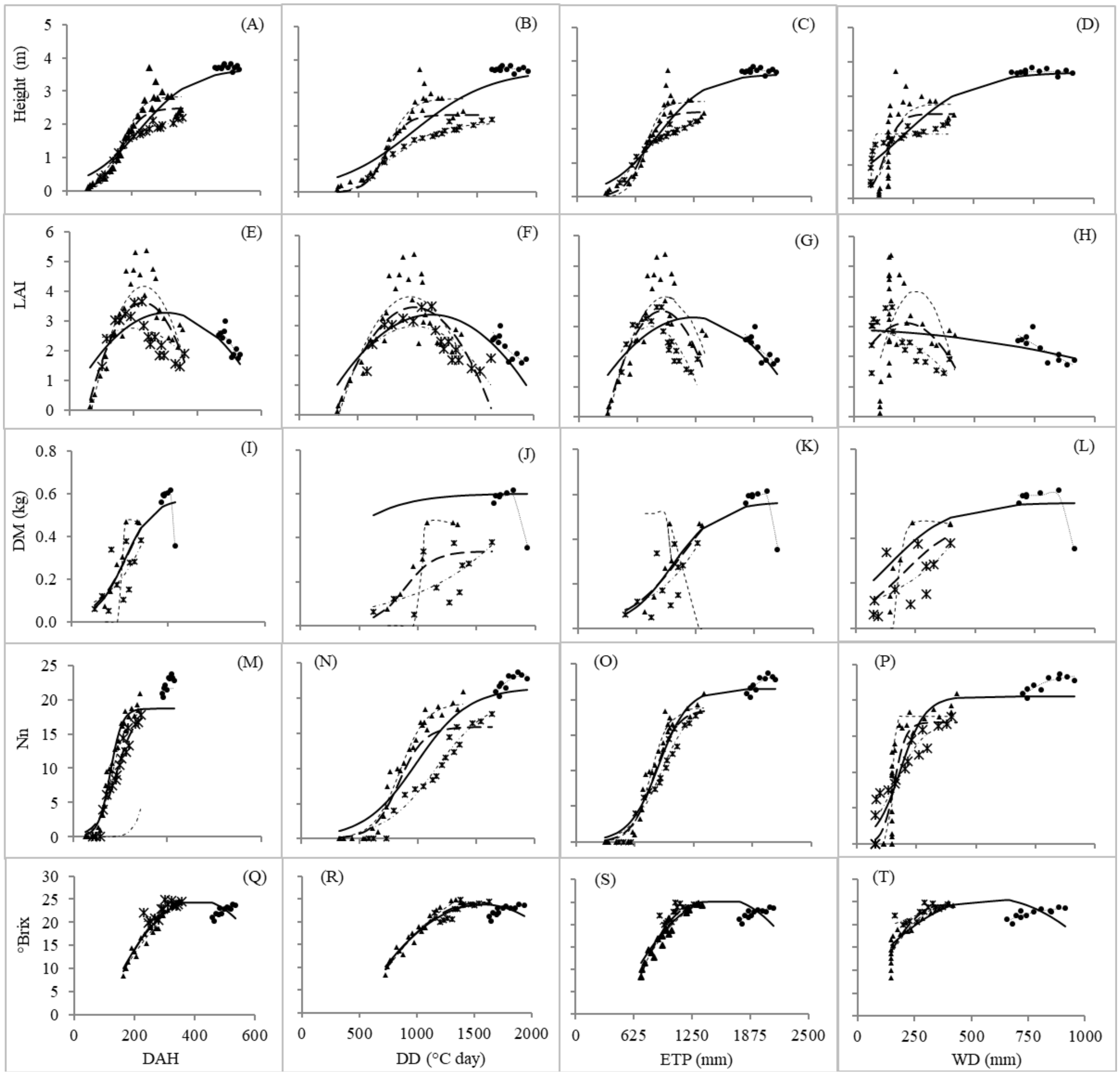

Figure 4. Plant height (H, m), leaf area index (LAI), dry matter (DM, kg), number of nodes (Nn) and soluble solids content (°Brix), measured in the plant cane (•) ratoon 1 (▲) and ratoon 2 (∗) cycles, as well as the estimated values for plant cane (········), ratoon 1 (- - - - - -), ratoon 2 (-·-·-·-), for 3 harvest (——) and ratoon 1 and 2 (– – – – –); as a function of the days after planting/harvest (DAH), degree days (DD, °C day), potential evapotranspiration (PET, mm) and water deficit (WD, mm) accumulated under the weather conditions of Santo Antônio de Goiás, GO, Brazil.

For DM (Figures 4I, J, K and L), the equations demonstrate excellent performance for the three crop cycles (Table 1). Other authors also fit sigmoidal (Silva et al., 2012; Atique-Ur-Rehman et al., 2013) and quadratic models (Oliveira et al., 2007) satisfactorily.

In general, for the number of nodes (Nn) (Figures 4M, N, O and P), the sigmoidal equations fit to Nn exhibited excellent performance (c > 0.85) and good accuracy (r= 0.92), for the three cycles studied (Table 1).

A quadratic fit was also determined for °Brix (Figures 4Q, R, S and T). Vieira et al. (2013) obtained similar results for the sugarcane maturation index (MI), with a quadratic trend. The fit of °Brix values for plant cane and ratoons as a function of DAH, DD and PET showed excellent performance (c > 0.85) and was considered very good (c = 0.78) as a function of WD (Table 1).

Table 1. Parameters of the sigmoidal equation (a, b, x_o), coefficient of determination (R^2), standard error of estimation (SEE), mean square error (MSE), root mean square error (RMSE), mean absolute error (MAE), agreement index (d), correlation coefficient (r) and confidence index (c), from estimated height, leaf area index, dry matter, number of nodes and soluble solids content values as a function of days after planting/harvest (DAH), degree days (DD), potential evapotranspiration (PET) and water deficit (WD), for plant cane, ratoon 1, ratoon 2, all 3 harvests and ratoon 1 and 2.

		a	b	x_o	R^2	SEE	MSE	RMSE	MAE	d	r	c
Height												
DAH	Plant cane	3.72	10.11	407.30	0.01	0.07	0.23	0.07	0.05	0.88	0.10	0.09
	Ratoon 1	2.83	27.75	174.80	0.93	0.29	1.53	0.28	0.18	1.00	0.96	0.96
	Ratoon 2	2.07	40.00	152.40	0.97	0.09	0.39	0.09	0.08	1.00	0.98	0.98
	3 harvests	3.69	81.95	226.50	0.85	0.44	3.38	0.44	0.34	1.00	0.92	0.92
	Ratoon 1 and 2	2.50	31.97	167.30	0.84	0.37	2.51	0.37	0.26	1.00	0.91	0.91
DD	Plant cane	3.72	26.42	149.50	0.01	0.07	0.23	0.07	0.05	0.87	0.00	0.00
	Ratoon 1	2.83	95.03	755.70	0.92	0.31	1.62	0.30	0.21	1.00	0.96	0.96
	Ratoon 2	2.11	192.10	793.40	0.97	0.10	0.40	0.09	0.08	1.00	0.98	0.98
	3 harvests	3.69	327.80	968.70	0.75	0.58	4.40	0.57	0.49	1.00	0.87	0.86
	Ratoon 1 and 2	2.33	86.80	729.80	0.77	0.43	2.94	0.43	0.32	1.00	0.88	0.88
PET	Plant cane	3.72	35.58	158.10	0.01	0.07	0.23	0.07	0.05	0.87	0.00	0.00
	Ratoon 1	2.81	80.46	726.10	0.92	0.31	1.63	0.30	0.21	1.00	0.96	0.96
	Ratoon 2	2.13	153.20	640.20	0.97	0.09	0.39	0.09	0.08	1.00	0.98	0.98
	3 harvests	3.62	257.00	862.90	0.85	0.45	3.42	0.44	0.34	1.00	0.92	0.92
	Ratoon 1 and 2	2.50	103.90	696.90	0.82	0.39	2.63	0.38	0.29	1.00	0.91	0.90
WD	Plant cane	3.72	25.79	525.90	0.01	0.07	0.23	0.07	0.05	0.87	0.09	0.08
	Ratoon 1	2.76	34.93	146.70	0.88	0.68	3.59	0.67	0.56	0.99	0.80	0.79
	Ratoon 2	1.90	3.36	77.73	0.86	0.20	0.85	0.20	0.17	1.00	0.92	0.92
	3 harvests	3.70	142.50	209.30	0.68	0.65	4.98	0.65	0.50	1.00	0.82	0.82
	Ratoon 1 and 2	2.48	30.38	132.70	0.51	0.64	4.31	0.63	0.53	1.00	0.72	0.72
Leaf area index												
DAH	Plant cane	-12.47	7.33E-02	-8.74E-05	0.64	0.25	0.79	0.24	0.18	0.99	0.80	0.79
	Ratoon 1	-4.25	7.24E-02	-1.55E-04	0.77	0.69	3.66	0.68	0.56	1.00	0.88	0.87
	Ratoon 2	1.43	1.37E-02	-3.47E-05	0.12	0.54	2.24	0.53	0.45	0.98	0.76	0.74
	3 harvests	0.27	1.99E-02	-3.27E-05	0.27	0.98	7.36	0.97	0.77	0.99	0.52	0.51
	Ratoon 1 and 2	-2.83	5.60E-02	-1.21E-04	0.50	0.80	5.39	0.79	0.61	1.00	0.77	0.76
DD	Plant cane	32.72	-3.07E-02	7.63E-06	0.65	0.25	0.78	0.23	0.18	0.99	0.81	0.80
	Ratoon 1	-5.46	2.01E-02	-1.06E-05	0.72	0.76	4.01	0.74	0.63	1.00	0.85	0.85
	Ratoon 2	-1.52	9.19E-03	-4.68E-06	0.56	0.47	1.95	0.46	0.37	0.99	0.75	0.74
	3 harvests	-1.22	8.12E-03	-3.60E-06	0.39	0.89	6.68	0.88	0.70	0.99	0.63	0.62
	Ratoon 1 and 2	-3.96	1.55E-02	-7.94E-06	0.62	0.75	5.11	0.75	0.58	1.00	0.79	0.79
PET	Plant cane	14.71	-9.92E-03	1.80E-06	0.63	0.25	0.79	0.24	0.18	0.99	0.80	0.79
	Ratoon 1	-5.29	1.99E-02	-1.07E-05	0.71	0.77	4.10	0.76	0.65	1.00	0.84	0.84
	Ratoon 2	-1.98	1.28E-02	-8.21E-06	0.58	0.46	1.90	0.45	0.37	0.99	0.76	0.75
	3 harvests	-0.13	5.62E-03	-2.30E-06	0.26	0.98	7.41	0.97	0.77	0.99	0.51	0.50
	Ratoon 1 and 2	-4.24	1.74E-02	-9.77E-06	0.51	0.87	5.87	0.86	0.67	0.99	0.71	0.71
WD	Plant cane	6.78	-7.27E-03	1.92E-06	0.68	0.24	0.75	0.23	0.17	0.99	0.82	0.81
	Ratoon 1	-2.56	5.24E-02	-1.02E-04	0.23	1.26	6.69	1.24	1.10	0.98	0.48	0.47
	Ratoon 2	2.81	1.59E-03	-1.32E-05	0.44	0.53	2.19	0.52	0.39	0.98	0.67	0.66

Table 1. Contd.

	3 harvests	2.89	-2.18E-04	-8.87E-07	0.05	1.11	8.36	1.10	0.81	0.98	0.23	0.23
	Ratoon 1 and 2	1.46	1.55E-02	-3.61E-05	0.09	1.18	7.97	1.16	0.94	0.98	0.30	0.29
		a	b	x_o	R²	SEE	MSE	RMSE	MAE	d	r	c
						Dry matter						
DAH	Plant cane	0.59	-0.97	535.40	0.96	0.02	0.04	0.02	0.01	1.00	0.98	0.98
	Ratoon 1	0.47	0.78	262.50	1.00	0.13	0.31	0.12	0.07	0.98	0.93	0.91
	Ratoon 2	98.26	178.60	1359.00	0.39	0.09	0.30	0.09	0.07	0.98	0.66	0.64
	3 harvests	0.58	73.75	271.70	0.71	0.10	0.47	0.09	0.08	1.00	0.87	0.86
	Ratoon 1 and 2	0.66	89.02	297.80	0.53	0.10	0.41	0.10	0.08	0.99	0.74	0.73
DD	Plant cane	0.59	-5.37	1938.00	0.96	0.02	0.04	0.02	0.01	1.00	0.98	0.98
	Ratoon 1	0.47	1.60	1039.00	1.00	0.13	0.31	0.12	0.07	0.98	0.93	0.91
	Ratoon 2	76.12	703.50	5380.00	0.40	0.09	0.29	0.09	0.07	0.98	0.67	0.65
	3 harvests	0.60	303.40	119.00	0.54	0.29	1.49	0.28	0.22	0.98	0.69	0.68
	Ratoon 1 and 2	0.34	124.20	886.00	0.31	0.11	0.47	0.11	0.09	0.98	0.62	0.61
PET	Plant cane	0.59	-5.29	2126.00	0.96	0.02	0.04	0.02	0.01	1.00	0.98	0.98
	Ratoon 1	0.51	-10.50	999.74	0.43	0.37	0.91	0.34	0.28	0.85	-0.69	-0.59
	Ratoon 2	48.30	526.00	3831.00	0.41	0.09	0.29	0.09	0.07	0.98	0.67	0.66
	3 harvests	0.56	242.90	1004.00	0.71	0.09	0.46	0.09	0.06	1.00	0.87	0.87
	Ratoon 1 and 2	0.68	308.20	1125.00	0.53	0.10	0.40	0.09	0.07	0.99	0.75	0.74
WD	Plant cane	0.59	-2.64	914.70	0.96	0.02	0.04	0.02	0.01	1.00	0.98	0.98
	Ratoon 1	0.47	2.33	187.00	1.00	0.13	0.31	0.12	0.07	0.98	0.93	0.91
	Ratoon 2	43.96	294.00	1802.00	0.37	0.10	0.30	0.09	0.07	0.98	0.64	0.63
	3 harvests	0.56	129.40	136.40	0.70	0.13	0.67	0.13	0.10	0.99	0.84	0.83
	Ratoon 1 and 2	0.50	117.50	204.40	0.49	0.11	0.44	0.10	0.09	0.99	0.69	0.68
						Number of nodes						
DAH	Plant cane	21.71	52.58	229.50	0.94	1.28	3.84	1.21	1.04	0.94	0.87	0.82
	Ratoon 1	18.38	39.01	207.80	0.93	1.67	8.85	1.64	1.40	1.00	0.99	0.99
	Ratoon 2	23.99	33.79	412.40	0.75	10.44	43.05	10.15	8.87	0.97	0.68	0.66
	3 harvest	18.70	31.24	197.10	0.98	2.54	18.98	2.51	1.91	1.00	0.95	0.95
	Ratoon 1 and 2	18.59	50.37	229.00	0.95	2.43	16.47	2.40	1.96	1.00	0.96	0.96
DD	Plant cane	23.51	89.67	1493.00	0.74	0.58	1.73	0.55	0.47	0.99	0.86	0.85
	Ratoon 1	19.28	112.60	843.20	0.98	1.16	6.14	1.14	0.90	1.00	0.99	0.99
	Ratoon 2	19.96	220.90	1153.00	0.95	1.22	5.05	1.19	1.00	1.00	0.98	0.98
	3 harvests	21.54	224.10	985.00	0.84	3.15	23.58	3.12	2.78	1.00	0.92	0.91
	Ratoon 1 and 2	15.84	106.90	832.80	0.80	2.99	20.29	2.96	2.37	1.00	0.90	0.90
PET	Plant cane	23.61	119.70	1585.00	0.75	0.57	1.71	0.54	0.46	0.99	0.86	0.86
	Ratoon 1	18.90	95.02	797.90	0.97	1.23	6.49	1.21	0.95	1.00	0.99	0.99
	Ratoon 2	19.70	163.50	904.90	0.95	1.21	4.97	1.17	0.99	1.00	0.98	0.98
	3 harvest	21.54	157.00	880.90	0.94	1.91	14.30	1.89	1.60	1.00	0.97	0.97
	Ratoon 1 and 2	18.63	121.10	826.90	0.92	1.87	12.67	1.85	1.49	1.00	0.96	0.96
WD	Plant cane	23.56	83.75	533.40	0.76	0.55	1.66	0.53	0.45	0.99	0.87	0.86
	Ratoon 1	17.73	4.64	149.90	0.84	2.97	15.73	2.92	2.18	1.00	0.92	0.92
	Ratoon 2	17.14	62.94	162.20	0.91	1.86	7.66	1.80	1.41	1.00	0.95	0.95
	3 harvests	20.53	52.36	180.90	0.80	3.46	25.91	3.43	2.87	1.00	0.90	0.89

Table 1. Contd.

	Ratoon 1 and 2	16.97	24.27	155.60	0.74	3.42	23.23	3.39	2.83	1.00	0.87	0.86
		a	b	x_o	R²	SEE	MSE	RMSE	MAE	d	r	c
Solid soluble content												
DAH	Plant cane	-82.58	0.39	-3.51E-04	0.79	0.50	1.66	0.48	0.40	0.99	0.89	0.88
	Ratoon 1	-10.49	0.14	-1.22E-04	0.96	0.99	4.30	0.96	0.84	1.00	0.98	0.98
	Ratoon 2	7.18	0.07	-5.79E-05	0.63	1.04	3.77	1.01	0.82	0.99	0.80	0.79
	3 harvests	-16.91	0.20	-2.51E-04	0.84	1.67	11.18	1.65	1.25	1.00	0.92	0.91
	Ratoon 1 and 2	-21.02	0.23	-2.93E-04	0.90	1.45	8.34	1.43	1.04	1.00	0.95	0.95
DD	Plant cane	-108.80	0.14	-3.66E-05	0.77	0.53	1.76	0.51	0.44	0.99	0.87	0.87
	Ratoon 1	-24.89	0.06	-1.68E-05	0.96	1.00	4.37	0.98	0.85	1.00	0.98	0.98
	Ratoon 2	-11.26	0.04	-1.10E-05	0.62	1.05	3.64	1.01	0.80	0.99	0.78	0.77
	3 harvest	-23.87	0.06	-1.94E-05	0.88	1.41	9.36	1.39	1.12	1.00	0.94	0.94
	Ratoon 1 and 2	-27.80	0.07	-2.17E-05	0.93	1.19	6.71	1.17	0.98	1.00	0.97	0.97
PET	Plant cane	-76.18	0.09	-2.24E-05	0.76	0.54	1.78	0.51	0.44	0.99	0.87	0.86
	Ratoon 1	-31.93	0.08	-2.65E-05	0.95	1.06	4.63	1.04	0.79	1.00	0.98	0.98
	Ratoon 2	-15.23	0.06	-2.11E-05	0.58	1.12	4.03	1.08	0.86	0.99	0.76	0.75
	3 harvest	-21.69	0.06	-1.95E-05	0.76	2.05	13.78	2.03	1.58	1.00	0.87	0.87
	Ratoon 1 and 2	-47.48	0.11	-4.20E-05	0.90	1.49	8.56	1.47	1.07	1.00	0.95	0.95
WD	Plant cane	-10.46	0.07	-4.06E-05	0.73	0.56	1.86	0.54	0.44	0.99	0.86	0.85
	Ratoon 1	-3.14	0.14	-1.76E-04	0.83	2.03	8.83	1.97	1.45	1.00	0.91	0.91
	Ratoon 2	17.38	0.02	2.94E-06	0.60	1.09	3.92	1.05	0.86	0.99	0.78	0.77
	3 harvests	7.61	0.06	-5.39E-05	0.62	2.56	17.15	2.53	1.92	1.00	0.79	0.78
	Ratoon 1 and 2	-4.17	0.15	-2.10E-04	0.80	2.04	11.73	2.01	1.39	1.00	0.90	0.89

In addition, there are empirical multivariate linear regression models in the literature that satisfactorily estimate total recoverable sugars (TRS) (Scarpari and Beauclair, 2004; Cardozo et al., 2015).

It is important to emphasize that there might be a need for model adjustments based on the adopted cultivation specifics. This is because the model's express parameters tailored to each study region where they were formulated, encompassing soil, climate, and genetic characteristics of the varieties. Therefore, it is relevant to employ a broader range of sugarcane varieties for validation to confirm that equations can be generalized across different varieties and locations.

For future studies, new approaches can be explored, such as those based in remote sensing that can be applied for monitoring crop growth and development, as well as providing soil physical-hydraulic information as an alternative to traditional field data collection methods. Another avenue is conducting studies in other production locations, under distinct climate and soil conditions, integrating factors like more varieties and harvests, irrigation, fertilizer use, adopted management techniques, and soil physicochemical traits. It is also vital to foster a collaborative network between researchers and mills, facilitating knowledge exchange and information sharing, to establish a robust database that can be utilized in the development of artificial intelligence models and decision support tools for more accurate predictions and real-time insights on the crop. Finally, continuous study of sugarcane responses to climate and soil conditions is necessary to enable the development of varieties better adapted to the production environment and to promote sustainable farming practices that ensure proper crop growth, improve soil health, and reduce water stress.

Conclusions

Minimum air temperatures and thermal amplitude, typical of South-Central Brazil, do not induce sugarcane maturation, which occurs by accumulated water deficit.

The growth and soluble solids content of sugarcane are compromised when soil water content is below the storage limit for the crop, resulting in lower biometric variable rates.

The higher soluble solids content and sucrose accumulation rates at the end of the cycle are observed when soil moisture is close to field capacity in the germination, tillering and vegetative growth phases (until 250 DAH), followed by an accumulated water deficit (resetting at each water replenishment) not greater than ≈30 mm. Accumulated water deficit depths above 190 mm, 80 days before cutting reduced the accumulated sucrose rate.

Plant height and number of stem nodes exhibited sigmoidal fitting, while the leaf area index and soluble solids content are better decribed by second-order polynomial equations, both as a function of time, agroclimatic variables and water deficit. The best sugarcane growth estimates are obtained as a function of degree days, potential evapotranspiration and accumulated water deficit.

CONFLICT OF INTERESTS

The authors have not declared any conflict of interests.

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