Australian Journal of Crop Science AJCS
AJCS 18(1):11-20 (2024) ISSN:1835-2707
doi: 10.21475/ajcs.24.18.01.p4001

Received: 27/05/2023
Revised: 04/10/2023
Accepted:29/11/2023

Forecast sugarcane maturity from agrometeorological data and soil water storage

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Abstract

The environment (climate and soil) can stimulate the accumulation of sugars in the cane, inducing the plant´s maturation process. In this way, we can estimate sugarcane maturity based on the crop's growth response to environmental conditions, which allows us to quantify the raw material (ethanol or sugar) and plan the harvest. The aim of this study was to evaluate the effects of agrometeorological variables and soil water storage on the sugarcane maturation process and to generate forecasting models for soluble solids content (°Brix) and total recoverable sugars (TRS, kg t^{-1}). The experiment was carried out in the Santo Antonio de Goiás, Brazil. We evaluated °Brix and TRS of the sugarcane cycles (cane-plant, 1st ratoon, 2nd ratoon). The agrometeorological data was obtained from a weather station, which made it possible to calculate the crop's water balance and degree-day. All the variables were subjected to multivariate statistical analysis, which selected the most significant variables. The models used degree-days, reference evapotranspiration and soil water storage as independent variables, which obtained multiple coefficients of determination (R_p^2) greater than 0.60. The estimates showed a good fit for both °Brix and TRS models, which determined a mean absolute error (MAE) of 1.15 °Brix and 9.88 kg t^{-1}, respectively; and very good confidence index (c > 0.75). Independent estimates obtained MAE < 2.60 ºBrix, while TRS resulted in MAE < 21.30 kg t^{-1}, with "c" ranging from good to optimum (c > 0.70). Models based on multivariate analysis can be used to estimate the sugarcane harvest point based on the sugar content in the stalks, agrometeorological variables and soil water storage.

Keywords: *Saccharum* spp., maturation index, harvest point, modeling, plant bioclimatology.
Abbreviations: DAC_Days after cut; AWC_available water capacity; EXC_water surplus; WDS_soil water storage; WD_water deficit; SD_saturation deficit; ET_0_reference evapotranspiration; R_rainfall; MI_maturation index; DD_degree-day; °Brix_solids content; TRS_recoverable sugars; cr_current values; ac_accumulated values; rt_rates; AIC_Akaike information criterion; BIC_Bayesian information criterion; R_p^2_multiple coefficients of determination; PC_principal components; SEE_standard estimation error; ME_mean error; RMSE_root mean square error; MAE_mean absolute error; R²_coefficient of determination; r_coefficient of correlation; d_agreement index; c_confidence index; VIF_variance inflammation factor.

Introduction

The maturation of sugarcane stalks marks the last stage of the crop's phenological cycle, when sucrose accumulates, which determines the quality of the raw material that will be supplied for industrialization. When the ripening process begins, the plant reduces assimilation (production of glucose and fructose), stops growing and starts concentrating sugar until it reaches values acceptable to the industry (Leite et al., 2010; Pereira et al., 2017).

The physiological maturation process of sugarcane depends on the seasonal drop in temperature, which down the rate of vegetative growth without significantly affecting the photosynthetic process to obtain a greater balance of photosynthesized products transformed into sugar for storage in the plant tissue (Cintra et al., 2008; Cardozo et al., 2013; Sanghera, 2020). In the case of maturation, we consider that temperatures below 20°C slow down sugarcane growth and provide sucrose accumulation in the stalk (Scarpari and Beauclair, 2004), since when sugarcane develops under low temperatures (13 to 19°C), there are reductions of up to 61.9% in net CO_2 assimilation, and 56.0% in the maximum carboxylation rate of RuBisCO (Guerra et al., 2014).

In tropical areas, where temperature does not limit growth, sugarcane maturation is mainly induced by the depletion of water stored in the soil (André et al., 2010). Water deficit induces a reduction in the growth of the aerial part (Silva et al., 2008; Mauri et al., 2017), causing a reduction in the elongation of the stalk of approximately 60%, a 55 to 75% reduction in its diameter (Ecco et al., 2014), and a 64% loss ofleaf area (Barbosa et al., 2015). These reductions cause an increase of at least 10% in the plant's sucrose content (Machado et al., 2009) due to the low demand for photo-assimilated compounds in the meristematic regions.

Sugar mills estimate sugarcane maturity mainly by quantifying the sucrose and reducing sugar content in the plant's stalks. This quantification involves field sampling and laboratory analysis, which makes it expensive. The sugarcane crop is subjected to different environmental conditions during the phenological stages, which directly affects maturation (Scarpari and Beauclair, 2004; Cardozo et al., 2013). Therefore, the investigation of the crop's maturity takes place over a period of weeks in order to determine its harvest point.

Predicting sugarcane ripeness based on agrometeorological variables using models is a useful tool, as it reduces the costs of determining ripeness and helps sugarcane mills to estimate productivity, aiding management and strategic decision-making throughout the harvest (Scarpari and Beauclair, 2009; Cardozo et al., 2015). They also help to understand the crop's response mechanisms to environmental conditions (Tejera et al., 2007; Cardozo et al., 2015).

Estimating the transformation of photo-assimilated compounds into sucrose is still difficult due to the insufficient knowledge of the processes involving the interactions of climatic conditions and the physiological responses of sugarcane (Scarpari and Beauclair, 2009). Determining the degree of ripeness of sugarcane and quantifying the accumulation of sucrose in its stalks is essential information for planning the crop's harvest, which maximizes its economic yield (Cardozo et al., 2015).

Considering the complex sugarcane production system, which involves different growing environments (climate and soil) (Paixão et al., 2020; 2021; Flores et al., 2021) and varieties (Anjos et al., 2020; Antunes Júnior et al., 2021), identifying sugarcane maturity is one of the key aspects, since the constant operation of the facilities during the harvest period depends on the continuous flow of raw material. There is an inherent need to develop tools to help describe and understand sugarcane maturity patterns, since this knowledge is essential for harvest planning. Therefore, this study aimed to quantify the relationships between agrometeorological variables, water storage and sugarcane ripeness, as well as to propose empirical models for estimating °Brix and TRS.

Results and discussion

Relationships between agrometeorological variables, water deficit and sugarcane maturation

In 2013/14 harvest, the soluble solids content was 0.031 °Brix day^{-1} from 458 days after planting - DAP (start of data collection for this harvest), when the sugarcane was in the process of maturing (MI=0.78). The accumulated water deficit was 658.00 mm and the actual water content in the soil was 150.89 mm (63% of field capacity), for an accumulated 1628.61 °C day-degree. During this period, we recorded three days of average air temperature below the minimum base temperature of sugarcane (20 °C), and the increase in the soluble solids content was accompanied by an increase in air temperature (5.14 ° C of thermal amplitude), with r=0.7, meaning that for the current growing conditions, the ripening process was not influenced by the occurrence of thermal stress.

In the 2014/15 harvest, at the sugarcane vegetative growth stage (up to 280 days after cut - DAC), we observed an accumulated water deficit of 236.50 mm and a soluble solids content of 0.055 °Brix day^{-1}. In the ripening phenological stage (from 280 DAC) these values were 418.73 mm and 0.052 °Brix day^{-1}, respectively. In June and July, there were less than 10 days (non-consecutive) when the average air temperature was below 20 °C, that is, below the minimum base temperature for sugarcane, and it was found that the reduction in temperature did not contribute to sucrose accumulation (r=0.4).

The accumulated water deficit in the 2015/16 crop year, up to 280 DAC, was 230.2 mm, for a soluble solids content of -0.021 °Brix day^{-1}. At maturity, the soluble solids content was 0.035 °Brix day^{-1} and the accumulated water deficit was 395.27 mm. This crop year also saw less than 10 days with an average air temperature below 20 °C, with these temperatures occurring mainly in the months of June and July. For this crop year, temperatures below 20 °C did not influence sucrose accumulation in sugarcane (r = 0.2).

In the crop years analyzed, we observed an accumulated water deficit of 214.50 mm (2013/14), 192.91 mm (2014/15) and 107.20 mm (2015/16) in the 80 days prior to cutting, when the cane was in the process of maturing (maturity index between 0.60 and 0.85), for accumulated degree days in the crop of 1,658.58, 1,134.89 and 1,378.19 °C, respectively. During this period, the accumulated sucrose levels were 21.1 °Brix (2013/14), 18.6 °Brix (2014/15) and 20.5 °Brix (2015/16) and the soluble solids levels at harvest were 23.7, 24.8 and 24.4 °Brix, respectively. Thus, based on these results and considering the soluble solids content rates, the value of 192.91 mm seems to be the critical water deficit for the start of the reduction in soluble solids content rates. According to Scarpari and Beauclair (2004), an accumulated deficit level of more than 130 mm in four months prior to harvest affects the accumulation of sucrose in the stalks. Inman-Bamber (2004) concluded that sucrose accumulation is reduced (34%) with a water deficit of more than 145 mm.

Other studies have indicated that sugarcane is more sensitive to water deficit in the growth stage, when there is marked leaf expansion and greater water demand and gas exchange with the atmosphere, which can result in a decrease in sucrose accumulation. According to Machado et al. (2009), water deficit (40% of field capacity) reduces sucrose accumulation in sugarcane stalks 25% when it occurs during the vegetative growth stage. For the same water deficit in the maturation stage, no significant variations in sucrose values were observed.

The optimum water would be capable of maintaining the plant's dry matter, favoring the concentration of sucrose in the stalks and also allowing the sucrose synthesis process to continue (Araújo et al., 2016). It is understood that identifying a specific and optimal water level in the soil, which is responsible for the star of the sugarcane maturation process, is difficult determination, since the crop can be exposed to different environmental and management throughout its phenological stage, and the soluble solids content is a function of these conditions.

At the maturation stage (535 DAP in the 2013/14 crop year and 360 DAC in the 2014/15 and 2015/16 crop years) the sucrose content in the cane-ratoon cycles showed higher values (≥24.4 °Brix) compared to the content obtained in the cane-plant cycle (23.7 °Brix). These results corroborate those presented by Batta et al. (2011), who obtained a higher sucrose value in the cane-ratoon cycle (215.6 mg g^{-1}) than in the cane-plant cycle (188.2 mg g^{-1}), and according to the authors, this result indicates the greater potential of cane-ratoon to store the photoassimilates translocated by the leaves, as well as indicating better quality of the cane-ratoon juice. Simões et al. (2015) also found significant differences in the soluble solids content between cane-plant and cane-ratoon cycles, and this difference was attributed to environmental conditions, specifically the reduction in precipitation rates which may have contributed to the higher soluble solids content. According to these authors, the soluble solids content of the cane-plant was 21.9 °Brix, and the values were 22.9 and 23.6 °Brix for the cane-1st and 2nd ratoon cycles, respectively.

Multivariate analysis of agrometeorological variables and water deficit

We grouped the agrometeorological variables and water deficit levels into two principal components, and the adjustment was able to explain 79.0% of the variance (Table 1). In the principal component analysis, we used the first principal components (PC1 and PC2) in the analysis of the data set, since, according to the Kaiser criterion (Kaiser, 1958), they have eigenvalues greater than 1, which is sufficient to explain the total variance of the sample (Hongyu et al., 2016).

Using the biplot (Figure 2), we can see that the water surplus (EXC), soil water storage (WDS), and rainfall (R) show a high correlation with each other and that the occurrence of these variables indicated a lower maturity index (MI), that is, the occurrence of soil water availability in the soil hindered the star of the sugarcane maturation process, resulting in MI < 0.6. Sugarcane maturation (MI > 0.85) occurred mainly due to the water deficit (WD) and atmospheric water vapor saturation deficit (SD).

Water availability in the soil contributes positively to the growth and development of sugarcane (Brunini et al., 2018), as it plays a fundamental role in the biochemical processes that activate sprouting, contributes to the tillering process and in the accumulation of root and dry matter in the aerial part (Marin et al., 2009). According to Muraro et al. (2009), the availability of water in the soil interferes with the accumulation of sucrose in the plant, with surplus water acting as a diluent of the sucrose present in the stalks, which is unfavorable for maturation.

Water deficit in the soil reduces the photosynthetic rate, causing a decrease in carbohydrate synthesis and an increase in sucrose content, contributing to a reduction in the vegetative growth of sugarcane and the beginning of the maturation process (André et al., 2010; Ecco et al., 2014). Water deficit induces stomatal closure as a response to immediate dehydration, consequently reducing leaf transpiration (Machado et al., 2013). According to Trentin et al. (2011), the daily transpiration rate of sugarcane can reach values of less tha 73% under conditions of soil water stress (-1.500 < Ψ < -1.100 kPa).

Plant transpiration and, consequently, the evapotranspiration process, is also affected by the vapor pressure deficit of the atmosphere (Trentin et al., 2011; Massmann et al., 2019). An increase in SD results in an increase in ET_0. However, it should be noted that this environmental condition can lead to excessive water loss by the leaves, which, in a situation of leaf water deficit, causes stomatal closure with a consequent reduction in photosynthetic CO_2 assimilation (Bergonci et al., 2000; Silva et al., 2013), paralyzing the growth and development of the crop and development of the crop and the accumulation of sucrose. Thus, atmospheric vapor pressure deficit can also directly interfere with the sugarcane maturation process. According to Machado et al. (2009), the decrease in CO_2 assimilation by sugarcane in response to water deficit (40 to 50% of field capacity) varies in intensity according to the phenological phase of the crop. There is an average reduction of 58% in the initial growth phase (exposed to 43 days of water deficit), approximately 75% in the maximum growth phase (exposed to 15 days of water deficit), and 89% in the maturation phase (14 days under water deficit condition). As a plant with a C4 metabolism, sugarcane is efficient at carboxylation using the enzyme PEPcase (phosphoenolpyruvate carboxylase), which gives it higher photosynthetic rates and low CO_2 assimilation (Matsumura et al., 2020). According to the results presented by Simões et al. (2015), even with the 70% reduction in transpiration, there were no reductions in the net photosynthetic rates of sugarcane.

Mathematical modeling

The edaphoclimatic variables of water deficit (WD, mm), atmospheric vapor pressure deficit (SD, kPa), reference evapotranspiration (ET_0, mm), water surplus (EXC, mm), degree-day (DD, °C day), soil water storage (WDS, mm), and rainfall (R, mm) to select the variables used to obtain the models for estimating soluble solids content (°Brix) and total recoverable sugars (TRS), analyzing their current values (cr), that is, the values obtained on the days the data was collected, their accumulated values (ac) over the studied period studied and their respective rates (rt). Only the data obtained from the beginning of the maturation process (MI > 0.60) was considered for the modeling process, with the aim of estimating sucrose accumulation.

In relation to the collinearity trend assessments and the normality, homoscedasticity, and independence tests, as well as the tests that analyze the existence of outlier in the residues of the technological (soluble solids content and total recoverable sugars) and edaphoclimatic variables, we found that the data residuals had a normal distribution (Anderson-Darling test, p > 0.05), homoscedasticity (Breusch Pagan test, p > 0.05), and no trend depending on the order in which the data was collected, suggesting that the errors were independent. Using the Bonferroni test (p > 0.05), we did not reject the hypothesis that the observations were not outliers. There was also no indication of multicollinearity in the variables with VIF < 10 (Hair et al., 2009).

Considering the results obtained with the criteria for choosing and adjusting the models, we adopted the variables obtained by the technique for selecting all possible models, which selected the variables DD_{ac} (°C day), ET_{0ac} (mm) and WDS_{cr} (mm) for the ºBrix model. For these variables, the AIC and BIC values obtained were 155.5 and 163.3, respectively, and multiple coefficients of determination (R_p^2) of 0.616. The selected variables and their respective coefficients in the multiple linear regression equation multiple, including the intercept of the model, were significant (p < 0.05) for the estimation of the soluble solids content (ºBrix), consisting on the following (Equation 1):

$$°Brix = 23.30506 + 0.011492DD_{ac} - 0.00552ET_{0_{ac}} - 0.06914WDS_{cr} \quad (1)$$

To estimate TRS (kg t^{-1}), the technique of all possible models also presented the most satisfactory results for data selection, indicating the variables DD_{ac} (°C day), ET_{0ac} (mm), and WDS_{cr} (mm), and obtaining AIC = 324.0, BIC = 332.4, and R_p^2 = 0.662. The edaphoclimatic variables selected to obtain the model (Equation 2) were significant (p < 0.05) for estimating TRS (kg t^{-1}), and for their respective coefficients in the equation and intercept.

$$TRS = 157.4421 + 0.09705DD_{ac} - 0.04043ET_{0_{ac}} - 0.53469WDS_{cr} \quad (2)$$

When developing the models, the range values for each variable were 929.89 to 1935.72 °C (DD_{ac}), 877.02 to

2123.63 mm (ET_{0ac}), and 144.04 to 191.61 mm (WDS_{cr}). Considering the modeling procedures carried out, both models (Equations 1 and 2) were predicted using the same edaphoclimatic variables, with DD_{ac} as an additive variable, that is, a variable directly proportional to sucrose accumulation, and the ET_{0ac} and WDS_{cr} variables as inversely proportional to the response variables (e.g. ºBrix and TRS). These predictor variables have a significant influence on the sugarcane maturation process, justifying the significance indicated by the variable selection process.

The concept of accumulated day-degree, or thermal sum, is widely and satisfactorily used to relate the effect of air temperature to the growth and development of a crop and is based on the response of plants to air temperature and the existence of base temperatures (Pilau et al., 2011). In addition to the importance of this variable in estimating biological time, its simple determination has a notable advantage and has been investigated in several studies for various crops, such as sugarcane (Teruel et al., 1997; Almeida et al., 2008). These studies have shown a positive linear relationship between accumulated degree-day and sugarcane maturation (r > 0.95). This relationship is also indicated in the ºBrix and TRS estimation models by the positive coefficients of the DD_{ac} variable. In all harvests, accumulated day-degree show linear behavior ($R^2 > 0.992$).

Throughout the harvests, the predominant degree-day (90%) was between 2 and 7 °C. The highest degree-day, between 7 and 9 °C, occurred mainly in September and October, which corresponds to the harvest period. The lowest recorded day-degree, between 0 and 2 °C, occurred mainly in May and June, when the plants were in the process of maturing (MI > 0.6). We would point out that, although the milder temperatures (which resulted in DD ≤ 2°C) occurred during the same period as the maturation process, we found no relation between the lower DD values and the increase in maturation indices, obtaining an average linear correlation (r) of 0.4, indicating that the milder temperatures did not affect the sugarcane maturation process. ET_0 is a meteorological variable that expresses the maximum loss of water or the maximum water demand of crops for the weather conditions, establishing the ideal level of water availability in the soil-plant-atmosphere system, in order to achieve the maximum possible production (Massmann et al., 2019; Paixão et al., 2020; 2021). Based on the plant's transpiration process, ET_0 is directly related to the production and accumulation of sucrose in sugarcane, since the plant's transpiration and photosynthesis processes use the stomata simultaneously. According to Ometto (1981), the meteorological elements that affect ET_0 values are solar radiation, air temperature, atmospheric vapor pressure deficit and rainfall. In the Santo Antonio de Goias (Brazil), the maximum ET_0 values occur in August and September, when the sugarcane enters the phenological phase of maturation (MI > 0.85). We also found that during the maturation process (0.6 < MI < 0.85), from June onward, ET_0 values tended to increase until the end of the harvest. Therefore, ET_{0ac} showed a quadratic behavior ($R^2 = 0.99$) in all the crop years studied. Sucrose accumulation also showed quadratic behavior ($R^2 = 0.84$), but ET_0 accumulation increased between June and September, while sucrose accumulation rates, on average, decreased during this same period, which justifies the ET_{0ac} variable being inversely proportional to the soluble solids content (°Brix) and total recoverable sugar (TRS) values in the multiple linear regression models.

In tropical regions, the sugarcane maturation process is mainly induced by the depletion of water stored in the soil (André et al., 2010; Cardozo et al., 2013; Casaroli et al., 2019), characterized when soil water storage is below the limiting soil water content for the plants (Casaroli et al., 2010). In the study area, soil water storage averaged 148.6 mm, predominantly below 191.61 mm (the level of water needed for the soil to reach $\theta_{crit} = 0.319$ cm^3 cm^{-3}), from May to September, characterizing soil water deficit. Considering the negative coefficients of the WDS_{cr} variable in both equations, we infer that a decrease in soil water content contributes positively to an increase in the amount of sucrose. Inman-Bamber (2004) found that soil water content influences sucrose accumulation in sugarcane. These authors state that the occurrence of a water deficit of more than 120 mm (and up to 145 mm) contributed positively to increasing sucrose accumulation, even if there was a reduction in dry matter. Vieira et al. (2013) also observed that the water content in the soil interferes with the maturation of sugarcane, variety RB86-7515, but found that after 29 days of water deficit, there was a 3.8% reduction in the maturation index. Machado et al. (2009) fond no significant variations in sugarcane sucrose values in relation to changes in the water table in the soil during the ripening period. Oliveira et al. (2012) found that different varieties of sugarcane showed different behavior in terms of sucrose accumulation as a function of soil water content, and these responses may or may not be significant.

The variables in the °Brix estimation equation (Equation 1) explain 61.6% (R_p^2) of the data collected, that is, the accumulation of soluble solids content in the parenchyma cells of sugarcane stalk. The model performed very well (c = 0.774) and the linear correlation (r) of the observed and estimated data was 0.778, with ME = -0.010 °Brix and MAE = 1.149 ºBrix, verifying the accuracy of the values observed in the field when compared to the values estimated by the model, as indicated by the agreement of 0.995 (Table 2). Cardozo et al. (2015) proposed exponential models based on accumulated rainfall, specific to the municipality of Piracicaba, SP (Brazil), to estimate the °Brix for sugarcane varieties. In all models, the adjusted R^2 values were higher than 0.97, which, according to the authors, indicates good model accuracy. These models also showed accuracy (d > 0.94), optimum performance (c > 0.93), and a maximum mean absolute error of 1.1 °Brix. When applying the model to Capivari, SP (Brazil), the authors observed an overestimation of the results (ME > 0.68 °Brix), and for Jau, SP (Brazil), an underestimation of the °Brix values was observed (ME < -0.81 °Brix). The TRS (kg t^{-1}) estimation model (Equation 2) explains 66.2% (R_p^2) of the variability of the data obtained in the field due to the edaphoclimatic variables DD_{ac} (°C day), ET_{0ac} (mm), and WDS_{cr} (mm). For the estimates over the harvest periods, the model showed a mean absolute error (MAE) of 9.880 kg t^{-1} and MA of -0.226 kg t^{-1}. According to the coefficient of confidence, the model performed very well (c = 0.801) and there was a positive linear correlation (r = 0.813) between the estimated and observed values. The coefficient of agreement (d = 0.996) indicated that the observed and estimated data were close (Table 2), corroborated by the data dispersion graphic (Figure 3B), in which the sample distribution is close to the 1:1 line. Scarpari and Beauclair (2009) proposed multiple linear regression models for estimating TRS and obtained a coefficient of determination of 0.26 for the late variety (RB72-454). Cardozo et al. (2015) suggested exponential

Table 1. Principal component analysis of the variables water deficit (WD, mm), atmospheric vapor pressure deficit (SD, kPa), reference evapotranspiration (ET_0, mm), water surplus (EXC, mm), degree-day (DD, °C day), soil water storage (WDS, mm), and rainfall (R, mm), in Santo Antonio de Goias, Goias, Brazil.

Variance components	Principal components (PC)	
	1	2
Auto-values	4.19	1.33
Proportion (%)	59.9	19.1
Accumulated proportion (%)	59.9	79.0
Variables	Correlations with the principal components	
WD	-0.83	0.04
SD	-0.83	0.30
ET_0	-0.56	0.50
EXC	0.86	0.37
DD	-0.41	0.80
WDS	0.89	0.26
R	0.90	0.38

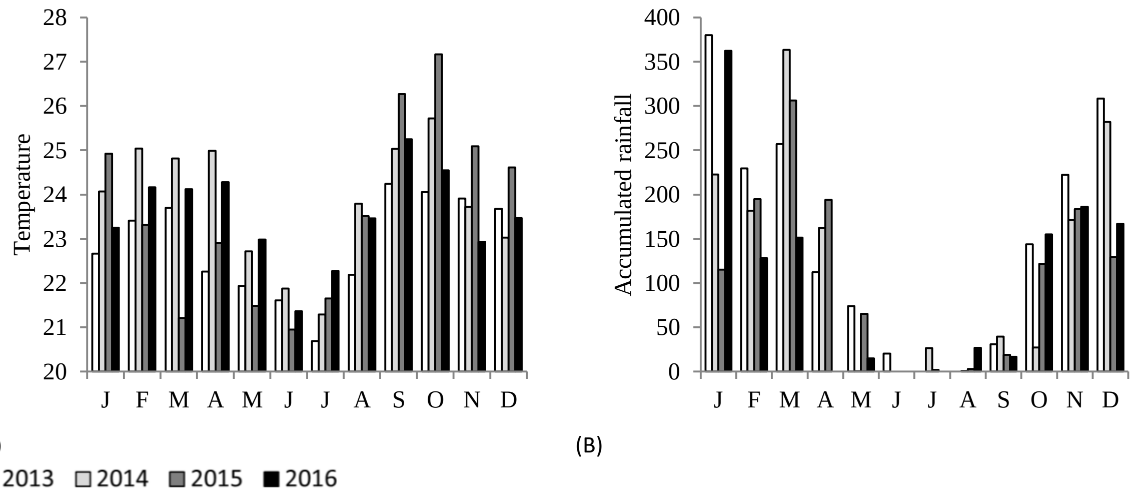


Fig 1. Monthly average air temperature (°C) (A) and accumulated rainfall (mm) (B), in Santo Antonio de Goias, Goias, Brazil, from 2013 to 2016.

Table 2. Coefficient of determination (R^2), standard estimation error (SEE), mean error (ME), root mean square error (RMSE), mean absolute error (MAE), coefficient of agreement (d), coefficient of correlation (r), and confidence index (c) of the estimation models for soluble solids content (°Brix) and total recoverable sugars (TRS, kg t^{-1}).

Model	SEE	ME	RMSE	MAE	d	r	c
°Brix	1.529	-0.010	1.509	1.149	0.995	0.778	0.774
TRS	12.493	-0.226	12.332	9.880	0.996	0.813	0.810

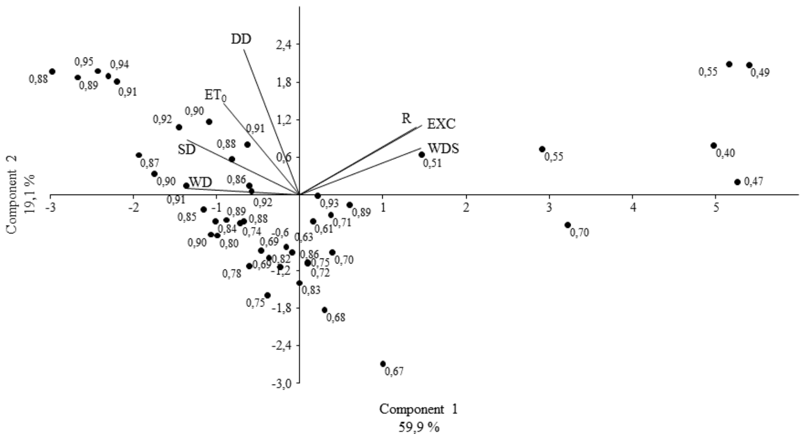
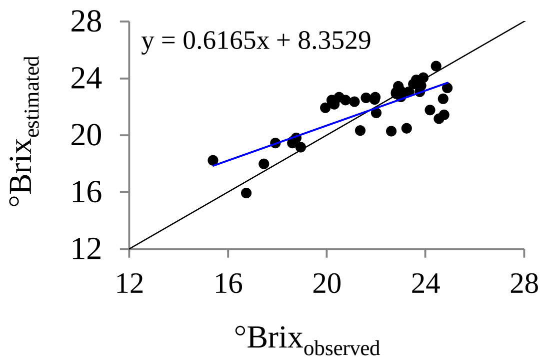
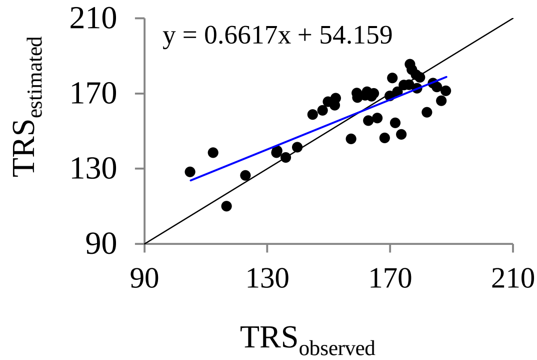


Fig 2. Principal component and biplot analyses of the variables water deficit (WD, mm), atmospheric vapor pressure deficit (SD, kPa), reference evapotranspiration (ET_0, mm), water surplus (EXC, mm), degree-day (DD, ° day), soil water storage (WDS, mm), and rainfall (R, mm), and the maturation index over the variables, performed by correlation matrix, in Santo Antonio de Goias, Goias, Brazil.

Table 3. Standard estimation error (SEE), mean error (ME), root mean square error (RMSE), mean absolute error (MAE), coefficient of agreement (d), coefficient of correlation (r), and confidence index (c) of the estimation models for soluble solids content (°Brix) and total recoverable sugars (TRS, kg t^{-1}) of the SP80-1842, SP70-1143, RB86-7515, and CTC-4 varieties produced in different crop years (2007/08, 2008/09, 2009/10, 2010/11, 2011/12, 2016/17, and 2017/18) in Santo Antonio de Goias, Goias, Brazil.

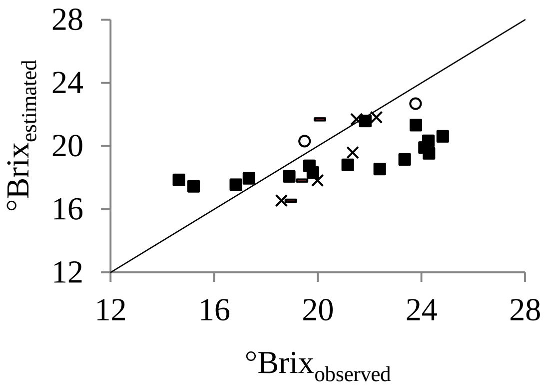
Model	Variety	SEE	ME	RMSE	MAE	d	r	c
°Brix	SP80-1842	1.760	-1.252	1.574	1.331	0.952	0.948	0.903
	SP70-1143	2.339	-0.803	1.910	1.869	0.831	0.989	0.822
	RB86-7515	3.048	-1.695	2.951	2.530	0.976	0.790	0.771
	CTC-4	1.372	-0.164	0.970	0.957	0.958	1.000	0.958
TRS	SP80-1842	18.469	-11.020	16.519	14.701	0.923	0.815	0.752
	SP70-1143	27.244	-11.754	22.245	21.255	0.720	0.996	0.717
	RB86-7515	24.235	-11.808	23.465	20.270	0.978	0.818	0.800
	CTC-4	6.326	4.006	4.473	4.006	0.982	1.000	0.982

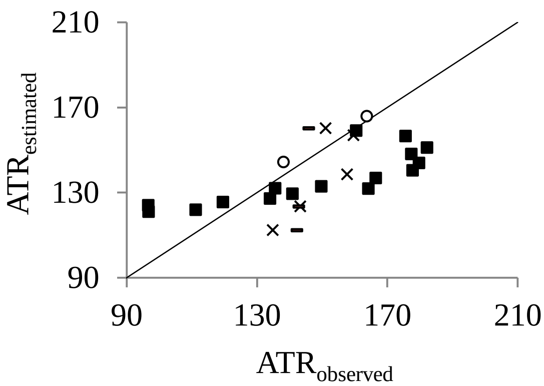




(A) (B)

Fig 3. Relationships between soluble solids content (°Brix) observed and estimated (A), as well as total recoverable sugars (TRS, kg t^{-1}) (B), using the multiple regression model for sugarcane in Santo Antonio de Goias, Goias, Brazil. The black line represents the proportion 1:1.





(A) (B)

Fig 4. Relationships between soluble solids content (°Brix) observed and estimated (A), as well as total recoverable sugars (TRS, kg t^{-1}) (B), using the multiple regression model of the SP80-1842 (×), SP70-1143 (-), RB86-7515 (■) and CTC-4 (○) varieties, in Santo Antonio de Goias, Goias, Brazil. The filled line represents the proportion 1:1.

models for determining TRS as a function of total accumulated rainfall in the 120 days prior to sampling, when studying agrometeorological variables and early, medium and late sugarcane varieties in the municipality of Piracicaba, SP, Brazil. The authors obtained excellent model performance (c = 0.99), with MAE of less than 6.0 kg t^{-1} and positive mean errors (ME > 4.13 kg t^{-1}) indicating overestimation of the data in Capivari, SP (Brazil), and negative mean errors (ME < -3.86 kg t^{-1}) due to underestimations in Jau, SP (Brazil).

The graphic analysis of the estimates can be observed in Figure 3, verifying that the distribution of the observed °Brix values versus the estimated values tends towards a 1:1 line (Figure 3A). However, the regression trend line showed that the model overestimates soluble solids content values below 22 °Brix by approximately 5% and overestimates values above 22 ºBrix by 2.3%. The relationship between the estimated TRS values and the values observed in the field also presented a distribution tending to the proportion of 1:1 (Figure 3B). However, it is worth noting that the model can overestimate ATR values of less than 160 kg t^{-1} by 5.5% and, from this value onwards, the model underestimates the results by up to 2.9%. This tendency to underestimate and overestimate can also be confirmed by the angular coefficients of the simple linear equations (ºBrix, b = 0.6165; TRS, b = 0.6617) presenting values of less than 1, which characterizes the occurrence of systematic percentage error, that is, the errors vary throughout the data series, with an increase in error in conditions of lower concentrations of soluble solids content and total recoverable sugar in the sugarcane juice.

Model validation

The model validation analyses are presented in Table 3. The model for determining the soluble solids content (°Brix) showed satisfactory results for the variables studied in the different harvest cycles and years (r=0.790 between varieties). The lowest mean absolute error occurred for the varieties CTC-4 (MAE = 0.957 °Brix), and SP80-1842 (MAE = 1.331 °Brix), obtaining the best confidence index (c > 0.900; d > 0.950). The largest errors were determined for the RB80-7515 variety (MAE = 2.53 °Brix), however, they still obtained good indices (c > 0.75; d > 0.97). These results indicate the great variability of this model for different varieties.

The TRS values estimated by the model (Table 3) also showed a positive linear correlation with the values obtained in the field (r > 0.81), with better results observed for the varieties CTC-4 (MAE = 4.006 kg t^{-1}, d = 0.982), and SP80-1842 (MAE = 14.701 kg t^{-1}, d = 0.923), presenting optimum and very good performance, respectively. The SP70-1143 and RB86-7515 varieties presented MAE values of more than 20 kg t^{-1}, approximately 14% absolute error in the estimate, although they performed well and very well, respectively.

Marin et al. (2011) used the DSSAT/CANEGRO model to estimate, among other variables, the soluble solids content of the RB72-454 and SP83-2847 varieties, obtaining coefficient of agreement (d) values of 0.68 and 0.72, respectively. These results were higher than those obtained by Nassif et al. (2012) for the CTC-4, CTC-7, and CTC-20 varieties, for which the coefficient of agreement values ranged from 0.47 to 0.55, with a root mean square error (RMSE) of up to 2.61 ºBrix. Inman-Bamber et al. (2009) point out that errors in estimating sucrose accumulation are due to insufficient knowledge of the plants' complicated ripening process.

We observe that for values of up to 18 °Brix the model overestimate the results by approximately 9.45%; however, for higher soluble solid contents (above 18 °Brix) there is an underestimation of 10.73% (Figure 4). For TRS values of up to 130 kg t^{-1}, the model presented overestimated results (13.80%), and for higher values, the results were underestimated (12.84%). The trends of underestimation and overestimation of °Brix and TRS were predicted from the curve describing the simple linear regression of the estimated data as a function of the observed data and the respective angular coefficients of the equation (Figure 3). However, the tendency to underestimate is more relevant, since practically all mean errors were negative (Table 3).

The results presented by Singels et al. (2008) for experiments carried out in South Africa, and Marin et al. (2011) for experiments conducted in the Southeastern region of Brazil, show the same trend observed in this study, overestimating the sucrose content in conditions of low sucrose concentrations, and the opposite as the soluble solids content increased. Cardozo et al. (2015) suggest the use of exponential models to optimize the adjustment of the estimation of sucrose accumulation and emphasizes the importance of validating the models in conditions other than those in which they were developed, and the possibility of the need for better adjustments in the estimates.

The validation of the models presented in growing environments with meteorological conditions and soil water contents distinct from those in which they were generated is essential and necessary, given that the applicability of empirical models to these conditions is continuously questioned. In this situation, models may need to be adjusted according to the particularities of the crop. This occurs because the models express specific adjustment parameters for the studied region in which they were generated, which involve soil, climate and genetic characteristics of the varieties. According to Dias and Sentelhas (2017), one of the primary reasons for the low performance of the estimation models for the sugarcane is the different management practices adopted in the many commercial fields, leading to a different response from the crop to the edaphoclimatic conditions.

Other aspects must be taken into account and can cause greater deviations in the estimates. The models do not take into account the use of mature plants, sugarcane flowering and attacks by pests and diseases, given that the occurrence of any of these events directly interferes with the accumulation of sucrose in the stalks of the plants. Soil management and correction, especially in terms of nitrogen availability, are environmental conditions that can influence the estimated values.

Materials and methods

Site, climate and soil

The study was carried out in the municipality of Santo Antonio de Goiás, GO, Brazil (16°29’8” S; 49°20’36” W; 780 m alt.), leased by the CentroÁlcool® mill. According to the Köppen climatic classification, the region has an Aw-type climate (tropical savannah), characterized by 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).

During the experiment (crop cycle), the average maximum and minimum air temperatures were 29.6 e 18.2 °C, respectively, and the average accumulated rainfall per harvest-year was 1,481.3 mm (Figure 1), according to meteorological data obtained from the automatic weather station. Furthermore, degree-days (DD, °C day) were determined throughout the sugarcane cycles following the set of equations proposed by Ometto (1981), with lower basal temperature Tb = 20 °C (Barbieri and Villa Nova 1977) and upper basal temperature TB = 35 °C (Pereira et al. 2015). The soil in the area was classified as a dystrophic Red-Yellow Latosol of sandy-clay-loam texture and constituted of 27% clay, 13% silt, and 60% sand (Embrapa, 2013). We prepared the soil by plowing and harrowing, applying 2.0 t ha^{-1} of agricultural gypsum and 4.0 t ha^{-1} of limestone to correct the soil. During planting, we applied 120 kg ha^{-1} of P_2O_5 and with a cover of 380 kg ha^{-1} of 18-00-27 NPK formula.

Cultivation characteristics

The data collected refers to the harvest-years 2013/2014 (cane-plant), 2014/2015 (cane -1st ratoon), and 2015/2016 (cane - 2nd ratoon). The sugarcane variety grown in the area was CTC-4. This variety is of medium maturity and harvest time is between June and September. It is characterized by a vigorous development, good tillering and a medium tendency to flowering and low isoporization. This variety is recommended for cultivation in locations with average to good soil fertility conditions, and stands out for its high productivity and high sucrose content (CTC, 2013).

The semi-mechanized planting system with pre-sprouted seedlings was carried out in April 2013. The rows were spaced 1.5 m apart, after the area had been furrowed. We harvested the cane manually, with the first cut in September 2014 and the second and third taking place in October 2015 and 2016, respectively.

We controlled the weeds by applying herbicide for large-leaf weeds in quantity recommended by the sugarcane mill.

Assessments

Three experimental plots were evaluated, which were formed by six rows and 15 m in length. In each plot, 20 stalks were sampled (two central rows). The soluble solids content (ºBrix) was quantified using a digital field refractometer in decennial samples, from four (cane-plant) to five (cane-ratoon) months before harvest. We used this data to calculate the maturation index (MI) of the sugarcane through the relation of the soluble solids content (ºBrix) of the upper and lower thirds of the stalk (Fernandes and Benda, 1985). The interpretation of MI was: immature sugarcane (MI ≤ 0.60); sugarcane under maturation process (0.60 < MI ≤ 0.85); mature sugarcane (0.85 < MI ≤ 1.00); and sugarcane in the process of decreasing sucrose (MI > 1.00).

Samples for obtaining total recoverable sugars (TRS) were collected monthly, from 4 (cane plant) and 5 (ratoon) months before harvest, totaling 14 repetitions. For each replicate, randomly selecting 40 stalks suitable for industrialization, from which we cut off the tips, removed the stalk (Bidoia and Bidoia, 2010), and sent it to the plant's laboratory.

Water balance

The sugarcane water balance was calculated on a weekly scale, with reference evapotranspiration (ET_0) obtained by the Penmam-Monteith method (Allen et al., 2006). The water balance was used to determine water storage in the soil. Readily available water (RAW = 47.57 mm) represents the multiplication of total available water (TAW) and the fraction of total available water (*f* = 0.5) at which evapotranspiration maintains its maximum value (ETc = 7 mm day^{-1}) (Doorenbos and Kassam, 1979). The TAW was determined (TAW = 95.14 mm) as a function of the effective depth of the root systema (Zr) and the soil's physical and water properties, determined from a preliminary study.

Close to the harvest/cutting dates, we conducted a visual evaluation of the root system profile. A trench (0.90 x 0.60 x 0.80 m in length, width and depth, respectively) was opened to determine the average effective depth of the root system (Zr = 0.60 m). Also, undeformed soil samples were collected at depths of 0.0-0.20, 0.2-0.4, and 0.4-0.6 m, using volumetric rings. These soil samples were saturated for 24 hours and drained until the mass stabilized, when they reached the water content of the soil at field capacity (θ_{FC} = 0.399 m^3 m^{-3}). We also determined the soil water content at the permanent wilting point (θ_{PWP} = 0.240 m^3 m^{-3}) from the water retention curve (Richards method; Embrapa, 2017).

Statistical analysis

A completely randomized design (homogeneous area) was used, with repetitions over time.

Principal component analysis estimated the relationships between meteorological data, soil water content and the sugarcane maturation index. We considered the first principal components whose values were greater than unity to generate the biplot graph (Kaiser, 1958).

The techniques of all possible models and automatic selection were used to select the variables for the multiple linear regression model. For the technique of selecting all possible models, we used Akaike's Information Criterion (AIC), the Bayesian Information Criterion (BIC) and the values of the multiple coefficients of determination ($R^2_{p\_}$). The Forward, Backward and Stepwise methods were used to select the variables using the automatic selection technique, in which the F test (α = 0.05) was used to add and/or remove variables. All statistical analyses were carried out using Action software (http://www.portalaction.com.br/).

After selecting the variables for the multiple linear regression models, we chose the models for estimating soluble solids content (ºBrix) and TRS (kg t^{-1}) using a series of criteria in which, for each response variable, we select for validation the model that best fitted the data and showed the lowest estimation errors. The values estimated by the regression models were evaluated based on the standard estimation error (SEE), mean error (ME), root mean square error (RMSE), and mean absolute error (MAE). The quality of the adjustment (exactness) obtained by the models is given by the coefficient of determination (R^2), which is related to the closeness of the estimated values to the observed values. This approximation was obtained by the agreement index "d" (Willmott et al., 1985), of which values range from zero (no agreement) to 1 (perfect agreement). The development of the models was also assessed using the confidence index (c). The coefficient c is interpreted as: great (c > 0.85), very good (0.75 < c ≤ 0.85), good (0.65 < c ≤ 0.75), average (0.60 < c ≤ 0.65), not good (0.50 < c ≤ 0.60), bad (0.40 < c ≤ 0.50, and very bad (c ≤ 0.40) (Camargo and Sentelhas, 1997).

For both variable selection and obtaining the estimated values, we analyzed these residues regarding the normality (Anderson-Darling test), homoscedasticity (Breusch Pagan test), and independence (graphic analysis of the residues versus order of collection). We also investigated the existence of a data outlier (Bonferroni test) and multicollinearity (variance inflammation factor – VIF). For validation, we employed the models to estimate the soluble solids content (°Brix) and TRS (kg t^{-1}) of the SP80-1842, SP70-1143, and RB86-7515 sugarcane varieties produced in the municipality of Santo Antonio de Goiás, GO (Brazil) in distinct crop years (2007/08, 2008/09, 2009/10, 2010/11, and 2011/12), with cane -1st ratoon, cane - 2nd ratoon, and cane - 3rd ratoon cycles and for the CTC-4 variety refer to the 2016/17, and 2017/18 crop years, with cane - 3rd ratoon, and cane - 4th ratoon cycles, totalizing 26 observations. We analyzed the validation results using the same criteria adopted in the analysis of the estimates.

Conclusions

The highest soluble solids content at the end of the harvest and the highest sucrose accumulation rates occurs when the soil water content remains close to field capacity in the phenological stages of sprouting, tillering and vegetative growth (up to 250 DAC) with subsequent reduction in soil water content to values below the soil water limit. The accumulated water deficit of 193 mm in the last 80 days before cutting causes a reduction in the rate of sucrose accumulation. The water deficit and air vapor pressure deficit are the agrometeorological variables that most influenced the maturation of sugarcane variety CTC-4. The variables that best explained the sugarcane maturation process in terms of the accumulation of total recoverable sugars and soluble solids content are the following accumulated degree-day (positive influence), accumulated ET_0, and current depth of water in the soil (inhibit maturation), explaining more than 60% of the variability in the data.

The proposed models are capable of determining the maturation process and the harvesting point of sugarcane, showing satisfactory performance in the evaluations and in the application for estimating data from other varieties.

We recommend that these models be used from the beginning of the sugarcane maturation process when the maturation index is greater than 0.6.

Acknowledgements

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors. We would like to thank the CentroAlcool® sugarcane mill for providing the production area; the Graduate Program in Agronomy at "Universidade Federal de Goiás" (PPGA-UFG) for the research grant to a doctor student in agronomy (first author); the Coordination for the Improvement of Higher Education Personnel (CAPES) for the master's research grant (fourth author) and the doctoral grant (sixth author) in agronomy; and the Research Support Foundation of the State of Goiás (FAPEG), for payment of the manuscript publication fee.

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