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ORIGINAL PAPER

Modeling sugarcane ripening as a function of accumulated rainfall in Southern Brazil

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Abstract The effect of weather variables on sugarcane ripening is a process still not completely understood, despite its huge impact on the quality of raw material for the sugar energy industry. The aim of the present study was to evaluate the influence of weather variables on sugarcane ripening in southern Brazil, propose empirical models for estimating total recoverable sugar (TRS) content, and evaluate the performance of these models with experimental and commercial independent data from different regions. A field experiment was carried out in Piracicaba, in the state of São Paulo, Brazil, considering eight sugarcane cultivars planted monthly, from March to October 2002. In 2003, at the harvest, 12 months later, samples were collected to evaluate TRS (kg t^{-1}). TRS and weather variables (air temperature, solar radiation, relative humidity, and rainfall) were analyzed using descriptive and multivariate statistical analysis to understand their interactions. From these correlations, variables were selected to generate empirical models for estimating TRS, according to the cultivar groups and their ripening characteristics (early, mid, and late). These models were evaluated by residual analysis and regression analysis with independent experimental data from two other locations in the same years and with independent commercial data from six different locations from 2005 to 2010. The best performances were found with exponential models which considered cumulative rainfall during the 120 days before harvest as an independent variable (R^2_{adj} ranging from 0.92 to 0.95). Independent evaluations revealed that our models were capable of estimating TRS with reasonable to high precision (R^2_{adj} ranging from 0.66 to 0.99) and accuracy (D index ranging from 0.90 to 0.99), and with low mean absolute percentage errors (MAPE≤ 5 %), even in regions with different climatic conditions.

Keywords *Saccharum* spp. · Empirical models · Rainfall · Total recoverable sugar

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Introduction

Renewable energy is a promising means for promoting sustainable development. The increase of biofuels in the global energy matrix helps mitigate the contribution of fossil fuels to climatic change and increase energy security worldwide. Most of the new renewable energy sources are still in development on a commercial scale, though some technologies are already well established, as ethanol is, in Brazil, made from sugarcane (Goldemberg 2007). Brazil is the largest sugarcane producer in the world with a production of 697.8 million tons covering 8.8 million hectares (FNP 2013). Sugarcane is the most important bioenergy crop in the country, as well as the main source for sugar, and is expanding into new areas where agroclimatic conditions are suboptimal (Vianna and Sentelhas 2014). This fact, associated with the inter-annual climate variability, has brought consequences for crop growth and ripening patterns since it is the weather conditions which are primarily responsible for both yield and juice quality (Cardozo and Sentelhas 2013; Keating et al. 1999; Barbieri 1993).

According to Alexander (1973), sugarcane plants retard its growth and enhance the sucrose accumulation under certain specific conditions of air temperature and soil moisture. Sucrose content is higher in the winter when more sucrose is stored

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because of a reduction in sink strength for structural growth (Singels et al. 2005) promoted by several factors (Clements 1962), such as low air temperature and water deficit. It is well known that sucrose in the stalk varies with the period of harvest (Cardozo et al. 2014; Inman-Bamber et al. 2002), but it also varies with crop age, water stress, and cultivar (Cardozo and Sentelhas 2013; Inman-Bamber et al. 2002; Redshaw and Nuss 2001; Evensen et al. 1997). Yates (1972, 1996) found that in places where there is no water deficiency, the low air temperatures promoted ripening, and Glover (1971) suggested that the average air temperature needs to be lower than 21 °C for 3 months to begin the ripening process and below 18 °C for an intense sucrose accumulation (Alexander 1973).

As sugarcane crops face different environmental conditions throughout the growing season, and according to that, the prediction of crop responses to these conditions allows for a better characterization of sugarcane planting and harvesting, optimizing both ethanol and sugar production (O'Leary 2000). Models able to estimate sugarcane quality are important tools for sugarcane harvest planning (Scarpari and Beauclair 2009), since they allow for characterizing management alternatives, create more realistic scenarios for decision making and crop optimization, and improve management efficiency and strategic decisions during the crop season (Boote et al. 1996; O'Leary 2000).

Although there are many models in the literature that could estimate biomass production (O'Leary 2000; Scarpari and Beauclair 2009; Monteiro and Sentelhas 2013; Vianna and Sentelhas 2014), modeling sucrose content in relation to carbon partitioning is still difficult. As reported by Singels and Bezuidenhout (2002), mechanistic models such as Canegro and Agricultural Production Systems Simulator (APSIM) use similar approaches to represent sugarcane ripening, whereby the sink for stalk structural growth under non-limiting conditions is determined by temperature. Even more complex than empirical models, the mechanistic ones generally have difficulty in simulating the subtle changes in sucrose content when growing conditions are modified (Singels et al. 2005). As a consequence of that, Inman-Bamber et al. (2002) proved that their empirical model for estimating sucrose content outperformed the APSIM model, confirming the apparent shortcomings of process-based sugarcane simulation models, which is mainly associated with the lack of sufficient knowledge about the sugarcane ripening process and all the biotic and abiotic factors that affect it (Inman-Bamber et al. 2009).

The main sugarcane quality indicator in Brazil is the total recoverable sugar (TRS, kg t^{-1}), which is used to pay sugarcane growers for the quality of their production (CONSECANA 2006; Cardozo et al. 2014). The TRS represents the amount of sugars (sucrose, fructose, and glucose), recovered after the industrial process (Fernandes 2011). As TRS is a variable that expresses sugarcane quality and weather variables are the main determining factors of sugarcane ripening, the hypothesis of this study is that empirical models derived from statistical relationships between weather variables and TRS can be used to estimate sugarcane TRS levels, giving support to growers and sugar mills to plan their actions based on how TRS performed in past years and also projecting it for the next month, based on the rainfall forecast. Therefore, the objectives of this study were to determine the influence of weather variables on the sugarcane ripening; to propose empirical models to estimate TRS for sugarcane crop with different maturity groups, classified as early, medium, and late ripening; and to evaluate the performance of these models with experimental and commercial independent data from different producing regions and growing seasons, under distinct climatic conditions.

Materials and methods

Location and experimental design

A field experiment was carried out in a commercial area of the Costa Pinto Sugar Mill, Raízen Company, located in Piracicaba (latitude (Lat), 22° 36′ 45″ S; longitude (Long), 47° 37′ 47″ W; and altitude (Alt), 597 m.a.s.l.), in the state of São Paulo, Brazil (Fig. 1), from March 2002 (beginning of planting) to October 2003 (final sampling).

The sugarcane (*Saccharum* ssp.) was planted every month from March to October 2002 and harvested after 12 months, from March to October 2003, every 30 days on the 15th day of the month. The experimental design was randomized blocks with eight cultivars and three repetitions. Each plot consisted of four rows of 15 m, with 1.4 m between rows. Eight sugarcane commercial cultivars were evaluated: SP91-1049, SP86-42, SP90-3414, SP86-155, SP87-365, SP83-2847, RB928064, and RB867515. All of them are still in use, representing 40 % of the area under sugarcane cultivation in southern Brazil. The experiments were conducted according to the regional recommendation, which includes soil correction with 2.5 t ha^{-1} of limestone, 2.0 t ha^{-1} of gypsum, and 220 kg ha^{-1} of triple superphosphate and soil fertilization with 500 kg ha^{-1} of the formulation 05–25–25 at the planting. Pesticides for insects and nematodes control were also applied during the planting, with 250 g ha^{-1} of Regent 800WG and 6 L ha^{-1} of Furadan 350SC. The climatic conditions of the experimental period were typical for the region, which is a Cwa (Alvares et al. 2013), and were characterized by the monthly weather variables presented in Table 1 and by the regional soil water availability (Fig. 2). Soil water availability was determined by a climatological water balance (Thornthwaite and Mather 1955) on a 10-day time scale using a soil water holding capacity (SWHC) of 125 mm for 1-m depth, which is commonly observed for the soils of this region, classified as Rhodic Acrustox. To run the water balance

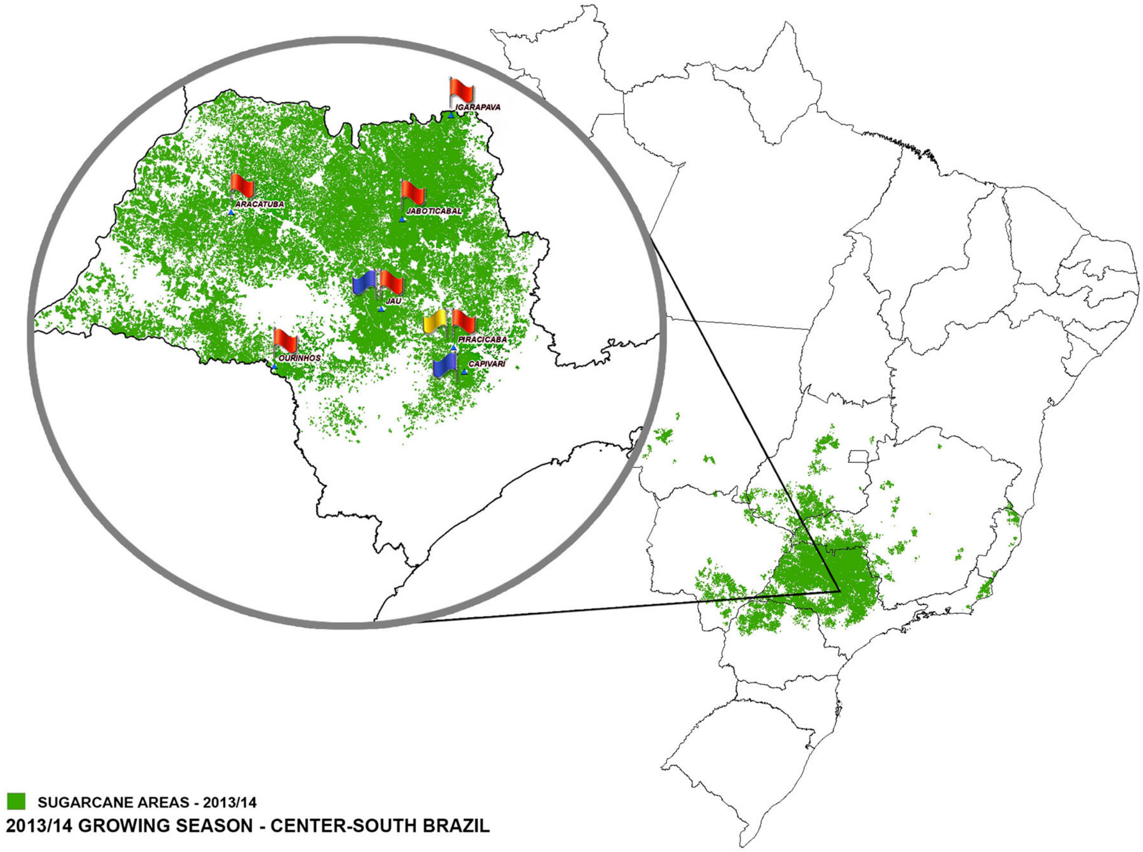

Fig. 1 Brazilian sugarcane areas in the 2013–2014 growing season. *Yellow flag* indicates the place where the experimental data were obtained from for developing the models; *blue flags* indicate the places where experimental data were obtained for validating the models; and *red flags* indicate places from where the commercial data used to validate the models came from. Source: CANASAT/INPE (2014)

for the experimental period, the reference evapotranspiration was estimated by the Penman-Monteith equation (Allen et al. 1998), which uses daily average inputs of net radiation, maximum and minimum air temperature and relative humidity, and wind speed at 2-m height (Table 1), all obtained from an automatic weather station in the region of the experimental station (≈9 km). Rainfall data were obtained from a rain gauge inside the experimental area.

Sugarcane sampling and weather data

Sugarcane samplings were collected monthly during the 8 months from March to October 2003, when the crop was 12 months old. The samples comprised the harvest of ten stalks per cultivar, which had their dead and green leaves removed. The samples were collected randomly from the central lines of each experimental plot and with three repetitions, totaling 30 stalks per cultivar, which were submitted to the technological analysis, in the lab of the Costa Pinto sugar mill, for determining the levels of reducing sugars (RS, %), soluble solids (°Brix), purity (Pur, %), polarizable sugars (Pol, %), TRS (kg t^{-1}), fiber (F, %), and moisture (M, %), according to the standards of the Brazilian Sugarcane Growers Council (CONSECANA 2006).

The weather data employed in the present study were obtained from the closest weather station in Piracicaba (at 9 km from the experimental site), in the state of São Paulo, Brazil (Lat, 22° 42′ 30″ S; Long, 47° 30′ 00″ W; and Alt, 546 m.a.s.l.). The daily weather data used were air temperature (maximum, average, and minimum), solar radiation, net radiation, photoperiod, sunshine hours, relative humidity, and rainfall. Rainfall data were also obtained from the Costa Pinto sugar mill data base. These weather data were employed to determine the accumulated water deficit and water surplus throughout the crop cycle, obtained by the serial climatological water balance of Thornthwaite and Mather (1955), for a SWHC of 125 mm for 1-m depth.

Cultivars clustering by ripening patterns

Before developing the empirical models for TRS estimate, the cultivars were grouped in early, mid, and late ripening, using clustering analysis (Sneath and Sokal 1973). The analysis was applied to the standardized values of sugarcane quality variables (RS, °Brix, Pur, Pol, TRS, F, and M), resulting in relative

Table 1 Monthly weather conditions represented by total rainfall, average daily incoming solar radiation, maximum, minimum, and average temperatures, average relative humidity, and wind speed at 2 m, in Piracicaba, SP, Brazil, from January 2002 to December 2003

Year	Month	Rainfall (mm)	SRad (MJ m^{-2} day^{-1})	Tmax (°C)	Tavg	Tmin	RHavg (%)	U_{2m} (m s^{-1})
2002	January	275.1	17.9	29.2	23.1	19.2	91.0	1.0
	February	167.8	17.7	28.5	22.7	18.8	90.5	1.1
	March	259.5	20.3	31.5	24.6	19.5	85.9	0.8
	April	26.7	18.5	31.2	23.7	17.7	82.5	0.9
	May	104.7	13.0	26.3	19.6	14.4	88.9	1.2
	June	0.3	13.5	27.4	19.3	12.6	82.9	1.2
	July	21.3	12.0	24.7	17.1	10.3	82.0	1.1
	August	63.0	14.4	28.5	20.9	14.4	77.2	1.2
	September	42.8	16.0	26.7	19.9	13.6	77.5	1.5
	October	48.9	20.2	33.0	25.0	18.5	69.7	1.7
	November	166.1	19.5	29.9	23.6	18.6	81.3	1.8
	December	169.1	20.7	30.7	24.3	19.8	85.7	1.5
2003	January	297.6	16.8	29.1	23.7	20.1	92.0	1.1
	February	52.5	21.1	31.9	25.3	20.4	84.9	1.0
	March	177.5	18.1	29.4	23.2	18.5	80.6	1.3
	April	55.0	16.0	28.4	21.8	16.5	76.5	1.1
	May	54.2	14.0	25.3	18.1	11.8	75.0	1.1
	June	8.9	12.8	27.5	19.2	12.4	74.1	0.9
	July	16.4	12.7	26.4	18.2	10.9	65.8	1.3
	August	17.6	15.1	25.8	17.7	10.6	65.9	1.4
	September	12.0	17.1	28.9	21.0	13.7	63.1	1.7
	October	88.6	18.2	29.6	22.3	16.2	66.4	1.8
	November	138.3	19.4	29.2	22.6	17.5	72.5	1.8
	December	133.1	20.6	30.2	24.0	19.3	78.2	1.5

SRad solar radiation, *Tmax* maximum temperature, *Tmin* minimum temperature, *Tavg* average temperature, *RHavg* average relative humidity, U_{2m} wind speed at 2 m

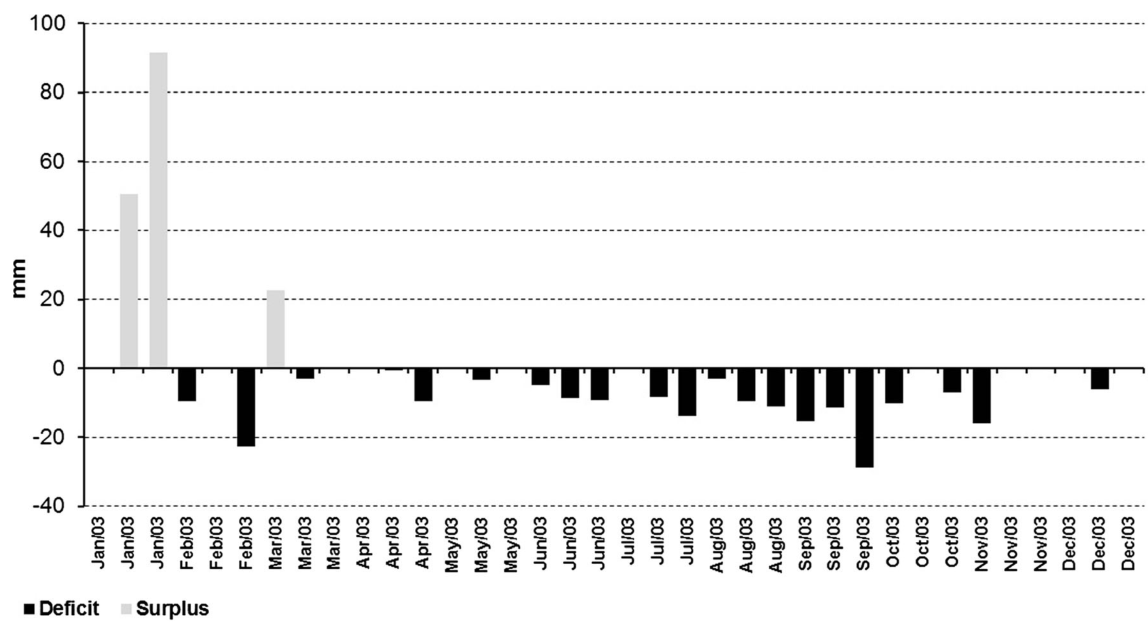

Fig. 2 Climatological water balance (*Surplus* = water surplus and *Deficit* = water deficit), over 10-day time periods from January to December 2003, in Piracicaba, SP, Brazil

values with null mean and unit variance (Hartingan 1975). The purpose of using all the quality variables in this analysis was to characterize the sugarcane cultivars as a whole and not only for a few quality variables, as TRS.

The standardization of the sugarcane quality data was done by removing the mean and dividing by the standard deviation. The non-standardization of variables could lead to inconsistencies in the results, since most of the distance measures are quite sensitive to different scales or magnitudes of the variables. The clustering analysis was carried out by calculating the Euclidean distance between cultivars, for all sugarcane quality variables obtained during the April–May period (early season), and by using Ward's algorithm. Statistical analyses were processed using STATISTICA version 9.0.

Selection of variables

Daily weather data were evaluated by calculating average and total values found in the following periods before sampling: 30, 60, 90, 120, and 150 days. A correlation matrix was constructed between the average or total values of the weather variables from each period and the TRS values. From the matrix of correlation, the weather variable that most influenced the ripening process was selected, considering Pearson's correlation coefficient (r) and also statistical significance. In addition to the correlation presented with the ripening process, another criterion considered for selecting the weather variable was its availability for being easily applied in the model on an operational scale. The following weather variables were evaluated: minimum air temperature; minimum air relative humidity; rainfall; and water deficit (WD).

To avoid the multi-collinearity effects between the variables selected during the modeling process, the linear correlations between the weather variables were determined. The variables selected by these procedures were correlated with the TRS values in order to generate models for each group of cultivars defined by the cluster analysis (early, mid, and late). Different models were adjusted for describing the ripening process, and the best model was selected by the highest adjusted R^2 and by the data normality and residual distribution, as recommended by Motulsky and Christopoulos (2003). All analyses were performed using the Minitab 16 software.

Evaluation of the models with experimental independent data

The performance analysis of the TRS models was conducted with independent data collected in two other experiments, under similar conditions to the ones used for modeling already described for the region of Piracicaba and with the same cultivars. These two experiments were carried out in different locations in other two sugar mills of the same company: Jaú (Lat, 22° 19′ 31 S; Long, 48° 38′ 21″ W; and Alt, 527 m.a.s.l.) and Capivari (Lat, 23° 1′ 38″ S; Long, 47° 32′ 35″ W; and Alt 587 m.a.s.l.), both in the state of São Paulo. As was implemented in Piracicaba, plantings were done monthly from March to October 2002 and samples collected from March to October 2003. The TRS values observed were correlated with those estimated by the proposed models, considering the different cultivar ripening groups, i.e., early, mid, and late. This procedure was implemented in order to assess the precision and accuracy of the estimates. The weather data for these two regions were obtained from the Agronomic Institute of Campinas (IAC), located at less than 5 km from the experimental sites, and also from the rain gauges available in the mills. Estimated and observed TRS data were compared by regression analysis (R^2_{adj}=adjusted determination coefficient, with $p<0.05$), Willmott index (D), Camargo coefficient (C), and by the evaluation of the mean error (ME) and mean absolute error (MAE), as suggested by Willmott et al. (1985) and Camargo and Sentelhas (1997):

$$D = 1 - \left\{ \frac{\Sigma (O_i - P_i)^2}{\Sigma (|P_i - O_m| + |O_i - O_m|)^2} \right\} \tag{1}$$

$$\text{EAM} = \frac{\Sigma (|P_i - O_i|)}{N} \tag{2}$$

$$\text{EM} = \frac{\Sigma (P_i - O_i)}{N} \tag{3}$$

$$C = D \times \sqrt{R^2} \tag{4}$$

where P_i is the estimated TRS; O_i is the observed TRS; O_m is the average measured TRS; and N is the number of events. R^2 is the determination coefficient. The performance of each model was classified as suggested by Camargo and Sentelhas (1997) (Table 2).

Evaluation of the models from independent commercial data

The models were also evaluated using independent data from commercial areas of six different mills and over six seasons, from 2005–2006 to 2010–2011. The monthly TRS data were

Table 2 Classification of confidence index (C) for model evaluation

C values	Classification
>0.85	Excellent
0.76 and 0.85	Very good
0.66 and 0.75	Good
0.61 and 0.65	Average
0.51 and 0.60	Tolerable
0.41 and 0.50	Poor
≤0.40	Very poor

Adapted from Camargo and Sentelhas (1997) collected in the sugarcane mills located in the regions of Piracicaba (Lat, 22° 36′ 45″ S; Long, 47° 37′ 47″ W; and Alt, 597 m.a.s.l.), Jaú (Lat, 22° 19′ 31 S; Long, 48° 38′ 21″ W; and Alt 527 m.a.s.l.), Ourinhos (Lat, 22° 58′ 19″ S; Long, 49° 44′ 52″ W; and Alt, 425 m.a.s.l.), Araçatuba (Lat, 21° 6′ 6″ S; Long, 50° 25′ 14″ W; and Alt, 375 m.a.s.l.), Jaboticabal (Lat, 21° 17′ 45 S; Long, 48° 18′ 21″ W; and Alt 605 m.a.s.l.), and Igarapava (Lat, 20° 0′ 22″ S; Long, 47° 48′ 2″ W; and Alt, 590 m.a.s.l.), all of them in the state of São Paulo, Brazil (Fig. 1). To estimate TRS by the proposed models, the rainfall data were obtained from the rain gauges installed in each one of these mills. The monthly TRS values were obtained by weighting the estimates of each model according to the proportion of each group of cultivars (early, mid, and late) processed per month in each mill (data not shown). The estimated and measured TRS data of all seasons for each region were compared by regression analysis, and the same indices and errors described previously were determined.

Results

Grouping cultivars for ripening by cluster analysis

The dendrograms obtained from clustering analysis by the hierarchical method for the sugarcane cultivar quality variables are presented in Fig. 3. In March, the maximum difference between groups, expressed by Euclidean distances, was 5.62 and decreased thereafter every month falling to a minimum of 1.82 in September. The cultivars SP91-1049 and SP86-155 were in a group with the highest Euclidean distance compared to the others (5.62), i.e., this is a group classified as early ripening. A second group of cultivars, comprising SP90-3414, SP87-365, RB928064, RB867515, with a Euclidian distance of 3.06 to the third group was classified as intermediate ripening. Finally, a third group, comprising cultivars SP83-2847 and SP86-42, was classified as late ripening.

Selection of weather variables for TRS modeling

The results from the correlation analysis indicated that there were high correlations between all the variables previously selected to describe the sugarcane ripening process and is therefore not recommended to be used together in multivariate models (Table 3). Based on the results presented in Table 4, it is clear that for the majority of the variables, except for WD, the periods between 120 and 150 days before sampling are those more associated with the sugarcane ripening process. Considering this and the fact that rainfall is the easiest variable to be measured on an operational level in the sugarcane fields and also by the official weather stations in Brazil, it was decided to model TRS as a function of accumulated rainfall in the 120 days before sampling. Although a normality distribution of TRS data (Anderson-Darling test, $p>0.05$) had been detected, an exponential fit was chosen to represent the variation of this quality variable as a function of accumulated rainfall. In all the cases, the models were generated considering the accumulated precipitation during the 120 days before sampling, since it provided the highest adjusted R^2 values and the best residual distribution.

TRS models based on rainfall data

The relationship between TRS and 120-day accumulated rainfall (R_{120}) for the early, mid, and late sugarcane cultivars is

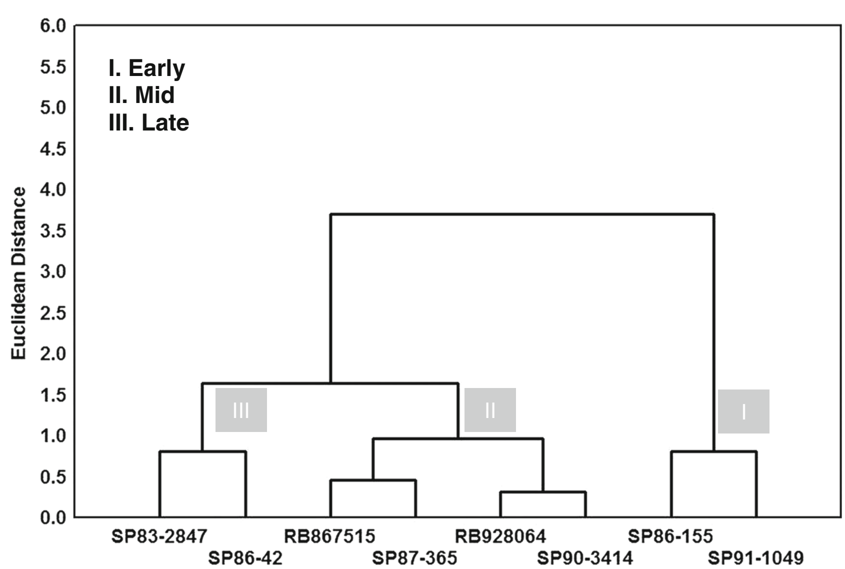

Fig. 3 Dendrogram obtained from clustering analysis using the hierarchical method for the quality variables of eight Brazilian sugarcane cultivars at the beginning of the 2003/2004 season, in Piracicaba, SP, Brazil

Table 3 Pearson's correlation coefficients for the relationship between the weather variables selected to estimate total recoverable sugars (TRS): rainfall, minimum air temperature, water deficit, and minimum air relative humidity

	Tmin	WD	RHmin
R	0.911*	−0.932*	0.982*
Tmin	–	−0.961*	0.981*
WD	–	–	−0.980*

R rainfall, *Tmin* minimum air temperature, *WD* water deficit, *RHmin* minimum air relative humidity

*Significant at $p<0.01$

presented in Fig. 4. The models resulting from these relationships were as follows:

$$\text{Early cultivars}: \text{ TRS } = 170.80' \text{EXP} \left(-0.0007' R_{120}\right)$$

$$\text{Mid cultivars}: \text{ TRS } = 168.56' \text{EXP} \left(-0.0009' R_{120}\right)$$

$$\text{Late cultivars}: \text{ TRS } = 163.08' \text{EXP} \left(-0.0010' R_{120}\right)$$

with adjusted R^2 values of 0.92 ($p<0.01$), 0.95 ($p<0.01$), and 0.94 ($p<0.01$), respectively, for early, mid, and late cultivars. For all models, no values beyond the confidence interval of 95 % were observed. The proposed models represent a significant improvement for TRS estimates when compared to the multivariate linear models presented by Scarpari and Beauclair (2009), which showed determination coefficients of 0.48 for early (SP80-1842), 0.32 for mid (SP81-3250), and 0.26 for late (RB72454) Brazilian cultivars.

The normality and residual distribution of each model (early, mid, and late cultivars) showed low dispersion in relation to the estimated values, ranging between −1 and 1, indicating the absence of outliers. There were no trends of increasing or decreasing residues as a function of the estimated TRS values, showing that no problem with heteroscedasticity occurred. Furthermore, the residuals showed normal distribution with $p<0.05$ (Anderson-Darling normality test).

Table 4 Pearson's correlation coefficients between total recoverable sugars (TRS) and weather variables averaged (Tmin and RHmin) or accumulated (R and WD) during different periods of days before sampling

Days before sampling	Tmin	RHmin	*R*	WD
Early cultivars				
30	−0.5457	−0.8789	−0.7277	0.9122
60	−0.8420	−0.9228	−0.8705	0.9067
90	−0.9038	−0.9305	−0.9101	0.8841
120	−0.9301	−0.9333	−0.9423	0.8521
150	−0.9234	−0.9033	−0.9411	0.8030
Mid cultivars				
30	−0.5116	−0.9183	−0.7169	0.9216
60	−0.8290	−0.9622	−0.8639	0.9241
90	−0.9103	−0.9667	−0.9110	0.9111
120	−0.9513	−0.9662	−0.9556	0.8880
150	−0.9567	−0.9441	−0.9638	0.8409
Late cultivars				
30	−0.4568	−0.9085	−0.6780	0.9328
60	−0.7948	−0.9551	−0.8331	0.9370
90	−0.8822	−0.9615	−0.8846	0.9310
120	−0.9340	−0.9646	−0.9390	0.9125
150	−0.9483	−0.9470	−0.9527	0.8671

Tmin minimum air temperature, *RHmin* minimum air relative humidity, *R* rainfall, *WD* water deficit

Evaluation of the proposed models with experimental independent data

The relationships between observed and estimated TRS in the regions of Capivari and Jaú are presented in Table 5. In all cases, adjusted R^2 values were greater than 0.98 ($p<0.01$), indicating that the models were able to simulate the real data precisely, even for different regions where they were developed. The *D* indices were greater than 0.98 in both regions, confirming the accuracy of the estimates. All the TRS models evaluated for early, mid, and late cultivars had *C* coefficients above 0.98, performances considered "excellent," according to the classification proposed by Camargo and Sentelhas (1997).

The proposed models systematically overestimated the TRS in the Capivari region, where the TRS mean errors were negative for all cultivars. On the other hand, in Jaú, the TRS was underestimated, with positive mean errors (Table 5). Although these patterns are related to the climatic conditions prevailing in the year of the experiment (2003), they may suggest that the fact that local weather patterns are slightly different from those observed in Piracicaba (Table 6), may lead to different estimates, however modest the error (Table 5). In all cases, the slope (*b*) of linear equations was close to 1 (Table 5), which implies a systematic absolute error, which is proved by the same ME and MAE for all three cultivar groups.

Evaluation of the proposed models with independent commercial data

The relationships between the observed and estimated TRS for six different regions in the state of São Paulo, over six growing seasons, are presented in Fig. 5. The adjusted R^2 of these relationships varied according to the region analyzed, with the lowest value being observed in Ourinhos (adjusted R^2=0.66, $p<0.01$). In other regions, adjusted R^2s were greater than 0.79 ($p<0.01$), with *D* index above 0.89 for all locations

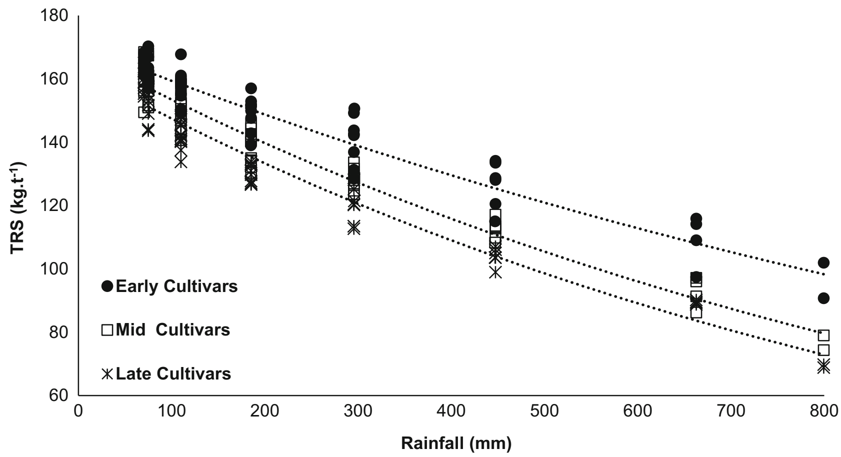

Fig. 4 Relationship between total recoverable sugar (*TRS*) and rainfall accumulated for 120 days before harvest (sampling) for early, mid, and late Brazilian sugarcane cultivars

considered, indicating that the models were able to estimate the TRS with sufficient precision and accuracy (Table 7). There was variation in the *C* index, with values considered "good" for Ourinhos (C=0.74), "very good" for Piracicaba (C=0.84), and Jaú (C=0.81) and "excellent" in Jaboticabal (C=0.97), Araçatuba (C=0.91), and Igarapava (C=0.95).

The regression slope of the relationship between observed and estimated TRS was very close to 1 in all regions (Table 7). However, in the case of ME and MAE, substantial differences were observed, all related to random errors. In Piracicaba, the relationship between observed and estimated TRS was very good, with adjusted R^2 around 0.79, with a slight tendency to underestimate the TRS at the end of the season. The underestimation of TRS values was also observed in the region of Jaú, keeping constant throughout the harvesting season. In Ourinhos, the tendency of TRS overestimation was observed early in the season, whereas the underestimation occurred at the end. In Jaboticabal, the tendency of overestimation was very small, showing the good performance of the models in this region. The opposite pattern was observed in Araçatuba, where the models underestimated TRS early in the season, also observed in Igarapava, and overestimated TRS at the end. Despite the trends described, the mean absolute percentage errors were very low, no greater than 4 % in all regions, which for operational purposes can be considered as a small error.

Table 5 Regression analysis (intercept and slope), adjusted coefficient of determination, Willmott index, confidence coefficient, mean error (kg t^{-1}), and mean absolute error (kg t^{-1}) related to the TRS estimated by the rainfall models for early, mid, and late Brazilian sugarcane cultivars in Capivai and Jaú, in the state of Sao Paulo, Brazil

Site	Intercept	Slope	R^2_{adjust}	*D*	*C*	ME	MAE
Early cultivars							
Capivari	4.345	1.00	0.993	0.99	0.98	4.35	4.35
Jaú	−5.979	1.02	0.985	0.99	0.98	−3.86	4.13
Mid cultivars							
Capivari	6.514	0.99	0.991	0.99	0.99	5.85	5.85
Jaú	−4.866	0.99	0.987	0.99	0.98	−5.97	5.97
Late cultivars							
Capivari	3.823	1.00	0.990	0.99	0.99	4.13	4.13
Jaú	−5.462	1.00	0.996	0.99	0.99	−4.96	4.96

R^2_{adjust} adjusted coefficient of determination, *D* Willmott index, *C* confidence coefficient, *ME* mean error, *MAE* mean absolute error

Discussion

The hierarchical cluster analysis, represented by the dendrogram, produced three groups of sugarcane cultivars with different ripening patterns, classified as early, mid, and late (Fig. 3). The models were then generated from the relationship between ripening, expressed by TRS, and the accumulated rainfall in the previous 120 days. Although the initial goal was to obtain a linear fit integrating variables related to precipitation and air temperature, as proposed by Scarpari and Beauclair (2009), this was not feasible considering the high correlation between these variables. This statement does not rule out the importance of air temperature on the sugarcane ripening process. However, when considering southern Brazil, the intense water deficit, typical of the autumn–winter months (from April to September), becomes the main ripening factor, since cool air temperatures (less than 18 °C) throughout this period are not enough to induce sugar storage, as is the case in

Table 6 Annual rainfall (mm) and air temperature (°C) occurring in 2003 at the experimental sites in the state of São Paulo, Brazil

Region	Rainfall (mm)	Tmax (°C)	Tavg	Tmin
Piracicaba	1,051.7	28.5	21.4	15.7
Capivari	977.5	29.8	22.2	14.5
Jaú	1,585.6	29.4	22.7	16.0

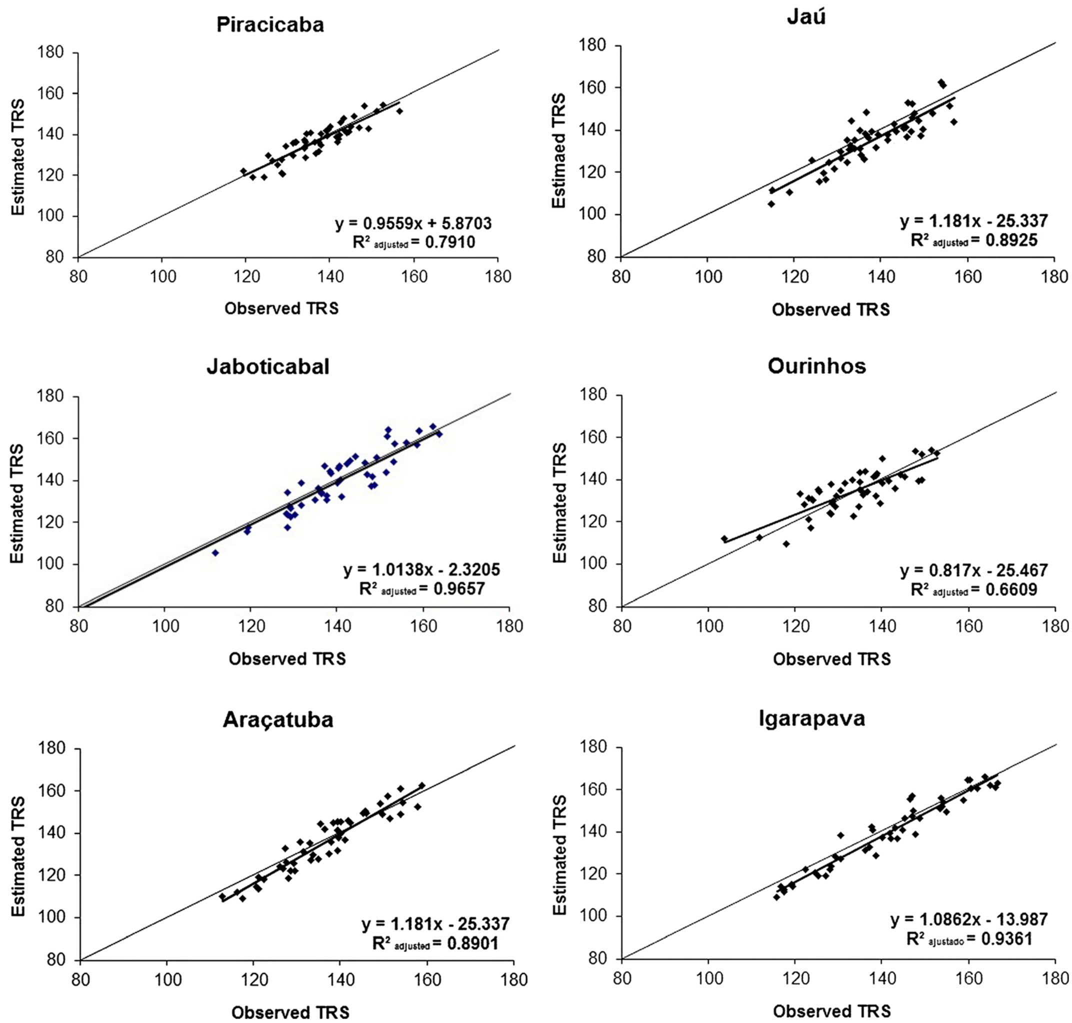

Fig. 5 Relationship between TRS observed and estimated by the empirical models for Piracicaba, Jaú, Jaboticabal, Ourinhos, Araçatuba, and Igarapava, in the state of São Paulo, Brazil, for the growing seasons from 2005–2006 to 2010–2011

the state of Paraná, Brazil, where the water deficit normally does not occur and the mean air temperature during the winter reaches less than 17 °C for at least 2 months.

Low air temperatures promote reduction in the levels of invertase acid in the stems, thereby increasing the concentration of neutral invertase and consequently increasing their

Table 7 Slope of the regression analysis, adjusted coefficient of determination, Willmott index, confidence coefficient, mean error (kg t^{-1}), mean absolute error (kg t^{-1}), and mean absolute percentage error (%) relating to sugarcane TRS estimated by the rainfall models for the regions of Piracicaba, Jaú, Jaboticabal, Ourinhos, Araçatuba, and Igarapava, in the state of São Paulo, Brazil, during the 2005–2006 to 2010–2011 growing seasons

Site	*b*	R^2	*D*	*C*	ME (kg t^{-1})	MAE (kg t^{-1})	MAPE (%)
Piracicaba	0.96	0.79	0.94	0.84	−0.19	3.47	2.5
Jaú	1.07	0.77	0.92	0.81	−2.63	5.34	4.0
Jaboticabal	1.01	0.97	0.99	0.97	−0.46	4.85	3.7
Ourinhos	0.82	0.66	0.90	0.74	1.04	5.33	4.0
Araçatuba	1.18	0.89	0.96	0.91	−0.61	4.46	3.3
Igarapava	1.09	0.94	0.98	0.95	−1.75	4.02	3.0

Obs: The intercept of the regression analysis was not different from zero, so it is not shown

b slope of regression analysis, R^2_{adjust} adjusted coefficient of determination, *D* Willmott index, *C* confidence coefficient, *ME* mean error, *MAE* mean absolute error, *MAPE* mean absolute percentage error sucrose concentration (Alexander and Samuels 1968; Ebrahim et al. 1998). However, such reduction in the invertase acid levels occurs only during prolonged periods of low air temperature (Lingle 2004), which does not happen frequently in southern Brazil, as in the state of São Paulo even during the winter months. Glasziou et al. (1964) found that high sucrose values were produced when low air temperature was maintained for at least 3 months. According to these authors, the sugar concentration did not exceed 12 % of the fresh weight when the air temperature was kept constant or when daily variations were small. However, when the average air temperature was reduced over a long period of time, from 3 to 6 months, sugar concentration reached about 17 % of fresh weight.

Another aspect to be considered relates to the type of models used to estimate TRS. Firstly, a linear model was tested. However, it was observed that such a model was not able to express the different processes involved in sugarcane ripening. The increase of sucrose in stems is not only an active response to adverse climatic factors (low temperature or water deficit) but is also due to dehydration of the stems, especially during periods of hot and dry weather, which normally occur at the end of the harvest season, between August and September in southern Brazil (Cardozo 2012). Robertson and Donaldson (1998) found similar results in Australia, where drought occurrence promoted increases in sucrose concentration of up to 15 %, with a mean value of 8 %. According to these authors, the increase in sucrose content was affected not only by the favorable weather conditions but also by dehydration of the stems, which was proven by the reduction in the stems' fresh weight. Based on this, the exponential model was considered more appropriate for fitting the relationship between TRS and environmental conditions, since the increase in TRS is limited by the reduced growth of the stems under severe climatic conditions and increases of fiber levels which also affect sucrose extraction process given the lower water content in the stems.

The proposed and tested TRS models estimate this sugarcane variable through its relationship to the total rainfall accumulated during the R_{120}. As mentioned above, the use of an exponential equation allowed a more appropriate description of the processes associated with sugarcane ripening, differing from models proposed by other authors (Scarpari and Beauclair 2004, 2009). The models showed a reduction of the sucrose accumulation potential among the cultivar groups, represented by the constant coefficient, from the early (170.80 kg t^{-1}) to the late (163.08 kg t^{-1}), and also an increase in the response of the cultivar groups to water availability (rate of decay), ranging from −0.0007 kg t^{-1} mm^{-1}, for early ripening, to −0.0010 kg t^{-1} mm^{-1}, for late maturity. These results are a clear evidence of the differences among cultivars in terms of their potential for sucrose accumulation and of how they react to soil water availability during their maturation.

Besides the precision and accuracy of the estimated TRS, another positive aspect of the proposed models is the uniformity in variability of the residuals. The models estimated TRS with precision, accuracy, and small errors when compared to observed data obtained in different experiments and regions (commercial data). In spite of this, we recognize the importance of air temperature as a ripening factor in the regions with cooler climates and where water deficit does not occur. The proposed models show the importance of the weather conditions to sugarcane juice quality as well as the importance of better understanding the processes involved with the sugarcane ripening.

In addition to the physiological conditions of the plants and their interaction with local weather conditions, there are several other variables that must be considered to obtain better results when estimating the raw material quality of the sugarcane. An aspect to be taken into account, when evaluating the proposed models, is the occurrence of different patterns of TRS estimations when they were applied in Capivari and Jaú. A possible explanation for this is the temperature difference of these regions in relation to Piracicaba, from where TRS data were taken for developing the models, since the soil types in these regions are approximately the same. As observed in Table 6, differences in minimum air temperature were observed for these locations. In Piracicaba, the minimum air temperature remained at an intermediate level, whereas in Capivari, it was slightly lower, and in Jaú, it was higher. As the minimum air temperature is another weather variable that affects sugarcane ripening (Glover, 1971; Yates, 1996), although with less intensity than the water deficit (Cardozo and Sentelhas, 2013), it is clear that in Capivari, lower temperatures were an additional factor that improved the ripening, while in Jaú, the opposite happened. Independent of this, the performance of the model for estimating TRS in Capivari and Jaú was excellent, with an error of less than 1 %. It shows that just a few adjustments in the models, including temperature, could improve the estimates even more.

The use of the models to estimate TRS with independent data from different seasons and locations (Table 8) was another way to prove the feasibility of the proposed models. In addition to its empirical approach, without taking into consideration all the other external factors which can cause interference in TRS, such as soil type and crop management, the models performed very well (Fig. 5), being able to estimate the seasonal variability of this variable from April to November, for all the 36 different combinations between regions and seasons. This information is extremely important for validating the use of these models under different conditions from those where they were developed, since the feasibility and applicability of empirical models are often questionable under these conditions. Furthermore, the majority of the errors observed were lower than 10 %, without any adjustments to the original models because of region or year.

Table 8 Monthly rainfall from 2005 to 2010 observed in Ourinhos, Piracicaba, Jaú, Ribeirão Preto, Araçatuba, and Igarapava, in the state of São Paulo, Brazil

Region	Year	Rainfall (mm)												
		January	February	March	April	May	June	July	August	September	October	November	December	Annual
Ourinhos	2005	451.9	31.7	153.3	90.7	121.6	47.8	32.5	13.2	110.1	293.0	38.0	128.1	1,511.9
	2006	181.6	183.4	170.3	65.7	1.4	14.8	33.4	14.0	117.8	82.3	56.9	220.8	1,142.4
	2007	300.7	166.6	170.2	46.4	45.0	22.2	190.3	2.5	12.8	135.6	103.6	230.8	1,426.7
	2008	240.8	216.5	64.1	199.4	72.0	59.9	1.5	128.3	71.5	122.6	113.4	32.1	1,322.1
	2009	330.9	71.1	52.9	41.3	76.8	80.1	162.0	71.4	132.3	187.5	152.8	225.6	1,584.7
	2010	213.8	88.8	89.9	69.6	25.5	37.3	34.5	5.3	64.1	185.0	32.1	140.8	986.7
Piracicaba	2005	238.7	67.8	111.6	30.7	164.3	42.5	8.1	24.1	38.4	120.4	117.8	127.1	1,091.5
	2006	240.5	176.2	154.0	33.7	2.0	18.6	32.4	17.4	54.7	80.3	200.2	251.7	1,261.7
	2007	267.0	241.9	80.5	36.8	58.4	22.6	169.3	0.0	1.9	92.6	120.3	188.6	1,279.9
	2008	418.5	153.7	132.4	174.6	72.4	43.5	0.0	68.7	46.1	108.7	24.3	153.0	1,395.9
	2009	162.0	143.5	125.1	21.8	10.6	55.1	61.6	61.4	143.8	56.7	196.5	274.3	1,312.4
	2010	250.2	158.6	99.0	76.4	24.4	16.7	62.9	0.0	98.3	87.4	39.9	244.1	1,157.9
Jaú	2005	328.3	146.3	102.9	65.1	101.4	40.4	5.5	19.6	40.4	104.1	91.1	212.6	1,257.7
	2006	215.0	212.7	160.0	22.0	5.4	12.8	28.3	11.6	89.4	110.9	182.5	314.4	1,365.0
	2007	513.0	161.0	100.8	51.3	82.3	5.8	239.9	0.0	2.6	51.2	218.6	240.5	1,667.0
	2008	185.6	194.0	192.8	146.9	64.5	57.8	0.0	53.0	34.2	163.3	100.9	233.8	1,426.8
	2009	323.0	184.0	205.0	38.0	63.0	60.0	83.0	119.0	146.0	158.0	286.0	215.0	1,880.0
	2010	431.0	98.0	48.0	90.0	33.0	26.0	57.0	0.0	111.0	92.0	63.0	387.0	1,436.0
Ribeirão Preto	2005	358.5	81.2	128.0	59.6	127.4	30.1	46.5	0.0	58.2	56.4	41.7	242.6	1,230.2
	2006	237.0	416.4	136.9	10.4	4.0	10.3	3.2	19.1	37.6	184.5	166.8	221.0	1,447.2
	2007	537.1	147.0	127.9	49.9	97.1	2.4	80.5	0.0	0.3	35.0	126.4	178.8	1,382.4
	2008	289.7	304.6	86.8	118.8	69.8	6.3	0.0	23.7	13.9	61.9	76.6	247.6	1,299.7
	2009	220.7	164.8	161.2	61.3	21.7	35.6	22.2	119.3	129.6	101.9	169.9	376.2	1,584.4
	2010	242.6	191.2	141.9	95.5	11.8	7.8	0.0	0.0	200.5	65.7	110.4	224.8	1,292.2
Araçatuba	2005	551.0	129.0	49.0	185.0	93.0	57.0	10.5	65.5	132.0	189.5	134.0	293.0	1,888.5
	2006	240.0	489.0	209.0	19.0	32.0	12.0	10.0	40.0	86.0	68.0	60.0	307.0	1,572.0
	2007	515.3	168.0	126.9	10.0	55.0	0.0	117.1	0.0	0.0	46.0	125.0	129.0	1,292.3
	2008	247.0	192.0	207.0	102.0	47.0	9.0	0.0	56.0	18.0	171.0	92.2	130.0	1,271.2
	2009	318.0	253.0	175.0	21.0	66.0	50.0	43.0	168.0	193.0	165.0	201.0	349.5	2,002.5
	2010	145.0	156.0	196.0	30.0	8.0	9.0	8.0	0.0	211.6	97.0	87.0	176.0	1,123.6
Igarapava	2005	394.9	141.3	192.5	43.5	110.8	41.5	7.2	3.0	108.5	56.0	162.2	161.2	1,422.6
	2006	298.4	290.4	141.1	72.1	1.3	7.0	0.0	32.7	66.6	238.2	259.7	453.9	1,861.4
	2007	541.6	258.6	137.5	54.6	34.3	0.0	26.0	0.0	12.0	86.2	161.8	280.3	1,592.9
	2008	270.8	337.7	228.1	154.1	35.8	1.4	0.0	10.0	29.2	57.9	105.9	514.9	1,745.9
	2009	423.1	216.7	158.1	70.4	49.5	36.9	15.3	26.4	153.2	197.3	286.8	347.5	1,981.2
	2010	297.6	174.4	140.4	47.3	10.1	19.0	0.0	0.0	98.0	125.1	342.9	271.0	1,525.7

The monthly rainfall data from 2005 to 2010 in the six locations used in the model validation process (Table 8) indicate different rainfall amounts and distributions not only among the regions but also among the years used. This factor is evidence that the proposed models can perform very well under a huge variety of climate conditions. As an example, during 2007 and 2009, the winter, normally dry, presented very wet conditions, drastically affecting the sugarcane juice quality. Our models were able to detect this efficiently (Fig. 5). Another example is for the region of Ourinhos, in the south of the state, which has a different rainfall regime from the other regions, with a much wetter winter. Again, the proposed models showed a very good performance under such climate condition (Fig. 5), showing that the proposed empirical models can be used for planning purposes in several regions in the state of São Paulo state, without adjustments. The better performance of empirical models in cases like these was also found by Inman-Bamber et al. (2002), when comparing the

APSIM and an empirical model for predicting sucrose content.

Although it is difficult to identify which are the causes and the weight of each one of the factors that affect sugarcane ripening estimation, some of them that can be considered are presented below:

1. Cultivars: At some stages during the harvesting season, but mainly in the beginning and end, a few cultivars processed at the mills may dominate, which can lead to deviations in TRS associated with their ripening characteristics.
2. Mechanized harvesting: The effects of mechanical harvesting are striking, especially in terms of increasing mineral and vegetal impurities, factors that may lead to a reduction of observed TRS values when compared to the estimates produced by the models.
3. Ripeners: The models do not consider the use of chemical ripeners and, therefore, the observed TRS at the beginning or ending of the season could be higher than the estimated one because of this factor.
4. Occurrence of pests and/or diseases: The effects of pests and diseases were not considered by the models, which may lead to lower TRS values in the field, depending on their intensity.
5. Representativeness of rainfall records: Given the great spatial variability of rainfall in the state of São Paulo, mainly during early fall and late spring, the keeping of a higher number of rainfall records would lead to better performance of the models.
6. Soil type: For the same rainfall event, different soil types can store water in different proportions, which can affect sugarcane ripening and, consequently, TRS differently. As the proposed models do not consider the water balance, which would make operational estimates impossible, some errors presented can be related to this factor.

Conclusions

Although simple, the rainfall accumulated for 120 days before harvesting was a factor sufficient in itself to explain the variability of TRS, considering the different cultivars and seasons evaluated, which was evidenced by the excellent performance of the proposed models for estimating this variable when validated by independent data (experimental and commercial) from different regions and years. The proposed models stand out as promising tools for TRS projections since they are based on rainfall data alone, which are very easy to obtain at a local level and observed with better spatial distribution than other weather variables. The commercial use of these models, however, will require adjustments for conditions specific to individual mills, which relate mainly to the mix of cultivars, soil type, presence of mineral and vegetal impurities, use of chemical ripeners, and occurrence of flowering.

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