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Influence of El Niño and La Niña on sugarcane yield and sucrose production in northern São Paulo, Brazil

Glauco de Souza Rolim[1], Natália Buzinaro Caporusso[1], Victor Brunini Moreto[1*], Angélica Prela-Pantano[2]

[1]**Faculdade de Ciências Agrárias e Veterinárias – UNESP. Via de acesso Prof. Paulo Donato Castellane, s/n 14884-900, Jaboticabal, SP. Brasil**
[2]**Agência Paulista de Tecnologia dos Agronegócios, Instituto Agronômico de Campinas. Brasil**

***Corresponding author: victor.moreto@hotmail.com**

Abstract

The El Niño Southern Oscillation (ENSO) influences the global agriculture globally, with complex effects on crop yields in the state of São Paulo in Brazil. We assessed the effects of ENSO on the yield of sugarcane (*Saccharum spp.*) (tonnes of sugarcane per hectare -TSH) and total recoverable sugar (TRS) at Jaboticabal, one of the most important Brazilian sugarcane producing regions. We determined Pearson linear correlation coefficients monthly and annually to analyze the interactions of TSH and TRS with climatic parameters associated with El Niño (EN), La Niña (LN) and neutrals (NE) years. The annual yield of sugarcane was highly variable, but TSH tended to be higher in NE years, followed by, EN and LN years, and TRS was higher in LN years, followed by NE and EN years. Conditions of the higher soil water storage (STO) and water excess (EXC) led to the higher TSH in NE years. Higher water deficiency (DEF) led to higher TSR in LN years. We developed agrometeorological models to estimate accumulated monthly TSH and TRS for EN, LN and NE years. The models as functions of a thermal index and sum of DEF were accurate for all years, with maximum mean absolute percentage errors of TSH of 12.78 and 8.15% for TSH and TRS, respectively in neutral years.

Keywords: Agrometeorology; yield; total recoverable sugar; model; ENSO.
Abbreviations: TRS_total recoverable sugar; STO_soil water storage; ENSO_El Niño Southern Oscillation; EN_El Niño; LN_La Niña; NE_Neutral; TSH_tonnes of sugarcane per hectare; EXC_water excess; AET_actual evapotranspiration; PET_potential evapotranspiration; DEF_water deficit (DEF = PET – AET); P_precipitation; T_mean air temperature; GDD_thermal index (growing degree days); MAPE_ mean absolute percentage error; Es_systematic error.

Introduction

Agriculture is an economic activity higly dependent on climate. Atmosferic conditions affect all stages of agricultural production, from soil tillage to harvest and product transport and storage. Sugarcane (*Saccharum* spp.) is a crop whose products have multiple uses and high economic importance. Vinasse and the bagasse are used to produce fertilizer and fuel, respectively (Caputo et al., 2008). The total recoverable sugar (TRS) expressed in kilograms per tonne, represents all sugars, especially sucrose, in the raw material. Meteorological parameters strongly influence TRS levels during the development of sugarcane, even at the harvest stage. Dry periods and the consequent water deficits induce a growth dormancy in the plants, but the sucrose continues to acumulate in the stalks, increasing the TRS (Andrade, 2006). Soil water storage (STO), wich tends to be higher in the low-lying areas, can also influence the TRS, by delaying matutity (Scarpari and Beuclair, 2009). The natural phenomena El Niño (EN) and La Niña (LN) cause climatic changes for agriculture on a global scale, such as variations in rain intensity, temperature and evapotranspiration. Vourlitis et al., (2014) reported that the Amazonian Basin had higher annual evapotranspiration in EN years. El Niño Southern Oscillation (ENSO) is a main source of interannual climatic variability in northeastern Iran, affecting the yields of rainfed cereal crops (Bannayan et al., 2011). García et al. (2014) confirmed that ENSO impacted plant phenology, rate and extent of forest growth and other gradual changes in forest ecosystems in northern Mexico. Del Ponte et al. (2011) even use the occurrence of EN to predict the risk of epidemics of soybean rust up to one month in advance in southern Brazil. El Niño has a large influence on crop yield and losses in several regions in Brazil, can reach 20 million tonnes of products, worth U$$ 1.5 trillion (Teracines, 2000). EN years are more favorable yhan NE years to soybean and maize yields in southern Brazil. LN years have already benefited wheat yields (Alberto et al., 2006), but have had no direct relationship with coffe yields in Campinas or maize in the central Paranapanema region (Camargo et al., 2002; Prela-Pantano et al., 2011). Braido and Tommaseli (2011) claimed that extreme climatic events could be harmful for the harvest of sugarcane. For example, the yield was better in 1982, an EN year, than in 1985, an LN year, in the Pontal do Paranapanema region of São Paulo. Our objective was to determine the influence of EN and LN on the local meteorological conditions and their effects on sugarcane yield and sucrose production in northern São Paulo, Brazil.

Results

Effects of El Niño, La Niña and neutral (NE) years on sugarcane yield and sucrose production

The tonnes of sugarcane per hectare (TSH) and TRS were highly variable on a monthly scale in all years analyzed (Fig. 1A and 1B, respectively). The highest TSH of 114.76 t ha^{-1} was recorded in April 2010, an LN year. The lowest, 61.21 t ha^{-1} was recorded in October 2000, also an LN year. The highest TRS of 163.79 kg t^{-1} was recorded in September 1999, an LN year and the lowest, 103.72 kg t^{-1}, was reported in December 2009 an NE year. Neutral years produced the highest TSHs (Fig. 2A), followed by EN and LN years, with medians of 87, 81 and 77 t ha^{-1}, respectively. The variability of TSH, however, was higher in LN years; 95% of the yields were between 73 and 86 t ha^{-1}. EN years, though, had minimum and maximum absolute values of 71 and 97 t ha^{-1}, respectively. Total recoverable sugar (TRS) (Fig. 2B) had a median of 132 kg t^{-1} in LN years, with extremes ≥ 136 kg t^{-1}, but TRS was most variable in NE years. TRS was least variable in EN year, with a median of 128 kg t^{-1}.

Analysis of temperature and water balance of the producing region

The lowest average monthly temperatures occurred in the warmer months in EN years in 5% of the cases (Fig. 3A).
Actual evapotranspiration tended to be higher in LN years, ranging from 40 to 115 mm mo^{-1}, in 95% of cases. The median actual evapotranspiration, though, was highest in NE years, at 95 mm mo^{-1} (Fig. 3B). Soil water storage (STO) was highest in NE years in 95% of cases (Fig. 3C), although the median was equal to that of the EN years (50 mm mo^{-1}). This indicator of soil water content did not generally differ among the years of EN, LN and NE analyzed. STO was superior in months of dry winter, in NE years (Fig. 3C). A more specific analysis of water deficit (DEF) and excess (EXC) on a montlhy scale in EN, LN and NE years (Fig. 4) indicated that the monthly water balance differed for these years, especially in NE years.

Effects of temperature correlations with sucrose production from sugarcane

Correlations of the temperatures in the year of harvest and the preceding years with the TRS of the harvest year demonstred that the air temperature in November and December of the year before the harvest was correlated the most (r = 0.40 and 0.56, respectively) with the TRS for May to October for EN years (Fig. 5A). Temperature had little effect on TSR in the LN years of the study period (Fig. 5B). Temperatures in most monthsof the harvest and preceding years were positively correlated (r as high as 0.40) with TRS in NE years, except for January to April when temperature was negatively correlated with the TRS of October and November (r = -0.40 and -0.69, respectively, Fig. 5C).

Agrometeorological models for estimating sugarcane yield and sucrose production

The MAPE, R^2 and Es values (Table 1) indicated that the agrometeorological models accurately estimated ∑TSH and ∑TRS on monthly scales from April to December for EN, LN and NE years. These models were designed as functions of ∑GDD and ∑DEF (Table 2). ∑DEF ranged from 0 to 600 mm and the ∑GDD ranged from 0 to 120 growing degree days. The accuracy of the ∑TSH and ∑TRS estimates by all models ranged between 5.14 and 12.78%, as indicated by the high R^2, but with variable bias (Es).

Discussion

The monthly and annual variability of both TSH and TRS suggested that EN and LN are influencing factors in the region, but the pattern of influence is complex, at least for the monthly scale, and will require further analysis. Berlato et al. (2005) reported similar results and concluded that EN increased and LN decreased maize yields in the state of Rio Grande do Sul, Brazil. The extreme values of TSH in EN, LN and NE years were likely climatic eventualities but may have been due to differences in the level of technology used. The highest values of TSH were generally associated with the lowest values of TRS in all conditions. This this relationship has been previously reported, for example by Segato et al. (2006), who suggested that unfavorable climatic conditions, such as increased rainfall at crop maturity could decrease TRS. Low temperatures, which are not common in southeastern Brazil, however, can also decrease yield. An analysis of the increase in temperature in São Paulo indicated that temperatures high as 38 °C would not affect plant growth (Doorenbos and Kassam, 1979). The climatic conditions of the EN, LN and NE years showed a few common differences at average monthly air temperature ranging from 24 to 21 °C, for warmer and cold months, this occurred in 95% of the cases for all years (EN, LN and NE). Sugarcane has been adapted to a wide variety of environmental conditions but grows primarily in tropical and subtropical regions with air temperatures ranging from 25 to 33 °C (Carvalho et al., 2015). The largest distinction between EN and LN years was associated with EXC in January, February and March, which was higher in LN years. EXC was also higher than the others conditions (EN and LN years) in NE years. November was characterized by EXC in NE years but by DEF in EN and LN. Sugarcane plants are more tolerant to water stresses, and some conditions such as water deficit associated with high temperatures may benefit crop yields. (Pinto et al., 2002). The agrometeorological models performed well for the EN, LN and NE years. ∑TSH was estimated best for EN years (Fig. 6A), with MAPE of 6.29% and a precision (R^2) of 0.97. ∑TRS was estimated the best EN years (Fig. 6B), with MAPE of 5.14% and a precision of 0.99. The agrometeorological models for LN years had MAPEs of 6.09% for TRS estimates (Fig. 7B) and 9.75% for TSH estimates (Fig. 7A), with high precision of 0.99 and 0.96, respectively (Table 1). Estimates for the NE years (Fig. 8) were the least accurate, with R^2 similar among the models for LN years. The estimates of ∑TRS for NE, LN and EN years were more accurate and precise with higher bias, although the estimates of ∑TSH were less accurate and similarly precise. The agrometeorological models are useful tools to describe the influence on sugarcane yield of climatic changes, such as the different conditions of EN, LN and NE years (Gouvêa et al., 2009). TSH, TRS, actual evapotranspiration (AET) and EXC were higher in NE years. DEF and EXC were most variable in February and March of EN, LN and NE years, due to the distribution of the precipitation. Rainfall in February was indicative of the importance of this period on sugarcane growth; dry spells at this phase could decrease on the final yield (Singels and Benzuidenhout, 1999). Rainfall was higher in November of NE years. The regional agrometeorological models developed for estimating ∑TSH and ∑TRS as function of ∑GDD and ∑DEF performed well for EN, LN and NE years.

Table 1. Mean absolute percentage error (MAPE), coefficient of determination (R^2) and systematic error (Es) for the sums of tonnes of sugarcane per hectare (∑TSH) and total recoverable sugar (∑TRS) for El Niño (EN), La Niña (LN) and neutral (NE) years.

	MAPE (%)		R^2		Es	
	ΣTSH	ΣTRS	ΣTSH	ΣTRS	ΣTSH ($t\ ha^{-1}$)	ΣTRS ($kg\ t^{-1}$)
EN	6.29	5.14	0.97	0.99	34.79	60.03
LN	9.75	6.09	0.96	0.99	28.93	47.27
NE	12.78	8.15	0.96	0.99	38.45	56.26

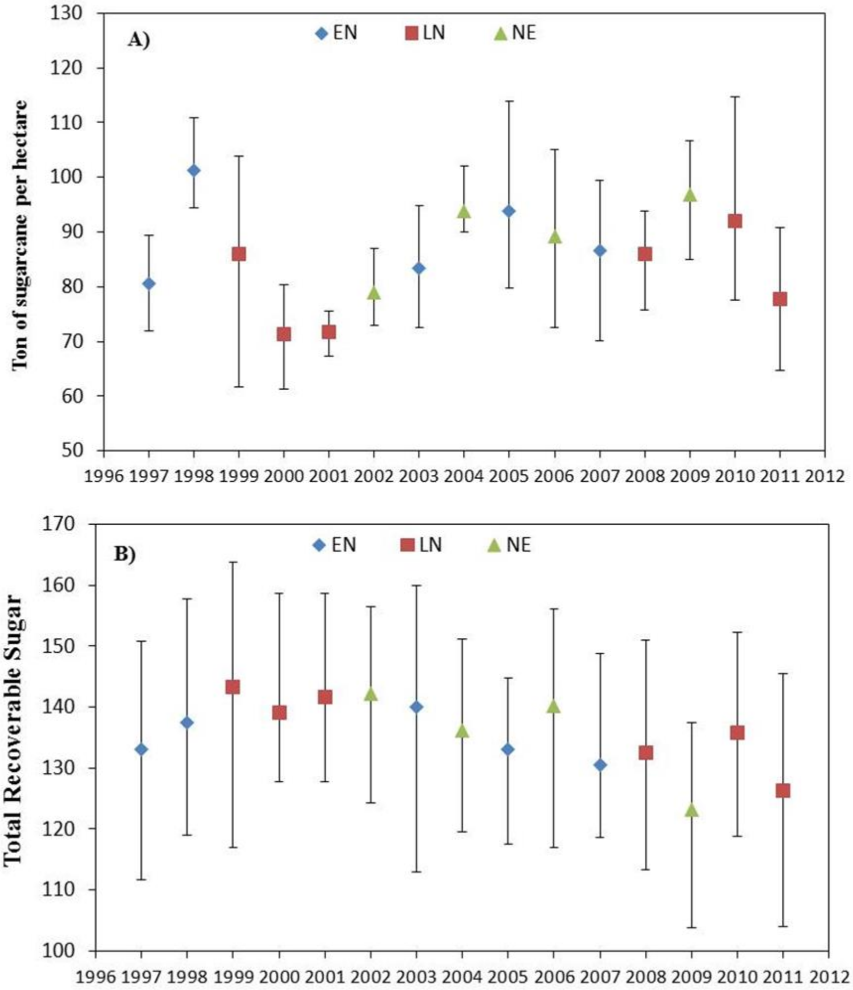

Fig 1. Annual average tonnes of sugarcane per hectare (A) and total recoverable sugar (B) in El Niño (EN), La Niña (LN) and neutral (NE) years from 1999 to 2011 for the Jaboticabal region.

TSH was positively correlated in most cases with spring and summer months in LN and NE years. TRS was correlated positively with spring and summer months and negatively with all seasons in the NE years (Table 3).

Material and Methods

Study area and climatic classification

Daily meteorological data for 1997-2011 were obtained for the Jaboticabal region (21°14'05" S; 48°17'09" W and 615 m a.s.l.). The regional climate is B_1rA'a' in the classification by Thornthwaite (1948).

Weather and sugarcane production data

A conventional meteorological station provided the data for evaporation by class A pan and the data of temperature and rain were obtained from an automatic meteorological station by the Micrologger CR23X system (Campbell Scientific Inc., Logan, Utah, United States). Average air temperature was recorded by a CS500 Temperature and Relative Humidity Probe (Campbell Scientific Inc.) and rainfall was recorded by an automated rain gauge. Monthly average sugarcane yield and quality data (TSH and TRS) were provided for 1997-2011 by several industrial plants in. The NE, EN and LN years were defined using the NOAA (2014) guidelines.

Analysis of meteorological components

Components of the water balance (DEF, EXC and STO), AET, mean air temperature and cumulative rainfall were analyzed for EN, LN and NE. These data were then correlated with TSH and TRS. The water balance model used was the Thornthwaite and Matter (1955) method, with an available water capacity of 100 mm and the potential evapotranspiration

Table 2. Values of X used in the equations generated by estimate models for estimating the sum of tonnes of sugarcane per hectare (∑TSH) and the sum of total recoverable sugar (∑TRS) for April to December as functions of the sums of water deficit (∑DEF) and the thermal index (∑GDD) for El Niño (EN), La Niña (LN) and neutral (NE) years.

	X_1	X_2	X_3	X_4	X_5	X_6
ΣTSH_{EN}	46.0896	9.6715	0.6106	0.0116	-0.0119	0.0005
ΣTRS_{EN}	-33.6762	11.6366	1.1158	0.0022	-0.0063	0.0014
ΣTSH_{LN}	-25.8386	13.0818	-0.5198	-0.1534	0.0408	0.0032
ΣTRS_{LN}	-23.6375	12.8270	0.4405	-0.0470	0.0084	0.0011
ΣTSH_{NE}	-41.8688	12.3511	-0.0301	-0.0349	-0.0012	0.0003
ΣTRS_{NE}	-56.7127	15.4584	0.0029	-0.0468	0.00071	0.0008

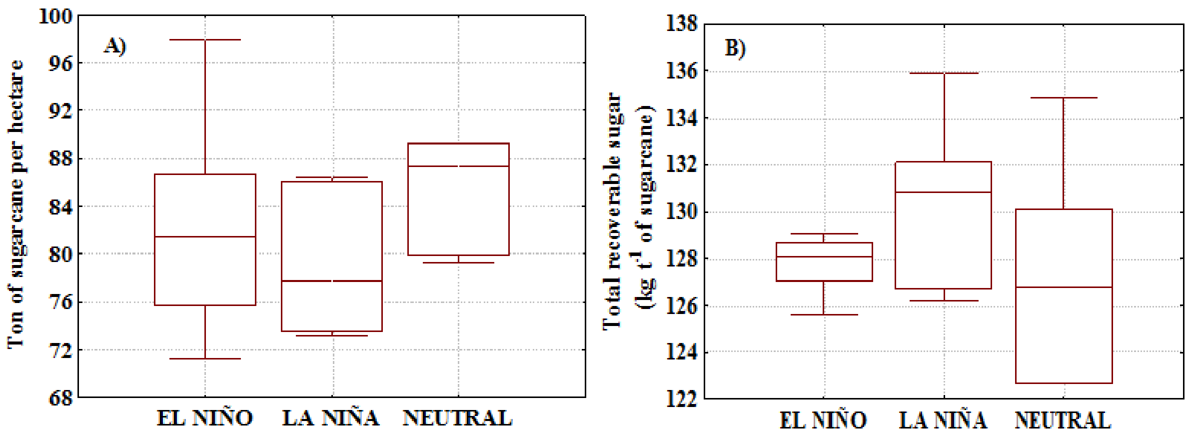

Fig 2. Average monthly tonnes of sugarcane per hectare (A) and total recoverable sugar (B) in El Niño, La Niña and neutral years between 1999 and 2011. median (—), 25-75% (□), 75-95% (⊤ ⊥), extreme (○) and outliers (⁎).

Table 3. Summary of correlations of TSH and TRS with meteorological parameters. * correlation during spring and summer, ** correlation during summer, *** yearly correlation; (-) negative and (+) positive correlation. P: precipitation (mm); AET: actual evapotranspiration; STO: soil water storage; EXC: water excess; DEF: water deficit and T: mean air temperature (°C). TSH: tonnes of sugarcane per hectare and TRS: total recoverable sugar. EN: El Niño, LN: La Niña and NE: neutral.

	EN	LN	NE
TSH	-T**	+P* +AET* +STO* +EXC* -DEF*	+P* +AET* +STO* +EXC* -DEF*
TRS			+T*** +DEF*** -AET* -STO* -EXC*

estimated by a class A pan following Doorenbos and Pruit (1977). The meteorological paremeters were correlated monthly to determine the dynamic influence of climate on TSH and TRS.

Statistical analysis and model development

The data were primarily analyzed using box plots to detect differences in TSH and TRS with the climatic conditions of EN, LN and NE years. The maximum, average and minimum annual values of TSH and TRS for these conditions were thus used. Distinct meteorological conditions in EN, LN and NE years that could account for the different values of TSH and TRS were also detected by box plots. Average monthly mean air temperature, AET and water balance components (DEF, EXC and STO) were analyzed. TSH and TRS values correlated to monthly temperature, P, DEF, EXC and STO. These correlations were made with data for the same year and the year before the sugarcane season for EN, LN and NE years. Contour plots were used for the analysis by the Pearson linear correlation coefficient (*r*).

Agrometeorological models (equation 1) were developed to estimate the accumulated monthly values of TSH and TRS as functions of the sums of water deficit (∑DEF) and the thermal index (∑GDD) with a base temperature of 10 °C for EN, LN and NE years.

$$\sum = x_{1+}x_2 * \sum GDD + x_3 * \sum DEF + x_4 * \sum GDD^2 + x_5 * \sum GDD * \sum DEF - x_6 * \sum DEF^2 \quad (1)$$

These models were evaluated using an analysis of accuracy based on the MAPE, an analysis of precision based on R^2 and an analysis of tendency analysis based on Es (equations 2, 3 and 4, respectively).

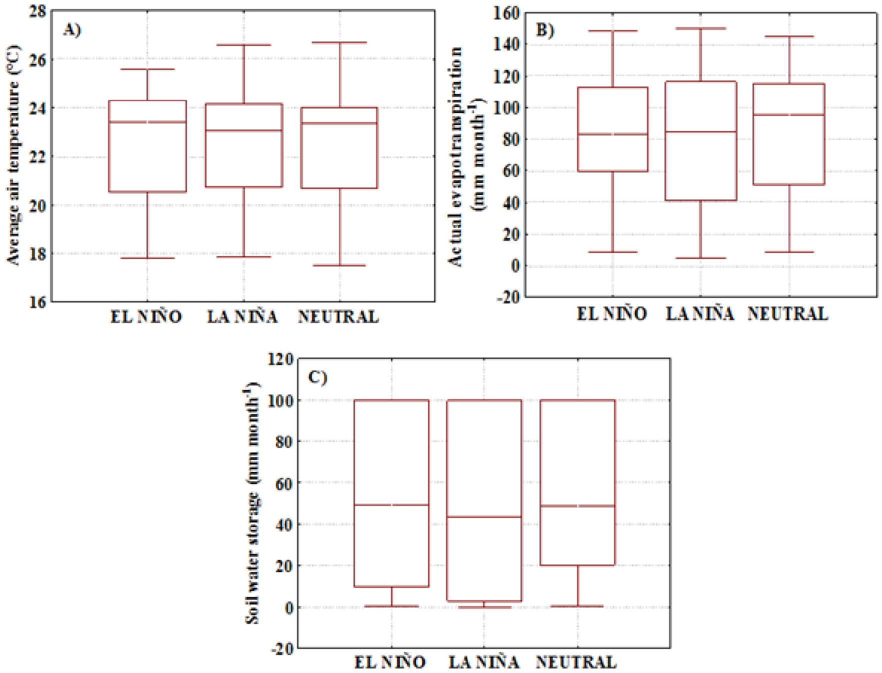

Fig 3. Average monthly temperature (A), actual evapotranspiration (B) and soil water storage (C) at El Niño, La Niña and neutral years. median (─), 25-75% (□), 75-95% (⊤ ⊥), extremes (○) and outliers (*).

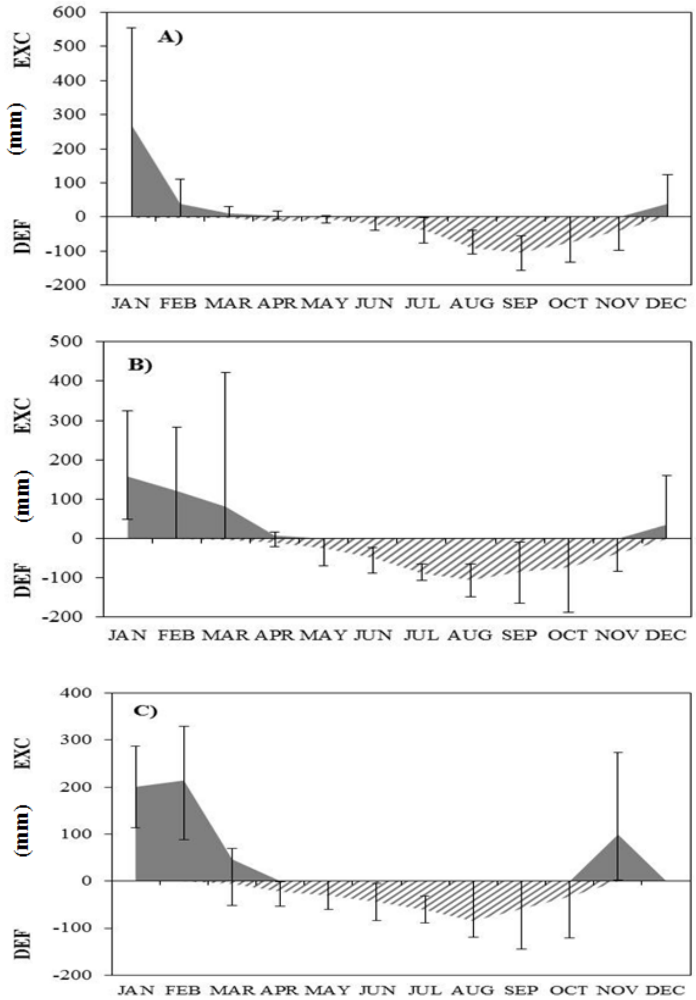

Fig 4. Monthly water deficit (DEF) and excess (EXC), with maximuns and minimuns for the El Niño (A), La Niña (B) and neutral (C) years. Available water capacity was 100 mm.

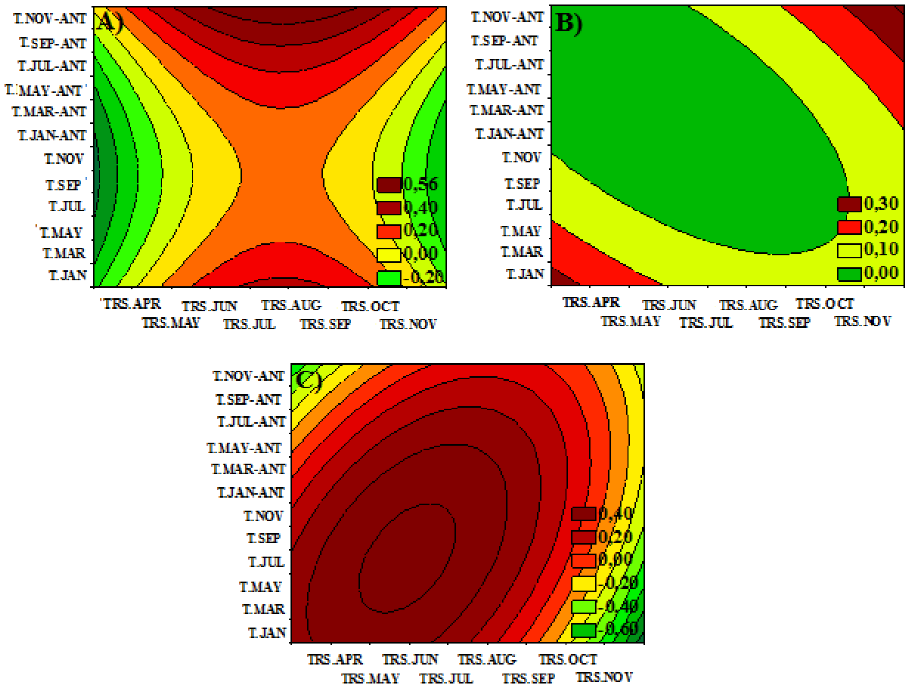

Fig 5. Pearson linear correlations (*r*) between total recoverable sugar (TRS) and temperature (T) of the harvest year and previous year in El Niño (A), La Niña (B) and neutral years (C).

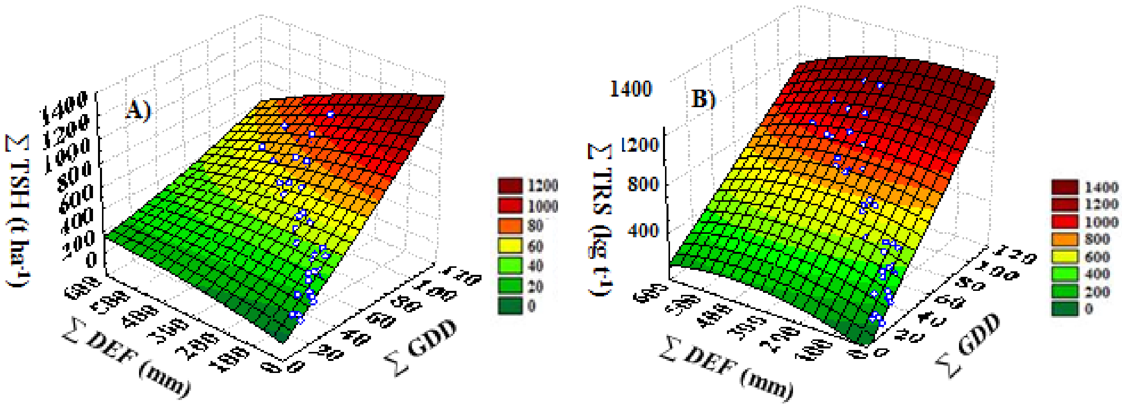

Fig 6. Agrometeorological models for estimating the sum of tonnes of sugarcane per hectare (∑TSH) (A) and the sum of total recoverable sugar (∑TRS) (B) for April to December, as functions of the sums of the water deficit (∑DEF) and the thermal index (∑GDD) in El Niño years.

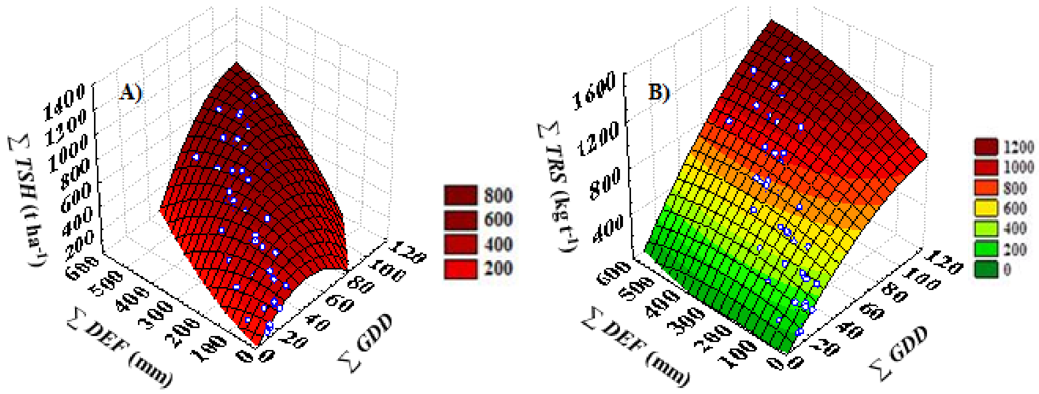

Fig 7. Agrometeorological models for estimating the sum of tonnes of sugarcane per hectare (∑TSH) (A) and sum of total recoverable sugar (∑TRS) (B) for April to December as functions of the sums of water deficit (∑DEF) and the thermal index (∑GDD) in La Niña years.

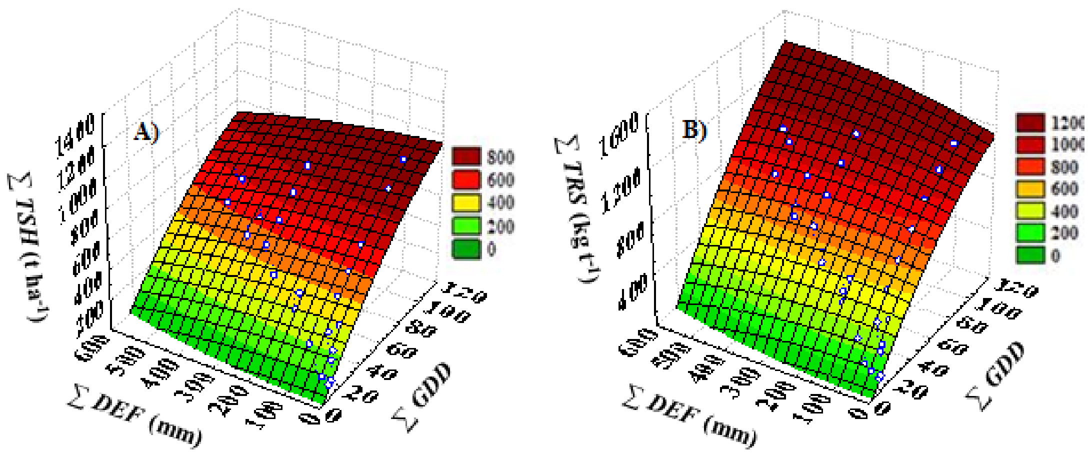

Fig 8. Agrometeorological models for estimating the sum of tonnes of sugarcane per hectare (∑TSH) (A) and sum of total recoverable sugar (∑TRS) (B) for April to December as functions of the sums of water deficit (∑DEF) and the thermal index (∑GDD) in neutral (NE) years.

$$MAPE = \frac{\sum_{i=1}^{N}\left(\left|\frac{Yest_i - Yobs_i}{Yobs_i}\right| \times 100\right)}{N} \quad (2)$$

$$R^2 = \frac{\sum_{i=1}^{N}(Yest_i - \bar{Y})^2}{\sum_{i=1}^{N}(Yobs_i - \bar{Y})^2} \quad (3)$$

$$Es = \sqrt{\frac{\sum_{i=1}^{N}(Yobs_i - \bar{Y})^2}{N}} \quad (4)$$

where, *Yobs* is the observed data; *Yest* is the estimated data by the models; $\bar{Y}$ is the average data and *N* the number of data.

Conclusions

TSH was higher in NE years; the water balance components of STO and EXC were higher than in the others years. Sucrose production (TRS) was higher in LN years, which also had higher DEF. Water balance components had largest variations among EN, LN and NE years in February and March. Rainfall in November was higher in NE years. The regional agrometeorological models developed for Jaboticabal accurately estimated ∑TSH and ∑TRS, as functions of ∑GDD and ∑DEF for EN, LN and NE years.

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