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Determination of favorable sowing date of sweet sorghum in the State of São Paulo, Brazil by crop modeling

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Sweet sorghum is a biofuel source for alternating with sugarcane in the State of São Paulo due to its short cycle, good sugar quantity and the possibility of using the same machinery that has been used for cane harvesting. The interest in the use of this crop is increasing because it keeps the sugar mills with material supply from all areas throughout the year. Thus we used an agrometeorological model to determine the best sowing dates for sweet sorghum, taking into account an early Brazilian cultivar (BRS 700), medium (BRS 601) and late (BRS 506). This model mainly relates solar irradiation, air temperature and water availability to crop yield. The simulations were done in important sugarcane regions in the State as north (Barretos), central-north (Jaboticabal), west (Tupã) and south (Itapetininga). After calibration, the model was used to estimate the potential yield, actual yield, climatic risk and the relative yield loss for 36 sowing dates per year with available data (1971-2012). The cultivars had the highest average yield in Itapetininga due to the increase of the cycles followed by Tupã, Barretos and Jaboticabal. The cultivar BRS 700 had the greatest climatic risk (84.19%) at Tupã and BRS 506 the lowest (63.17%) at Itapetininga. On average the best planting dates for cultivars were the second 10-day period (TDP) of September (2TDP-Sept) up to 2TDP-Jan to the Barretos, Jaboticabal and Tupã regions, and 2TDP-Jul up to 2TDP-Nov to Itapetininga.

Key words: Climate risk, yield estimation, planting season, Food and Agriculture Organization (FAO), agrometeorology.

INTRODUCTION

The demand for alternative fuels, particularly ethanol, is constantly rising in the world. Currently biofuels contribute 3% of global transportation and by 2050 is expected to increase to 10% (Yan et al., 2011). The cultivation of sorghum (*Sorghum bicolor* L. Moench), one of the important cereal in the world (Ferreira et al., 1999), has gained prominence, primarily sweet sorghum cultivars also known as cane sorghum. The sorghum cultivars exhibit high sugar content in the stem (Nan et al., 1994). The source of this sugar is the fermentable

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Table 1. Geographic coordinates of locations, period of data collection and the number of years used effectively.

Location	Latitude (°, south)	Longitude (°, west)	Altitude (m)	Period	Years	Climate[(3)]
Barretos[1]	20º33'26''	48º34'04''	530	1992-2008	18	$C_2dA'a'$
Jaboticabal[2]	21º15'17''	48º19'20''	607	1971-2012	41	$B_1rA'a'$
Tupã[1]	21º56'01''	50º30'45''	524	1993-2012	19	$B_1rB'_4a$
Itapetininga[1]	23º35'30''	48º03'11''	656	1994-2010	16	$B_1rB'_3a'$

Source: ([1]) Instituto Agronômico de Campinas, Centro Integrado de Informações Agrometeorológicas (CIIAGRO), ([2]) UNESP - Jaboticabal, ([3]) Folowing Thornthwaite (1948) climatic classification system.

carbohydrates (Teetor et al., 2011; Teixeira et al., 1999) allowing the production of biomass for ethanol production. In addition, these cultivars have short cycle, around 120 days (Parrella et al., 2012), have the possibility of mechanization with the same machinery for sugarcane (Embrapa, 2004), and presents high water use efficiency and can be grown in semi-arid conditions (Narayanan et al., 2013).

The crop yield is essentially dependent on climatic factors (Poudel and Koji, 2013). Hoogenboom (2000) points out that the weather elements most critical to agricultural production are usually the air temperature, solar radiation and rainfall. The air temperature regulates rates vegetative and reproductive development. The solar radiation provides the energy for photosynthesis affecting the partitioning of carbohydrates and growth of the individual components of the plant. Some cultivars of sorghum are photoperiodic, especially in relation to flowering (Craufurd and Qi, 2001), but none of them were selected for this study. Hoogenboom (2000) further states that water availability affects evapotranspiration, water uptake by the roots, the root system distribution, the size of the canopy, thereby affecting the rates of plant development. The same author emphasizes that the surface temperature of the soil is important for germination rates. The relative humidity, temperature, dew point and vapor pressure deficit influence the presence and activity of pests and diseases, and the wind affects the transpiration rate of the plants and spread of insects and diseases.

The origin of sorghum is the African tropical areas (Teetor et al., 2011), and water requirements are about 400 mm up to 600 mm to complete the cycle in the central area of Brazil (Sans et al., 2003). The sorghum is one of the crops with high sensitivity at low air temperatures, which occur most commonly at night. The optimum daily air temperature range is from 33 to 34°C. Air temperatures above 38°C and below 16°C decreases the yield of sorghum (Magalhães et al., 2008).

A model is a mathematical representation of a system and modeling is the process of development of this representation (Jones et al., 1987). The crop models seek to explain and estimate the plant development and yield, evaluating the effect of meteorological variables in physical and physiological processes of crops (Baier, 1979), helping the planning and decision making in agricultural areas (Niu et al., 2008).

The relationship between the crop development and climatic factors is complex, but Doorenbos et al. (1979) simplified this relationship and proposed that the actual yield (AY) is related to a potential yield (PY) modulated by water availability. The PY of a crop, calculated by a submodel named agroecological zone method (AEZ), depends basically of the photosynthetic rate which is related to solar irradiance, air temperature and plant genetic potential. The model relates the crop yield loss to water availability and also can be used to determine best sowing dates (Belmont et al., 2002). The most suitable sowing dates are those when weather conditions minimize the yield losses due to water deficit or excess (Neto et al., 2001). Von Pinho et al. (2007) determining the best sowing dates for maize and sorghum in the State of Minas Gerais, Brazil, found that sowing in November and January promote the increase of dry matter and higher nutritional value, respectively. This effect was due to lack of rain from February fostering a reduction in dry matter and increased amount of nutrients. The thermal and water available in State of São Paulo are somewhat similar of Minas Gerais but the variability of rain is greater.

Several papers are found in the literature on the determination of sowing dates using as models for the cultivation of upland rice (Wrege et al., 2001), bean (Silva et al., 2006b), maize (Maton et al., 2007), soybean (Dallacort et al., 2006) and wheat (Silva et al., 2009). As sweet sorghum is an option for ethanol production in periods alternating with the sugarcane the present work aims to determine the best sowing dates for four major sugarcane regions in the State of São Paulo using the agrometeorological model proposed by Doorenbos et al. (1979).

MATERIALS AND METHODS

Time series data of maximum and minimum air temperature (°C) and precipitation (mm) from four meteorological locations were used. The mean air temperature was calculated as the average between the maximum and minimum daily temperature. The sites selected were Barretos, Jaboticabal, Tupã and Itapetininga (Table 1), important sorghum regions at São Paulo State. The sweet

Table 2. Crop coefficient (Kc), available water capacity (CAD), coefficient of sensitivity to drought (Ky) and leaf area index (LAI).

Phenological phase	Kc	CAD (mm)	Ky	LAI
Establishment (EST)	0.4	20	0.0	0.2
Vegetative Development (DV)	0.7	40	0.2	3.0
Flowering (FLR)	1.1	70	0.6	5.0
Frutification (FRU)	0.8	80	0.5	4.5
Maturation (MAT)	0.5	80	0.2	4.0

sorghum cultivars were selected according to the cycle of each material, the variety BRS 506, hybrids BRS 601 and BRS 700, were late, intermediate and early, respectively, all without photoperiodic sensitivity, provided by the Brazilian Agricultural Research Corporation (EMBRAPA).

The crop water balance was calculated as proposed by Thornthwaite and Mather (1955) modified by Barbieri et al. (1997) which takes into account the variation of the crop coefficient (Kc), coefficient of sensitivity to water stress (Ky) and available water capacity (CAD) for each phenological phase. The values of these coefficients are those recommended by Doorenbos et al. (1979) (Table 2). The potential evapotranspiration (PET) was estimated by the method of Camargo (1962) (Equation 1).

$$PET = 0.01 \times \frac{Qo}{2.45} \times T \times N \quad (1)$$

Where, Qo = Extraterrestrial solar irradiation (MJ m^{-2} d^{-1}), T = daily mean air temperature (°C), N = number of days.

Using 10-day data, simulations were made estimating potential yield (PY) following Agroecological Zone proposed by Doorenbos and Kassam (1994), by Equation (2).

$$PY = PPB \times Ciaf \times Cres \times Ccol \times ND \quad (2)$$

Where, PPB = Gross potential yield of dry matter (kg ha^{-1}); Ciaf = coefficient of leaf area index; Cres = respiration coefficient; Ccol = coefficient of harvest index, ND = number of days of crop phenological phase.

Actual yield (AY) due to water restrictions was estimated according to the model proposed by Doorenbos and Kassam (1994), using the factor of crop sensitivity to water stress (Ky) by Equation (3):

$$AY = \left[1 - Ky \times \left(1 - {ETa}/{ETc}\right)\right] \times PY \quad (3)$$

Where: ETa = actual crop evapotranspiration (mm $period^{-1}$), ETc = crop evapotranspiration (mm $period^{-1}$);
The relative yield loss (Q) (Equation 4) was tested for 36 sowing dates per year and used for determining the best sowing dates.

$$Q = \left(1 - {AY}/{PY}\right) \times 100 \quad (4)$$

The analysis was divided into two stages: the first consisted of calibration of the cultural coefficients for each cultivar: lower base temperature (Tb), Thermal index for cycle duration (ΣGD), harvest index coefficient (Ccol) and humidity of the harvested product (U%). In this step we used the last five years meteorological data of each location. The second step consisted in simulating PY and AY and cycle duration in different sowing dates using the remain climatic data for each location. The calibration coefficients was done iteratively using linear programming model with the generalized reduced gradient (GRG2) (Lasdon and Waren, 1982) to minimize the difference between the estimated AY data and those collected from Silva et al. (2005, 2006a).

The climate risk (CR) was determined for each location relative to the cultivation of sweet sorghum (Equation 5). The CR indicates the sensitivity of the overall annual crop yield related to different regional climatic conditions. If CR is close to 0%, it means that the yield amplitude in many years is small caused by a stable climatic conditions therefore under low climatic risk.

$$CR = \left[{(AYmax - AYmin)}/{AYmax}\right] \times 100 \quad (5)$$

Where, AYmax = Absolute maximum actual yield (kg ha^{-1}) and AYmin = absolute minimum actual yield (kg ha^{-1}) in the analyzed period.

The best sowing dates were determined by the high values of AY with low variability and low values of Q, analyzed by box-plot charts and scatterplots.

RESULTS AND DISCUSSION

The calibration of cultivars coefficients using GRG2 algorithm showed that all cultivars present Tb equal to 8°C and U% equal to 80%. The other parameters were different for each cultivar (Table 3). The Barretos region had the high monthly air mean temperatures in relation to other areas (Figure 1a). Itapetininga was the coldest region (Figure 1d). The high air temperatures conditioned high evapotranspiration associated with low rainfall, Barretos exhibits greater water deficit (DEF) in comparison to other regions. Generally in all regions, DEF occurred between mid-March and October, except at Itapetininga where normal periods of DEF were from July to September. The greater values of AY for BRS 506, BRS 601 and BRS 700 were found in Itapetininga, 84104.6, 71536.7 and 57625.9 kg ha^{-1}, respectively, due to warm temperatures and minors DEF showed in this location in relation to others.

The lowest AY occurred at Tupã for BRS 601 and BRS 700 values 12131.29 and 7685.02 kg ha^{-1}, concurrently. BRS 506 for the location of production was lower Barretos, with 17005.81 kg ha^{-1}. Marin et al. (2006) working with sorghum in the region of São Paulo suggests that the fall of the AY can be attributed to

Table 3. Harvest index (Ccol), cycle duration and the sum of degree-days (ΣGD) for different phenological phases of sorghum cultivars.

Cultivar	Ccol	Cycle (Days)	∑GD					
			EST	DV	FLR	FRU	MAT	Total
BRS-506	0.9	125	380	608	456	228	228	1900
BRS-601	0.8	100	360	540	360	270	270	1800
BRS-700	0.8	92	244.6	231	380.4	203.8	190.2	1250

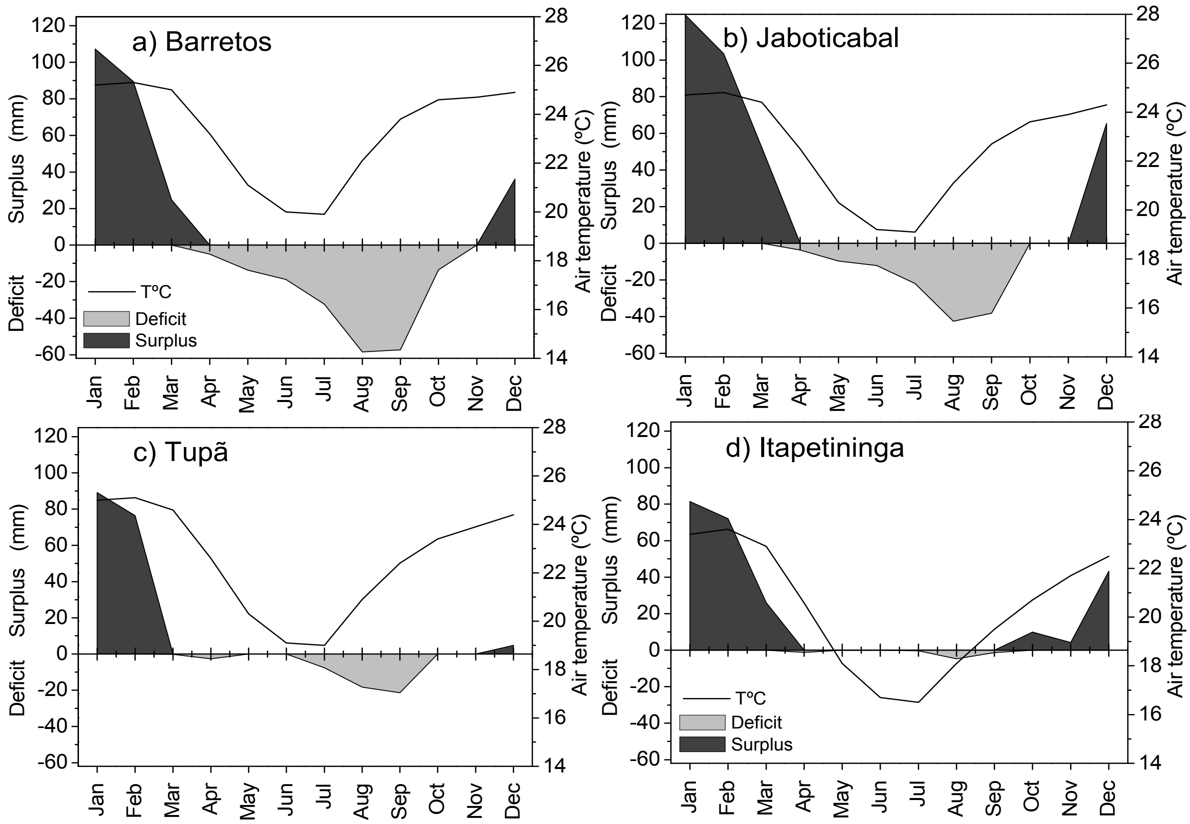

Figure 1. Monthly water balance (deficiency and surplus) following Thornthwaite and Mather (1955) method and mean air temperature. Source: INMET (1990).

severe water deficit and low air temperature during the winter. Climate risk (CR) found for the study sites was 75.57, 76.90, 75.93 and 63.74% compared to BRS 506, but for hybrid BRS 601 values were 75.69, 81.48, 80.46 and 65.23%, and the BRS 700, 64.98, 79.82, 84.19 and 70.42% to Barretos, Jaboticabal, Tupã and Itapetininga respectively.

The best planting dates for BRS 506 occurred from the second ten-day period of September (2TDP-Sept) up to 2TDP-Jan in Barretos, 2TDP-Sept up 1TDP-Jan in Jaboticabal, 1TDP-Oct up to 2TDP-Jan in Tupã and 1TDP-Jul up to 2TDP-Nov in Itapetininga because these times were higher AY, smaller Q (%) and relatively less variability (Figure 2), however, for Soybeans in the State of Paraná, the best sowing date were 2TDP-Oct up to 1STD-Nov (Dallacort et al., 2008).

The average AY of BRS 506 in favorable sowing dates were 53928.3, 55731.7, 52862.6 and 66557.9 kg ha^{-1} for Barretos, Jaboticabal, Tupã and Itapetininga respectively. The greater Q occurred in mid-April for all locations. This was due to the phase DV that had an average of 160 days (Figure 3), flowering (45 days) and maturation (40 days) occurred during periods of DEF. In similar experiment, analyzing the cultivar BRS 300 in the location of Ilha Solteira, SP, Marin et al. (2006) described a high Q in the sowing dates during 1TDP-Apr up to 1TDP-Aug.

The Itapetininga region had a decrease of AY from

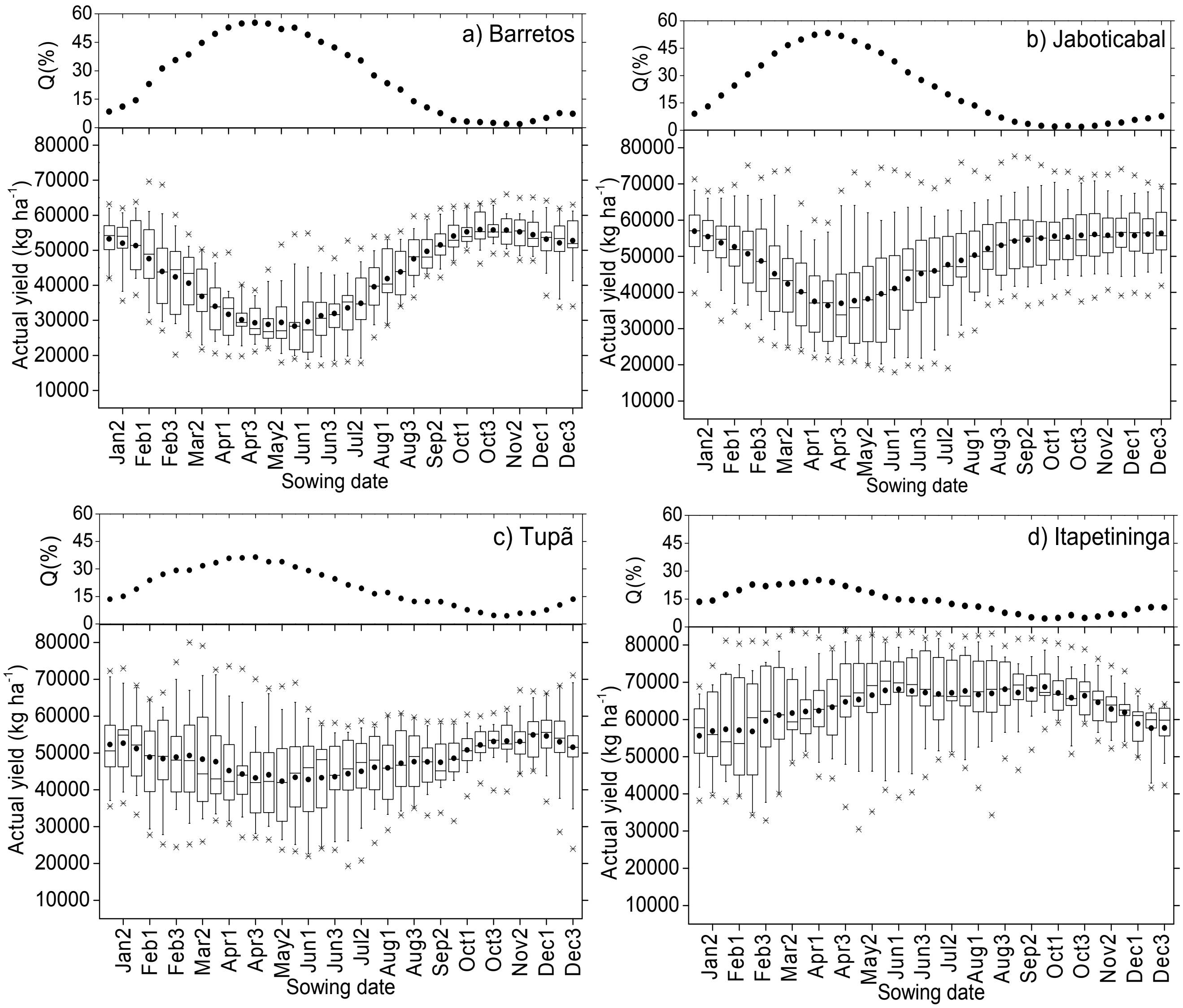

Figure 2. Simulation of actual yield (kg ha^{-1}) and relative yield loss (Q) (%) in relation to 10 days intervals of sowing dates for variety BRS 506 at a) Barretos, b) Jaboticabal, c) Tupã and d) Itapetininga.

2TDP-Nov, reaching a difference greater than 5000 kg ha^{-1} for BRS 506 variety and the hybrid BRS 601. These levels of AY were probably due to low air temperatures (Figure 1d) that maintained low atmospheric vapor demanding, favoring EXC conditions during flowering (45 days) and DEF during maturation. The simulation of different sowing dates for hybrid BRS 601 resulted in high AY, low Q and low variability from 1TDP-Oct to 3TDP-Jan in Barretos, 3TDP-Oct to 1TDP-Mar in Jaboticabal, 3TDP-Oct to 1TDP-Feb in Tupã and 2TDP-Jul to 2TDP-Nov in Itapetininga (Figure 2). The best sowing dates for BRS 700 were from 2TDP-Oct up to 3TDP-Feb, for all locations, except in Itapetininga in which the best dates were from 2TDP-Jul up to 3TDP-Dec (Figure 4). These results were similar to Silva et al. (2006a) that worked in Viçosa, MG, showing that the best sowing dates for BRS 700 ranged from 1TDP-Dec up to 1TDP-Jan.

In the best sowing dates for BRS 601 the Q were less than 20% and AY in Barretos, Jaboticabal, Tupã e Itapetininga were 47.201,7 kg ha^{-1}, 42.2558,8 kg ha^{-1}, 42.426,6 kg ha^{-1} and 56.090,8 kg ha^{-1}, respectively. The AY for BRS 700 was 33.767,1 kg ha^{-1}, 35.048,8 kg ha^{-1}, 29.788,1 kg ha^{-1} and 40.938,4 kg ha^{-1} in Barretos, Jaboticabal, Tupã and Itapetininga, respectively. The high values of Q of BRS 506 occurred in mid-may for all locations except Itapetining, where the higher Q were from March and April, period of EXC (Figure 4). But for BRS 700 the greatest Q occurred in 2TDP-May for Jaboticabal and in1TDP-Jun for all the other locations (Figure 5).

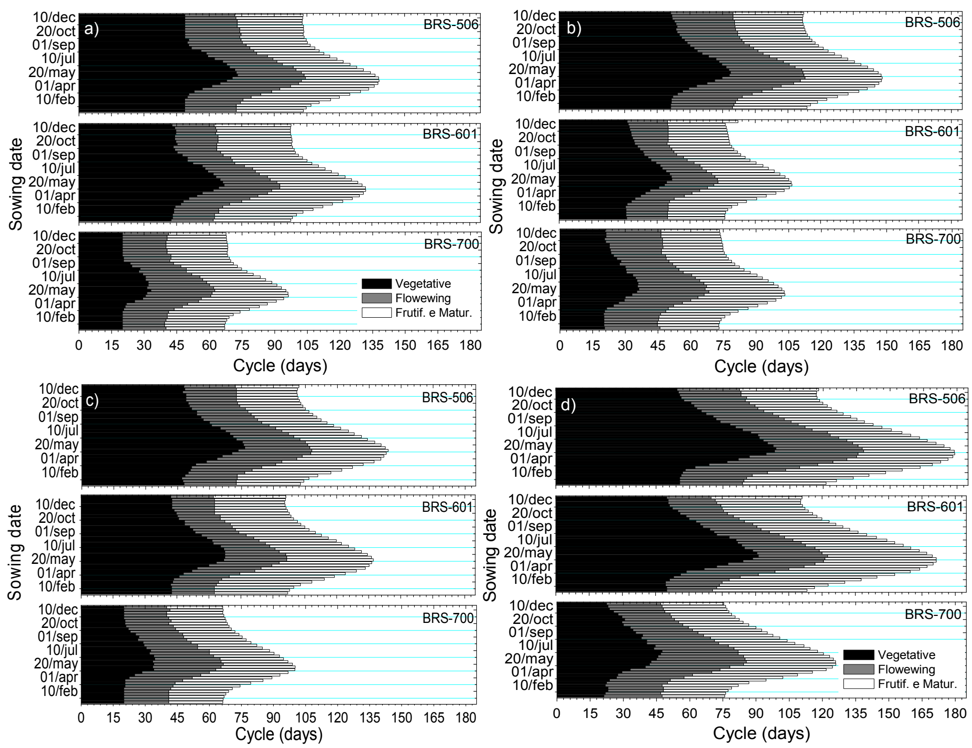

Figure 3. Simulation of the average duration of sorghum cycle in 10-days period of sowing dates, in different regions of State of São Paulo: a) Barretos; b) Jaboticabal; c) Tupã and d) Itapetininga.

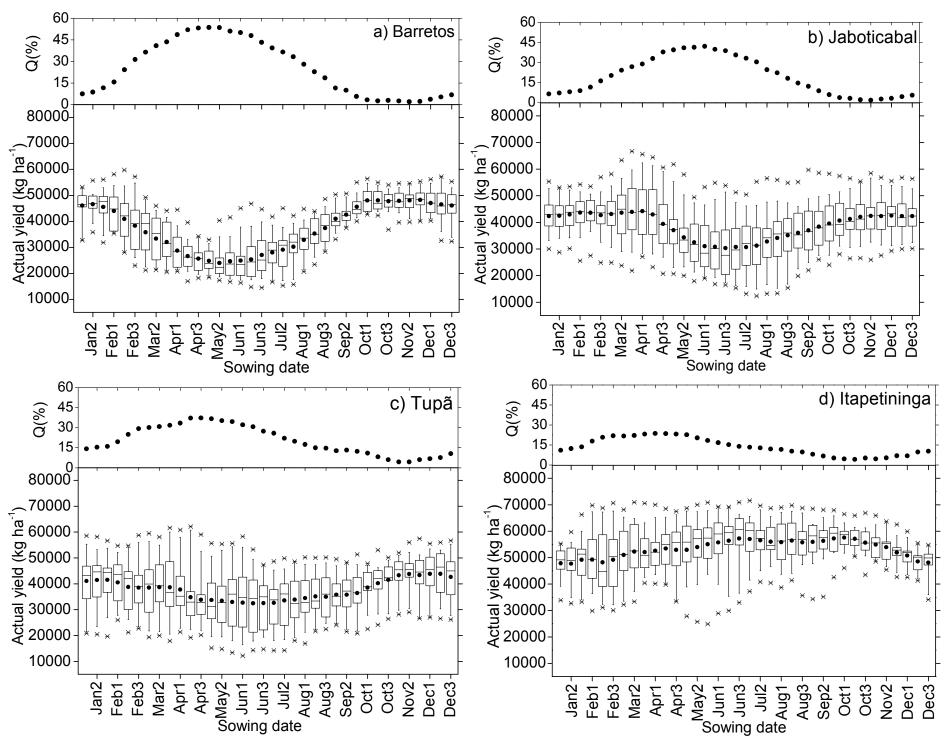

Figure 4. Simulation of actual yield (kg ha^{-1}) and relative yield loss (Q) (%) in relation to 10 days intervals of sowing dates for hybrid BRS 601 in a) Barretos, b) Jaboticabal, c) Tupã and d) Itapetininga.

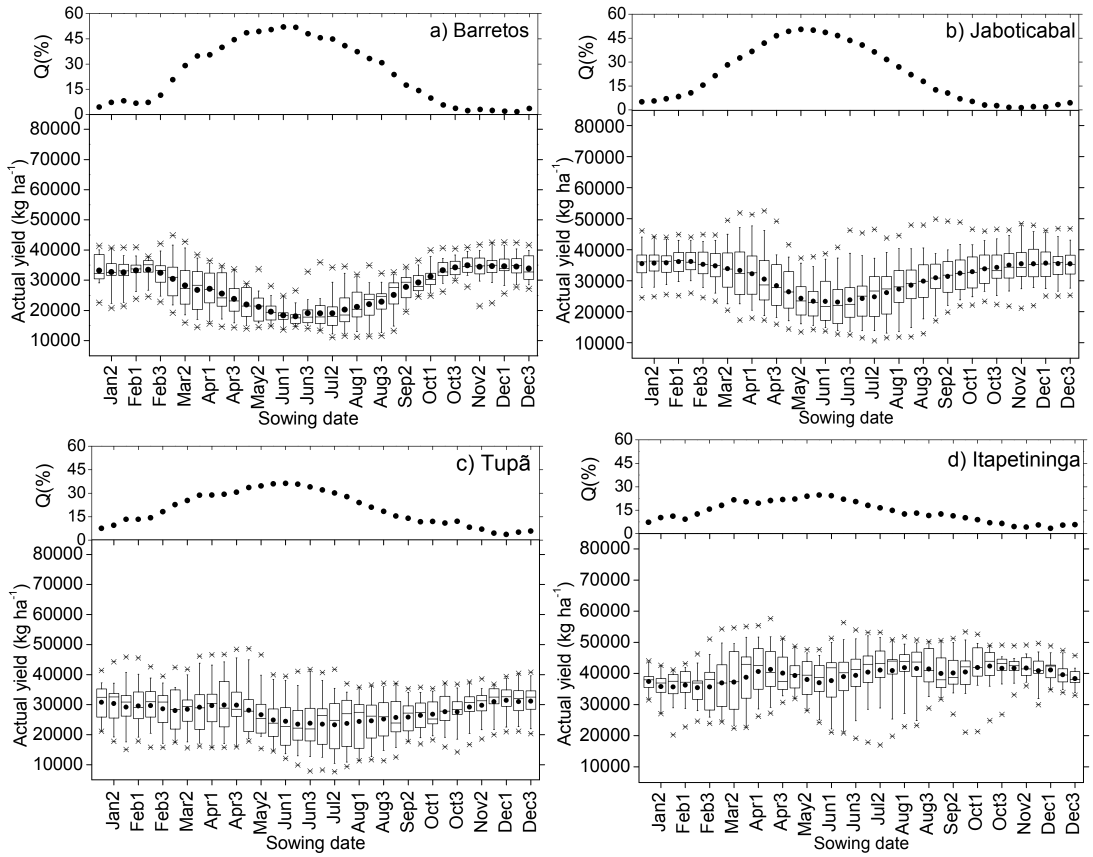

Figura 5. Simulation of actual yield (kg ha^{-1}) and relative yield loss (Q) (%) in relation to 10 days intervals of sowing dates for hybrid BRS-700 in a) Barretos, b) Jaboticabal, c) Tupã and d) Itapetininga.

Conclusion

Our study indicates that in Barretos, Jaboticabal and Tupã there are favorable sowing dates for sweet sorghum, cultivars BRS 506, BRS 601 and BRS 700, in the sugarcane inter-harvest period that are between December and April. The best sowing dates were from 20 of September up to 20 of January. In Itapetininga region the sweet sorghum does not show conditions for sowing dates in the sugarcane inter-harvest period because the favorable dates ranged from 20 of July up to 20 of November.

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Conflict of Interest

The authors have not declared any conflict of interest.

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