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Sugarcane Productivity Simulation Under Different Scenarios by DSSAT/CANEGRO Model in the Western São Paulo

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Abstract

Sugarcane (*Saccharum officinarum* L.) is one of the most important crops in Brazil and its growth and development can be simulated through process-based models. The current study evaluated a model based on the decision support system for the transfer of Agrotechnology DSSAT/CANEGRO to simulate the sugarcane crop productivity in the western region of São Paulo. The DSSAT/CANEGRO model was calibrated using published yield parameters from a selection of five Brazilian sugarcane cultivars, while sugarcane yield data (tons of stems per hectare) from commercial land were used as benchmark data. Other modeling inputs were derived from the primary regional cultivar. The root mean square error (RMSE), Willmott agreement index (d), and mean absolute error (MAE) were used as performance metrics. The DSSAT/CANEGRO model resulted in a good RMSE performance. The productivity estimates were better for the cultivars SP791010 and RB835486, with RMSE equal to 2.27 and 4.48 Mg ha^{-1}, respectively. The comparison between model-based estimates and observed data produced d values in the range from 0.86 to 0.99, and MAE values in the range of 1.84 to 4.22 Mg ha^{-1}.

Keywords: *Saccharum officinarum*, yield forecast, modeling

1. Introduction

The cultivation of sugarcane (*Saccharum officinarum*) is among the most important crops in Brazilian agribusiness. Brazil is the world's largest sugarcane producer and the second largest producer of ethanol. The areas under production continue to gradually increase, although at a slower pace in the midwest states in Brazil and southeast regions. Since 2008, industrial units of sugarcane processing facilities were installed in the west of São Paulo state, which facilitated developing additional sugarcane fields (CONAB, 2018). This region has some edaphoclimatic characteristics that are different from the other sugarcane regions of the state, such as sandy soils with low water retention capacity, high temperatures, heavy rains and long periods without rain (summer), which promote plant water stress.

There are different models for estimating growth and evaluating the development of process-based cultures that can facilitate monitoring and contribute to activities related to productivity forecasting, as well as assist in understanding those mechanisms that are directly involved in the different responses of culture to the environmental conditions (Marin et al., 2011; Nassif et al., 2012).

According to Marin et al. (2011), currently there are several models that can be used for sugarcane growth simulations, such as: AUSCANE (Jones et al., 1988), QCANE (Liu & Kingston, 1995), APSIM (Keating et al., 1999), and CASUPRO (Villegas et al., 2005). One of the main and most used models is the DSSAT/CANEGRO (Inman-Bamber, 1991; Singels & Bezuidenhout, 2002) is also one of the main simulation models of growth of the sugarcane currently in use (Nassif et al., 2012). The DSSAT/CANEGRO model is based on the Ceres-Maize model (Jones et al., 1986), which was developed to model the most important physiological processes related to sugar production processes in South Africa (Inman-Bamber, 1991).

The DSSAT/CANEGRO model is being used in different regions of the world to analyze the different sugarcane production systems (Inman-Bamber, 1991; Marin et al., 2011; Singels & Bezuidenhout, 2002; Singels et al., 2008; Nassif et al., 2012). In Brazil, Marin et al. (2011) calibrated the DSSAT/CANEGRO model for two cultivars in the production systems of the center-south of Brazil.

Thus, the aim of this study is to estimate the sugarcane productivity under conditions in the western portion of the state of São Paulo. The following specific objectives will be developed: (i) to evaluate the DSSAT model under different climatic and soil conditions for sugarcane production; (ii) to evaluate the performance of the DSSAT model using data reported by the sugarcane mills, and (iii) to evaluate the sugarcane productivity estimates in the western portion of the state of São Paulo, Brazil.

2. Method

2.1 Model Description

Sugarcane productivity simulations in western portion of São Paulo state were carried out with the DSSAT/CANEGRO version 4.5 to model the most relevant sugarcane physiological processes, whereas the Weatherman subroutine to analyze the climatic data.

The DSSAT/CANEGRO model requires water balance information and daily meteorological data (*i.e.*, solar radiation, maximum and minimum temperatures, and precipitation). The sugarcane growth modeling includes phenology, canopy development, accumulation of biomass and sucrose, partitioning, root growth, water stress and lodging data (Singels et al., 2008). The model also requires soil physics data (*i.e.*, field capacity, permanent wilting point, water saturation and soil depth) at the entrance of the process to adjust the water balance (Nassif et al., 2012).

2.2 Input Variables by the Simulations

The input variables were: precipitation (P) (mm), air temperature (Tmax) (Tmin) (Tmed) (maximum, minimum and average) (°C), solar radiation (Rs) (MJ m^{-2}), average relative humidity (RH) (%) and average wind speed (m s^{-1}) provided by the National Institute of Meteorology (INMET, http://www.inmet.gov.br) on a daily basis. The soil physical-chemical characteristics used to describe the soil's water storage capacity were: the permanent wilting point (cm^3 cm^{-3}), field capacity (cm^3 cm^{-3}), saturation point (cm^3 cm^{-3}), cation exchange capacity (cmol kg^{-1}) and soil organic matter (g kg^{-1}).

The varieties used to perform the simulations (RB835486, SP791011, RB931530, and RB93509) were selected based on the sugar mill productivity data for the last 15 years. The RB867515 cultivar parameters were used to calibrate the model. These cultivars were selected due to their representativeness in planting sugarcane fields in the studied region.

The soil profile characterizations were classified according to the Pedological Map of São Paulo state presented by Rossi (2017). The most representative soils of the Presidente Prudente-SP microregion were used in the simulation: Argilossos and Latossolos according to Brazilian System of Soil Classification (SiBCS) (Santos et al., 2013), which are equivalent to Ultisols and Typic Hapludox subgroups, respectively, according to U.S. Soil Taxonomy (Soil Survey Staff, 2019).

2.3 Method of Acquisition, Selection and Transformation of Climatic Data

The metadata used for weather stations are shown in Table 1. The region of western São Paulo state on the borders with Paraná and Mato Grosso do Sul state, has a tropical climate, type CWa according to the Köppen climate classification, characterized by hot and rainy summers, and cold and dry winters. The average annual precipitation is 1,308 mm, with a maximum of 2,049 mm in 2009. January has the highest average rainfall (212 mm), according to data recorded by the meteorological station of Presidente Prudente from 1969 to 2013. Severe drought events were observed, demonstrating again the great randomness and complexity of the atmospheric system, with the year 2001 being classified as unusual with relation to climate normals. La Niña's (a cold phase oscillation quasiperiodic of climate pattern that arises across the tropical Pacific Ocean on the coast of Peru and Ecuador every five years) (Gómez-Aguilar, 2020) years are no exception to this characteristic, even though they tend to be drier years. El Niño (describe the warm oceanic phase of climate pattern) (Gómez-Aguilar, 2020) years are characterized in most cases by the presence of extreme events in the region, such as intense rains (Berezuk & Neto, 2006) (Figure 2b).

Table 1. Weather stations in the region of Presidente Prudente, SP

Station	State	Code	Latitude	Longitude	Elevation (m)
Ivinhema	MS	83704	-22.3°	-53.81°	369.00
Londrina	PR	83766	-23.3°	-51.13°	566.00
Maringa	PR	83767	-23.4°	-51.91°	542.00
Presidente Prudente	SP	86863	-22.1°	-51.40°	435.55

Note. *MS: Mato Grosso do Sul PR: Paraná SP: São Paulo.

The analyzes were performed with production data provided by the industry (sugarcane yield observed), located in Dracena 22º07′51.3″ S; 51º24′9.6″ W, 436 m elevation, in the west of state of São Paulo, Brazil. The relative location of meteorological stations in the region of Presidente Prudente, São Paulo, Brazil are shown in Figure 1.

Figure 1. Relative location of the selected INMET meteorological stations

2.3.1 Determination of the Water Demands of Eugarcane (ETo)

To determine the reference evapotranspiration (ETo), the climatological data published by the National Institute of Meteorology (INMET, http://www.inmet.gov.br) were used. The calculation of ETo was performed using the Penman-Monteith method (Allen et al., 1998; Raes et al., 2012), as recommended by Jensen et al. (1990) according to Equation 1.

$$ET_o = \frac{0.408 \cdot s \cdot (R_n - G) + \gamma \cdot 900 \cdot U_2 \left[\frac{e_s - e_a}{T_d + 273}\right]}{s + \gamma \cdot (1 + 0.34 \cdot U_2)} \quad (1)$$

$$G = 0.38 \cdot (T_d - T_{3d}) \quad (2)$$

$$e_s = \frac{0.6108 \cdot e^{[(17.27T_{max})/(237.7 + T_{max})]} + 0.6108 \cdot e^{[(17.27T_{min})/(237.7 + T_{min})]}}{2} \quad (3)$$

$$e_a = \frac{(UR \cdot e_s)}{100} \quad (4)$$

$$e_a = \frac{4098 \cdot e_s}{(T + 237.3)^2} \quad (5)$$

Where, ETo: reference evapotranspiration (mm day^{-1}); Rn: total daily net radiation (MJ m^{-2} day^{-1}); G: soil heat flux density (MJ m^{-2} day^{-1}); γ: psychometric constant (0.063 kPa °C^{-1}); Td: average daily temperature (°C); U_2: wind speed at 2 m height (m s^{-1}); e_s: saturation vapor pressure (kPa); e_a: actual vapor pressure (kPa); s: rate of change of vapor pressure in relation to temperature (kPa °C^{-1}).

The description of the parameters of the cultivars and their units are based on work of Nassif et al. (2012) and Marin et al. (2015), as shown in Table 2.

Table 2. Description of the cultivar parameters and units needed to run the simulation in the DSSAT/CANEGRO model with the sugarcane cultivars representative of the western São Paulo.

Parameter	Unit	Description
Parcemáx	g MJ^{-1}	Maximum (no stress) radiation conversion efficiency expressed as assimilate produced before respiration per unit of photosynthetic active radiation (PAR)
APFMX	Mg Mg^{-1}	Maximum fraction of dry mass increments that can be allocated to aerial dry mass
STKPFmáx	Mg Mg^{-1}	Fraction of daily aerial dry mass increments partitioned to stalk at high temperatures in a mature crop
Suca	Mg Mg^{-1}	Maximum sucrose contents in the base of stalk
TBFT	ºC	Temperature at which partitioning of unstressed stalk mass increments to sucrose is 50% of the maximum value
Tthalfo	ºC d	Thermal time to half canopy
Tbase	ºC	Base temperature for canopy development
LFmáx	Leaves	Maximum number of green leaves a healthy, adequately irrigated plant will have after it is old enough to lose some leaves
MXLFArea	cm^2	Max leaf area assigned to all leaves above leaf number MXLFARNO
MXLFArno	Leaves	Leaf number above which leaf area is limited to MXLFAREA
Pl1	ºC d	Phyllocron interval 1 (for leaf numbers below PSWITCH)
Pl2	ºC d	Phyllocron interval 2 (for leaf numbers above PSWITCH)
Pswitch	Leaves	Leaf number at which the phyllocron changes
TTPLNTEM	ºC d	Degree-days to emergence for a plant crop
TTRATNEM	ºC d	Degree-days to emergence for a ratoon crop
ChupiBase	ºC d	Degree-days from emergence to start of stalk growth
TT_PopGrowth	ºC d	Degree-days from emergence to peak tiller population
Max_Pop	Mg m^{-2}	Maximum tillers population
PopTT16	Mg m^{-2}	Mg population after 1.600 degree-days
LG_AMBase	Mg ha^{-1}	Aerial or fresh mass (stalks, leaves and water attached to them) where lodging starts

Source: Singels et al., 2008; Nassif et al., 2012; Marin et al., 2015.

The RB867515 cultivar was previously calibrated for the DSSAT/Canegro and APSIM/Sugar models using inputs from six different regions of Brazil (Marin et al., 2013). The values of the parameters of each cultivar used in the simulation for the DSSAT/CANEGRO model are summarized in Table 3.

Table 3. Values of the cultivar parameters used in the simulation for the DSSAT/CANEGRO model.

Parameter	RB867515	RB835486	RB92579*	RB92579	SP791011	RB931530	RB93509
Parcemáx	12.860	13.520	10.8	13.5	7.7	6.5	9.86
APFMX	0.843	0.865	0.92	0.9	0.88	0.9	0.8
STKPFmáx	0.699	0.760	0.88	0.88	0.55	0.55	0.69
Suca	0.680	0.695	0.57	0.57	0.58	0.58	0.68
TBFT	25	26	25	25	25	25	25
Tthalfo	250.800	257.800	286	230	250	250	250.8
Tbase	15.710	15.620	14	14	15	14	15.71
LFmáx	9.960	9.518	8	8	12	12	9
MXLFArea	500.200	500.900	792	680	380	680	435
MXLFArno	17.190	15.350	22	14	14	14	14
Pl1	89.000	90.100	109	65	90	90	110
Pl2	150.000	149.400	117	179	179	179	200
Pswitch	16.140	16.330	22	18	18	18	14
TTPLNTEM	300.400	509.400	428	615	628	628	628
TTRATNEM	290.900	211.400	620	203	203	203	290
ChupiBase	855.000	547.600	1050	533	1050	1050	855
TT_PopGrowth	650.400	530.200	628	789	700	700	800
Max_Pop	20.350	19.620	28	28	15	16	19.7
PopTT16	8.190	9.556	12	11	9.2	7.8	8.3
LG_AMBase	220	220	220	220	200	200	220

Note. * Standard cultivar used for comparison purposes; ** Varieties parameterized by (Barros et al., 2016).

Source: Nassif et al., 2012.

2.3.2 Simulation Scenarios

The scenarios were based on the maturation cycle of the cultivars used: early, medium and late; three harvest seasons June 15th (early), August 15th (medium) and September 15th (late). Ten years of planting were simulated for each combination of climate and soil. Thus, for each location, the five varieties and two soils were considered, totaling 10 scenarios per region (Table 4). The planting date in all cases was on the 15th of June.

Table 4. List of items used to compose the simulation scenarios to evaluate the DSSAT/CANEGRO model

Weather Station	Soil	Cultivar	Maturity	Production System	Planting Depth (cm)	Harvest Date
Ivinhema	Latossolo (Typic Hapludox)* Argissolo (Ultisols)*	RB931530; RB835486	Early	Rainfed	20	15/Jun
Londrina		RB867515	Average			15/Aug
Maringa		SP791011				
Presidente Prudente		RB93509	Late			15/Sep

Note. * Soil classification according to the Brazilian System of Soil Classification (SiBCS) (Santos et al., 2013) and its equivalent according to the closest Soil Survey Staff (2019) (in parentheses).

2.3.3 Evaluation of Performance of the Models

In this study, the agreement index (d), mean error (ME), mean absolute error (MAE), and root mean square error (RMSE) were used as performance statistical metrics (Willmott et al., 1985), with Equations (6 to 9) as follows:

$$d = 1 - \left[\frac{\sum_{i=1}^{n}(Y_i - Y)^2}{\sum_{i=1}^{n}(|Y_i - Y_m| + |Y - Y_m|)^2}\right] \quad (6)$$

$$ME = \frac{\sum_{i=1}^{n}(Y_i - Y)}{n} \quad (7)$$

$$MAE = \frac{\sum_{i=1}^{n}(|Y_i - Y|)}{n} \quad (8)$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(Y_i - Y)^2}{n}} \quad (9)$$

Where, Yi and Y are the estimated and observed sugarcane yield, in Mg ha^{-1}, respectively; Ym are the average of estimated and observed sugarcane yield, in Mg ha^{-1}; and n is the number of observations.

3. Results and Discusions

3.1 Meteorological Conditions

Weather conditions during sugarcane period scenarios from January 1969 to December 2013 are shown in Figure 2a. The values of, ETo was lower than precipitation (P), with ETo equal to 200 mm in the summer humid season and 25 mm in winter (Figure 2b).

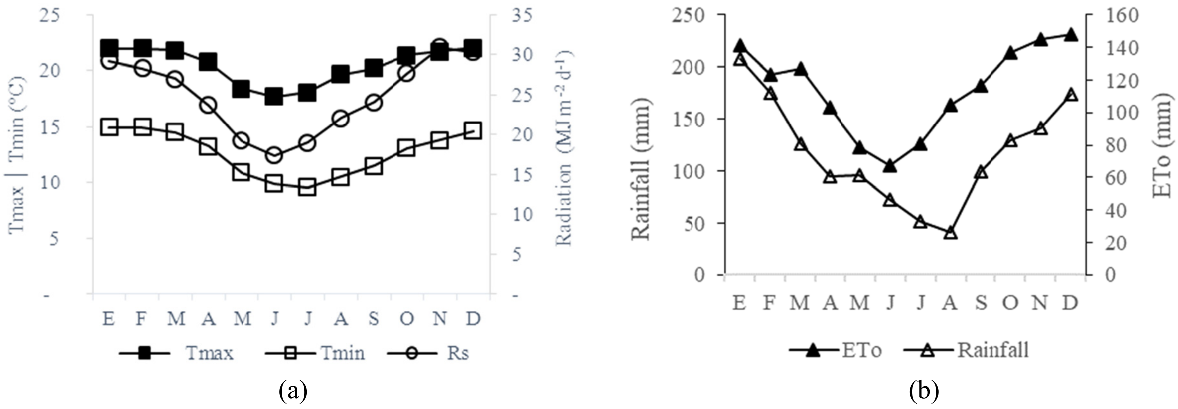


Figure 2. Maximum monthly average (Tmax) and (Tmin) air temperature and incident solar radiation (a), and daily precipitation and reference evapotranspiration (ETo) calculated in the region of Presidente Prudente - SP, based on data from selected stations (b)

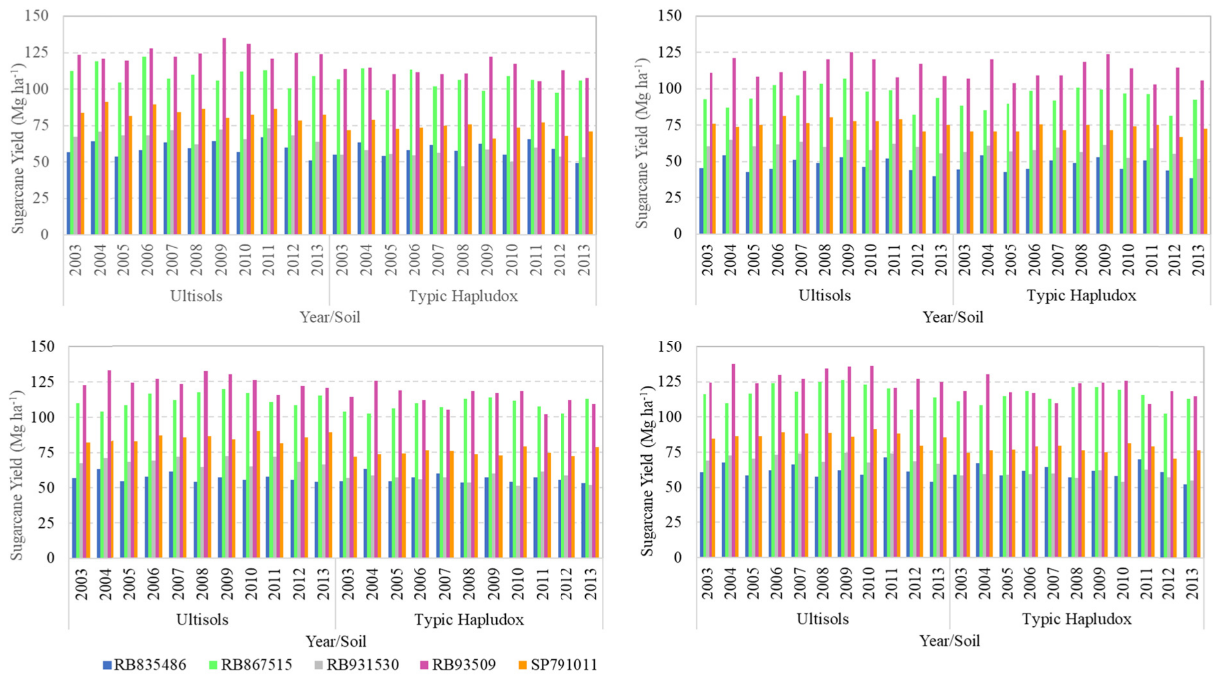
Outcomes from the DSSAT/CANEGRO model show that the RB98509 cultivar in the Ultisols soil type presented the highest productivity in the period 2009. The RB867515 cultivar showed high productivity throughout the periods of evaluation. Finally, the cultivars RB93509, RB931530, and RB835486 presented in all scenarios resulted in the lowest productivity in terms of Mg per hectare (Figure 3a). Figure 3b shows the average productivity of Mg $ha^{-1}$for all cultivars, with data from Londrina Station, in the Ultisols and Typic Hapludox soils, for the region of Oeste Paulista - SP, (10 yr average).

The cultivar RB98509 with the soil type Ultisols produced the highest productivity (above 120 Mg ha^{-1}) in 2009. Similarly, this same variety performed best (Mg ha^{-1}) in the Typic Hapludox soil in the same year. In the case of Ultisols, only achieved 110 Mg ha^{-1}. On the other hand, the RB867515 showed high productivity in all soil types during all the evaluation periods. The varieties RB93509, RB931530, and RB835486 resulted in the lowest yields in all scenarios with average yields between 40 and 70 Mg ha^{-1}.

The average yields for RB835486, RB867515, RB931530, RB93509 and SP791011, are shown in Figure 3 when grown on Ultisols and Typic Hapludox soils during a 10-year period (2003-2013) at the Maringá Station in the western- SP region. Note that the variety RB98509 in the Ultisol soils in 2009 produced the greatest yields, over 130 Mg ha^{-1}. Similarly, this same variety produced high yields on the Typic Hapludox soil in the same year. In the case of Ultisols, just exceeded 110 Mg ha^{-1}. The behavior of the RB867515 variety, was characterized by high productivity in the soil types during all the evaluation periods.

Finally, in each scenario the varieties RB93509, RB931530, and RB835486 produced the lowest yields, averaging between 55 and 85 Mg ha^{-1} (Figure 3c). Interestingly, RB98509 in 2004 on the Ultisols produced the highest yields with values close to 140 Mg ha^{-1}. The RB867515 variety with an average maturation showed high productivity above 120 Mg ha^{-1} in all the soil during all the evaluation periods. Finally, the varieties RB93509, RB931530, and RB835486 resulted in the lowest yield in all scenarios evaluated with average yield values between 60 and 85 Mg ha^{-1} (Figure 3d).

(a) (b)



(c) (d)

Figure 3. Productivity in Mg ha^{-1}, for varieties RB835486, RB867515, RB931530, RB93509 and SP791011, with data from Ivinhema Station (a), Londrina (b) Maringá (c) and Presidente Prudente (d), in the Ultisols and Latossolo soils, for the region of Oeste Paulista-SP and the validation period (10 years)

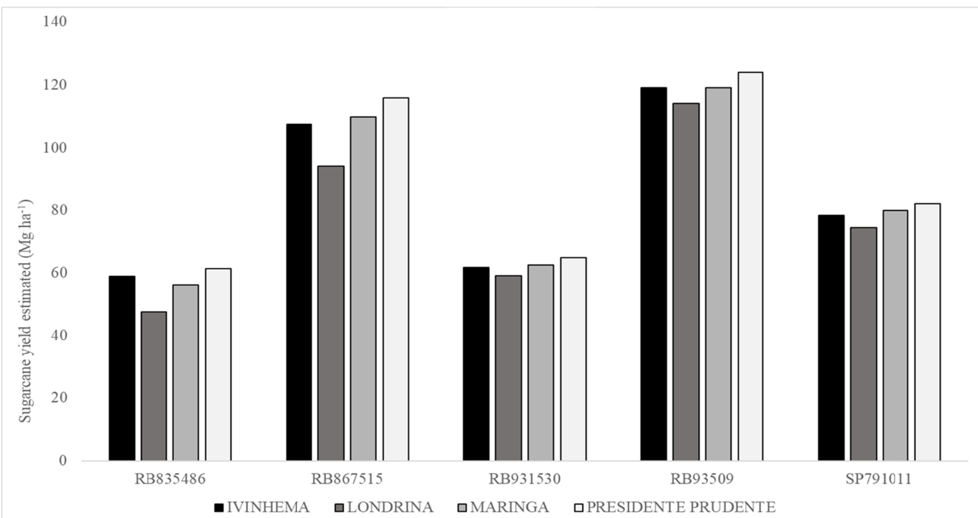


Figure 4. The sugarcane yield averages estimated expressed in Mg ha^{-1} for the varieties RB835486, RB867515, RB931530, RB93509 and SP791011, with data from Ivinhema, Londrina, Presidente stations Prudente, Maringá in the Ultisols and Typic Hapludox soils, for the region, over a 10-year period. Note that in all locations the variety RB93509 was the one with the highest productivity, with 118 Mg ha^{-1}, whereas the opposite is observed for the variety RB835486 with values close to 60 Mg ha^{-1}

The relationship between the estimated productivity and the sugarcane yield observed in Mg ha^{-1} is shown in Figure 5. In terms of observed productivity for the RB835486 variety, the simulated values underestimated the registered data by the industry.

The simulation results for RB867515 exceeded the productivity data provided by the industry. Regarding the SP791011 variety, the simulation was closer to the observed data provide by the industry. The varieties RB92579 and RB931530 were disregarded in this analysis due to the absence of productivity records during the evaluated period.

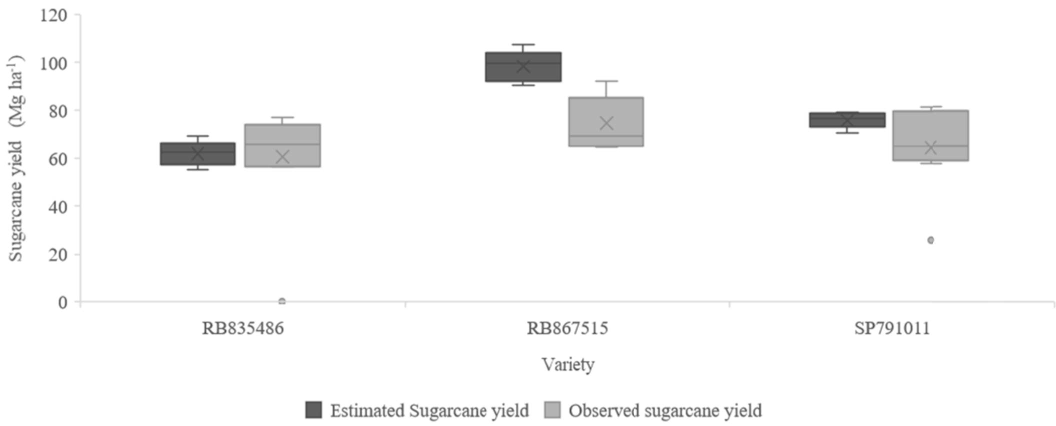


Figure 5. Relationship between estimated sugarcane yield and observed sugarcane yield at the evaluated locations

3.1 Performance of the Models

The performance indicators for the evaluated locations are shown in Table 5. In terms of precision and accuracy, it was found that the estimates are consistent with the results of some previous studies in Brazil (Marin et al., 2015, 2013; Nassif et al., 2012; Marin et al., 2011; Nassif et al., 2012; Dos Santos & Sentelhas, 2016). Note, however, that the RMSA values were lower or similar to those reported by these authors. For example, Singels et al. (2010) obtained RMSE = 29.8 Mg ha^{-1} from simulations with DSSAT/CANEGRO considering several cultivars considering in Piracicaba, SP.

The RMSE values found in this study were also lower or similar to those obtained with DSSAT/CANEGRO for different cultivars in South Africa, Australia, Zimbabwe and Thailand by Singels et al. (2008).

Table 5. Performance statistical metrics in the evaluated locations

Cultivar	d [dimensionless]	ME [Mg ha^{-1}]	ME [Mg ha^{-1}]	RMSE [Mg ha^{-1}]
RB835486	0.86	3.16E^{-15}	3.85	4.48
RB867515	0.98	-6.09E-^{15}	4.22	4.93
SP791011	0.99	0.00	1.84	2.27

4. Conclusion

The DSSAT model allowed the simulation of sugarcane productivity in the region of western São Paulo state to establish comparisons with the data observed by the industry, making it possible to evaluate the behavior of the variables considered in the simulation. These results make it possible to use a large amount of existing data from this crop to conduct modeling studies. The simulation errors were comparable to those found in other models and reported in the literature. The DSSAT/CANEGRO model estimates were better for the SP791011 variety. The yield forecast was less accurate for the RB835486 variety. The model reasonably simulated the sugarcane growth and development under the edaphoclimatic conditions of this Brazilian region.

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