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Calibration and validation of a simple agrometeorological model to estimate sugarcane yield under operational field conditions[1]

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ABSTRACT: Brazil has leading the sugarcane production during the past decades due suitable environmental conditions, mainly the climatic characteristics. Crop simulation models are tools that have been employed to evaluate the efficient use of natural resources for agricultural production. For using crop simulation models is important to define which scales they will be applied once the complex simulation models use to have so many parameters to calibrate which frequently make them less suitable for large scale applications. The objective of this study was to calibrate and evaluate a simple sugarcane yield simulation model under operational field conditions. The potential yield (Yp) was estimated through solar radiation, photoperiod, and air temperature. Attainable yield (Yatt) was estimated by penalizing Yp by water deficit, using a multiplicative approach considering the phenological phases and their sensitivity to water deficit (ky). Weather data were obtained from the nearest meteorological stations of each one of 12 mills evaluated. Soil water holding capacity (SWHC) was determined according to the predominant soil type in each region. Model calibration was done in order to minimize RMSE and MAPE and maximize agreement index (d), all related to harvest index (HI), crop coefficient (kc) and sensitivity to water deficit (ky). In the calibration phase, the estimated cane yield was 81.9 (±22.2) Mg ha^{-1}, while observed cane yield was 82.3 (± 23.9) Mg ha^{-1}, resulting in R^2 = 0.65, d = 0.70, ME = -0.4 Mg ha^{-1}, RMSE = 13.2 Mg ha^{-1}, MAPE = 12.5%. On the other hand, in the validation phase, the estimated cane yield was 82.9 (± 27.5) Mg ha^{-1}, while observed was 86.9 (± 30.1) Mg ha^{-1}, resulting in R^2 = 0.79, d = 0.80, ME = -4.0 Mg ha^{-1}, RMSE = 13.8 Mg ha^{-1}, MAPE = 12.2%. Based on that, the proposed calibrated sugarcane yield model was able to capture the yield variability conditioned by weather conditions, management practices and crop system type (irrigated and rainfed), allowing it use for climatic risk analysis.

Key words: sugarcane, mathematical-physiological crop simulation model, potential and attainable yields.

INTRODUCTION

Currently, Brazil has leading the sugarcane producing around the world following by India, China, Thailand, and Pakistan (FAO, 2015). Therefore, a constant improvement of methods to evaluate and indicate suitable areas for sugarcane plantations expansionisa strategic point for agricultural planning.

Crop simulation models (CSM) have been used for testing agricultural options such as performance of new cultivars and their comparison, best sowing dates with lower climatic risks, irrigation schedules and fertilization rates (ASSENG et al., 2013). The most popular sugarcane simulation models are DSSAT/Canegro (SINGELS; BEZUIDENHOUT, 2002) and APSIM-sugarcane (KEATING et al., 1999). These models require several parameters related to genetic, ecotype, management options and detailed soil profiles to be run. Moreover, a great variety of cultivars, soils and crop management are employed by the mills, becoming complex their application under operational conditions. Considering the importance of sugarcane crop to the Brazilian agricultural sector and the necessity of a better planning of this crop based on yield estimates at regional and national levels, the objective of this study was to develop and calibrate a simple agrometeorological yield model based on operational sugarcane yield data under irrigated and rainfed conditions, and validate it with independent data in order to evaluate its feasibility for yield estimation in different Brazilian regions.

MATERIAL AND METHODS

The agrometeorological simulation yield model was developed based on the Doorenbos and Kassam (1979) approach, in which the potential gross production (PG) is weighted by correction coefficients of leaf area index (C_{LAI}), crop respiration (C_{resp}), harvest index (C_{HI}) and water content in the stalks (C_{WC}), allowing to calculate the potential yield (Yp) as a function of current incoming solar radiation, air temperature, photoperiod and cultivar characteristics. The equation to calculate Yp is:

$$Yp = \sum_{i=1}^{m}(PG_{total} \times C_{LAI} \times C_{resp} \times C_{HI}) \times C_{WC} \qquad (1)$$

where i = first until the last day of the cycle (m); C_{LAI} is the leaf area index coefficient, estimated as a function of maximum leaf area index (LAI_{max}) throughout each ten-day period; and C_{resp} is equal to 0.6 if average air temperature in each period is lower than 20°C, or 0.5 if average air temperature is greater than 20°C. The equation to estimate C_{LAI} can be found in Pereira et al. (2002); $C_{wc} = [1\text{-}WC(\%)]^{-1}$. The water content in the stalks is represented by WC and was used as 80%, as recommended by Monteiro and Sentelhas (2014).

The meteorological model inputs were collected from the nearest weather station from National Institute of Meteorology (INMET). The soil water holding capacity (SWHC) was determined according to the predominant soil type in each location, based on the Digital Soil World Map from FAO (2007). The attainable yield (Yatt) was estimated by the depletion of potential yield by the relative crop water deficit (1 – ETa/ETc) of each crop phase(j), according to thesensitivity towater stressindex (ky) (MONTEIRO; SENTELHAS, 2014). The following equation was employed to estimate Yatt:

$$Yatt_n = \prod_{j=1}^{n}\left\{Yatt_{j-1} \times \left[1 - ky_j \times (1 - ETa/ETc)_j\right]\right\} \qquad (2)$$

where $Yatt_n$ is final attainable yield (Mg ha^{-1}) at the end of crop cycle; Π indicates the productory of equation terms; j represents the crop phenological phases (Table 1); $Yatt_{j-1}$ is the yield at the end of the previous phenological phase – in case of first phenologicalphase, $Yatt_{j-1}$ is equal to Yp; ETa and ETc are the actual and maximum crop evapotranspiration (mm period^{-1}), respectively. ETc was calculated through the product between reference evapotranspiration (ETo) and crop coefficient (kc). ETo was estimated by Penman-Monteith equation (Allen et al., 1998).Actual crop evapotranspiration (ETa) was estimated based on crop water balance model, proposed by Thornthwaite and Mather (1955).

The model calibration was done through operational yield data under different crop systems (rainfed and irrigated), crop varieties, crop cycles (plant and ratoon canes) and climate and soil conditions. These data were collected from 12 sugarcane mills across Brazil, in which high technological managementwas employed (Figure 1). The parameters related to crop water consumption (kc), to crop sensitivity to water deficit (ky) and harvest index (HI) were changed until to reach the best statistical coefficients by “eye fitting” procedure, when observed and estimated sugarcane yields were compared. The HI was ranged from 65 to 85%, in a 1% step. The statistical coefficients evaluated were: coefficient of determination (R^2), agreement index (d) (Willmott et al., 1985), root mean square error (RMSE), mean absolute percentage error (MAPE) and mean error (ME). The whole dataset was composed by 206 data, in which 2/3 (137) were used for model calibration, while the remained yield data (69) were employed for model validation.

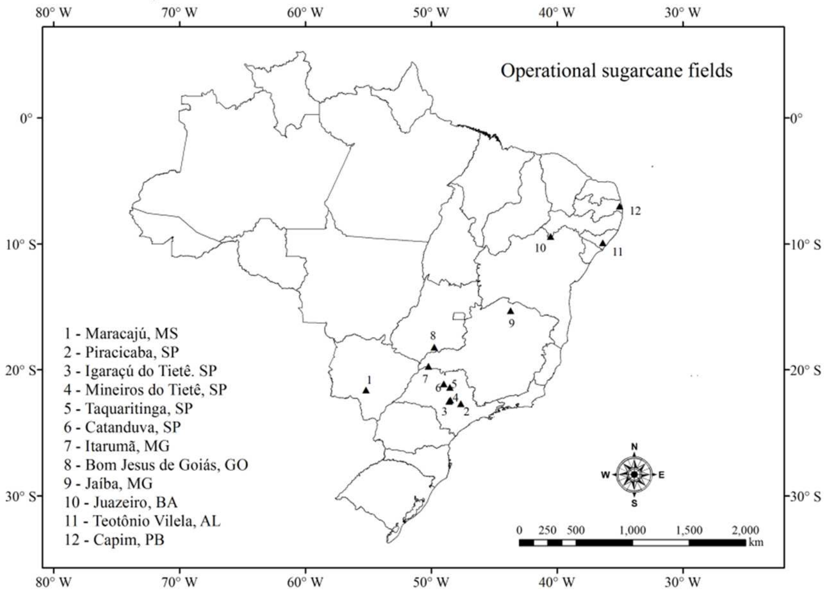

Figure 1 - Spatial distribution of the sugarcane operational fields employed for yield model calibration and validation

RESULTS AND DISCUSSION

Even being developed under a relatively simple approach, the sugarcane yield model provided satisfactory results, when properly calibrated. In addition, the model showed an accuracy to capture the sugarcane yield variability under different climates, soils, crop systems, crop cycles and management options.During the calibration phase, the average estimated and observed yields were, respectively, 81.9 and 82.3 Mg ha^{-1}. The best HI that generated the most suitable statistical coefficients was 77%. This means that for 100 Mg of biomass produced, in average, 77 Mg are millable stalks destined for sugar and ethanol production. The HI results found by Robertson et al. (1999) for sugarcane ranged from 65 to 83% under rainfed and well-watered field conditions, respectively, matching with the HI obtained in this study. In the Table 1 are shown the calibrated kc and ky for sugarcane.

Table 1 - Calibrated crop coefficient (kc) and crop response factor to water deficit (ky) for each sugarcane phenological phase

Phenologicalphase (j)	kc	ky
25% fullcanopy (1)	0.4	0.7
25-50% fullcanopy (2)	0.7	0.7
50-75% fullcanopy (3)	1.0	0.3
75 - 100% fullcanopy (4)	1.2	0.3
100% fullcanopy (5)	1.3	0.3
Senescence (6)	1.1	0.3
Ripening (7)	0.8	0.1

In the Table 2 are presented a general overview of the estimated and observed yields and their respective statistical coefficients.During the calibration phase, the estimated cane yield was 81.9 (±22.2) Mg ha^{-1}, while observed cane yield was 82.3 (± 23.9) Mg ha^{-1}, resulting in a precision (R^2) of 0.65 and accuracy (d) of 0.70. The errors were ME = -0.4 Mg ha^{-1}, RMSE = 13.2 Mg ha^{-1}, MAPE = 12.5%. On the other hand, in the validation phase, the estimated cane yield was 82.9 (± 27.5) Mg ha^{-1}, while observed was 86.9 (± 30.1) Mg ha^{-1}, resulting in R^2 = 0.79, d = 0.80, ME = -4.0 Mg ha^{-1}, RMSE = 13.8 Mg ha^{-1}, MAPE = 12.2%. Tests employing DSSAT/Canegro model in two experimental sites of Australia and South Africa showed that it was able to explain respectively 70 and 83% of observed yield variability (Inman-Bamber et al., 1998) which is similar to the present results, highlighting the acceptable employment of this yield model for agricultural planning. In Brazil, studies employing a similar yield model based on the same approaches also presentedsuitableresults in the state of São Paulo (MONTEIRO; SENTELHAS, 2014) and in the state of Minas Gerais (OLIVEIRA et al., 2012).

Table 2 - Observed and estimated average sugarcane yield, mean error (ME), root mean square error (RMSE), mean absolute percentage error (MAPE), agreement index (d) and coefficient of determination (R^2) for calibration and validation phases of the agrometeorological yield model

Averageyieldsand Statisticalindices	Units	Sugarcaneyieldmodelperformance	
		Calibration	Validation
Observed	Mg ha^{-1}	82.3	86.9
Estimated	Mg ha^{-1}	81.9	82.9
ME	Mg ha^{-1}	-0.4	-4.0
RMSE	Mg ha^{-1}	13.2	13.8
MAPE	%	12.5	12.2
d	-	0.70	0.80
R^2	-	0.65	0.79

The yield variability during the calibration and validation phases under the irrigated and rainfed crop systems are presented by boxplot analysis in Figure 2, where the agreement between observed and estimated data can be observed for these both conditions.

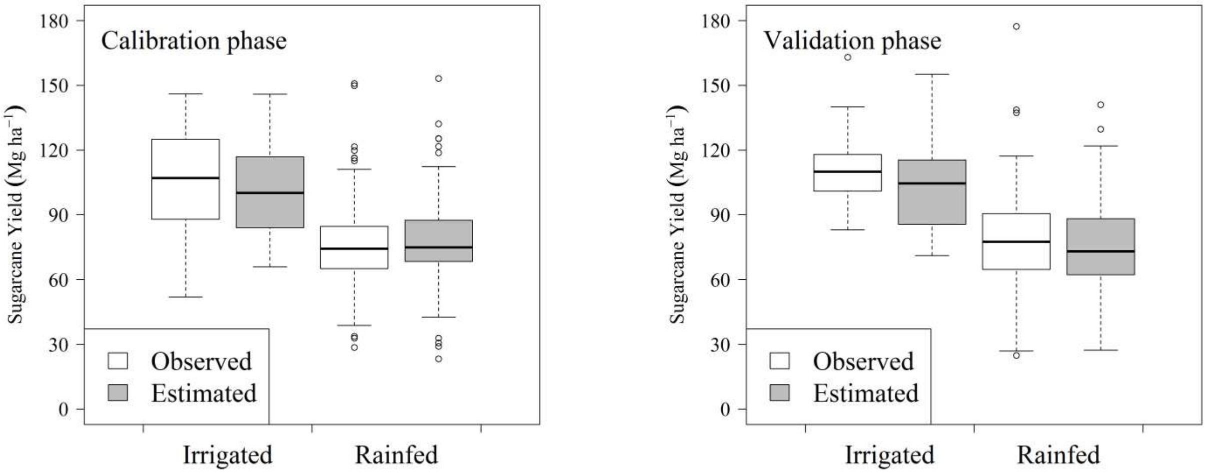

Figure 2 - Sugarcane yield variability during the calibration and validation phases under irrigated and rainfed crop systems.

CONCLUSIONS

1 - The sugarcane yield model presented a satisfactory performance, when the kc, ky and HI parameters were properly calibrated, what can be seen when estimated and observed yields were compared for rainfed and irrigated crops.;

2 - Due to the acceptable yield model performance, it can be applied for different Brazilian locations for agrometeorological studies, such as crop planning, climatic risk analysis, planting date recommendation, evaluation of irrigation strategies and yield gap analysis.

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