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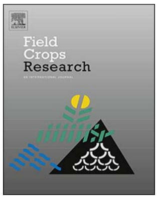

Evaluation of three sugarcane simulation models and their ensemble for yield estimation in commercially managed fields

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ABSTRACT

The sugarcane production system is very complex, involving a large number of variables, namely genotype, environmental conditions and crop management, which define yield level. Thus, estimation of sugarcane yield is also complex, nevertheless, highly important for planning and decision-making in the sugarcane industry. Crop simulation models calibrated to local conditions can be useful to estimate yield, since they can capture the effect of the crop management. On the other hand, recent studies have shown that the use of at least three simulation models in an ensemble can reduce simulation uncertainties, resulting in more reliable estimates than using a single model. Thus, the aims of this study were: i) to evaluate the performance of three sugarcane simulation models (FAO-AZM, DSSAT/CANEGRO and APSIM-Sugarcane), separately and in a multi-model approach, for commercially managed fields in Brazil; and ii) to propose a management factor (k_{dec}) associated with the yield decline along successive crop cycles to improve performance of these models. Sugarcane yield and meteorological data were obtained for seven Brazilian states. The FAO-AZM model was calibrated by changing the crop water deficit sensitivity coefficient values. For the DSSAT/CANEGRO and APSIM-Sugarcane models, small adjustments were made to coefficients previously calibrated for Brazilian cultivars to improve their performances. The three models presented a weak performance, with high mean absolute error (MAE > 29 t ha^{-1}) and low precision ($R^2 < 0.54$), which were caused by the lack of coefficients accounting for crop management. The introduction of k_{dec}, which reflects the crop management level, improved yield estimates for all models. When k_{dec} was applied, the mean absolute error decreased to ≤ 12.9 t ha^{-1} for the calibration phase, and between 13.0 and 14.9 t ha^{-1} for the validation with independent data. Precision was improved, with R^2 ranging between 0.70 and 0.72 for calibration phase and between 0.58 and 0.64 for validation. The multi-model approach also allowed an improvement in modelling performance, in both phases, reducing errors (MAE between 11.7 and 12.9 t ha^{-1}) and increasing precision and accuracy. The use of k_{dec} associated with the multi-model approach improved the performance of sugarcane yield estimates, representing more effectively the distinct commercial field conditions of sugarcane cultivated under different cropping systems and Brazilian regions.

1. Introduction

The sugarcane production system is very complex, once the season lasts eight months and thus the crop presents different phenological stages at the same time. Besides, the growing cycle ranges from 12 to 18 months for plant cane and from 10 to 14 months for ratoons. The harvesting season in the northeastern Brazil usually occurs from September to March and in the other growing regions in the country from April to early December. The ratoons are harvested as many times as possible, nevertheless, the most common number is between four and five for most Brazilian fields. After a five-year period, the sugarcane field is replanted, and the decision for that is usually based on the yield level. This characterizes a monoculture system, which is usual in the Brazilian sugarcane industry. Sugarcane yield decline over successive ratoons is the major constraint for cane production worldwide, which is mainly caused by the quality of crop management adopted (Bernardes et al., 2008; Ferraro et al., 2009; Garside et al., 1997; Gomathi et al., 2013; Ramburan et al., 2013).

Due to the great spatial inter-annual and inter-seasonal variability of sugarcane yield, estimates and forecasts for stalk and sucrose yield are of great value for planning and decision-making in the sugarcane industry (Bezuidenhout and Singels, 2007; Bocca et al., 2015; Everingham et al., 2016, 2009; Lisson et al., 2005). Forecast is normally carried out by experts based on historical data on the cropping area (soil and climate), cultivar characteristics, crop management practices, mainly associated to control of pests, weeds and diseases (Bocca et al.,

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2015). Another way to add value to sugarcane yield forecast is by using crop simulation models. These models can vary considerably in complexity, ranging from empirical and physiological-mathematical to mechanistic or process-based models. All crop models can be useful, when well calibrated for local conditions, providing results that are more realistic. For sugarcane, several crop models are available, however, the most used around the world are DSSAT/CANEGRO (Inman-Bamber, 1991; Singels and Bezuidenhout, 2002) and APSIM-Sugarcane (Keating et al., 1999). Both are mechanistic as they, although developed independently, have similar origins and approaches to simulate sugarcane phenology, canopy development and biomass partitioning (Lisson et al., 2005; O'Leary, 2000). The FAO Agro-ecological Zone Model (FAO-AZM, Doorenbos and Kassam, 1979) has a simpler structure in terms of simulated processes and parameters, nonetheless, it has generated satisfactory results when properly adapted to the regions of interest for agro-meteorological studies related to sugarcane in Brazil (Gouvêa et al., 2009; Marin and Carvalho, 2012; Monteiro and Sentelhas, 2017; , 2014; Scarpare et al., 2016).

All crop models present uncertainties in terms of their structure, parameters and input data (Wallach et al., 2012). Recent studies have shown that the use of different crop models in an ensemble (multi-model approach) has allowed to reduce the associated uncertainties, as observed for wheat (Asseng et al., 2013; Martre et al., 2015; Palosuo et al., 2011), barley (Rötter et al., 2012), maize (Bassu et al., 2014), rice (Li et al., 2015), potato (Fleisher et al., 2016) and soybean (Battisti et al., 2017). Marin et al. (2015) evaluated the performance of the DSSAT/CANEGRO and APSIM-Sugarcane models for plant cane under experimental conditions in different regions of Brazil and observed improvement of the estimated sugarcane yield and leaf area index when the average of the two models were used. However, when used under commercial field conditions, irrigated or rainfed, where different crop managements are adopted, according to the technological level of each farm/region, these good results cannot be replicated, since experimental data is normally obtained in small plots, with near optimum crop management and, therefore, far from growers and sugar mills reality.

Crop management practices applied to sugarcane in commercial fields varies considerably from one area to another, leading the crop to respond differently to edaphoclimatic conditions, which explains the poor performance of crop models when used for estimating yield. Thus, the use of a crop management factor could make sugarcane yield estimation more reliable, generating satisfactory results.

In order to improve sugarcane yield estimation in commercially managed fields, this study aimed to: (i) evaluate the performance of the FAO-AZM, DSSAT/CANEGRO and APSIM-Sugarcane models, in a single and multi-model approaches to estimate rainfed and irrigated sugarcane yields; and (ii) propose a crop management factor associated with yield decline over the successive ratoon cuts to improve performance of the sugarcane simulation models.

2. Material and methods

2.1. Yield, weather and soil data

The data on stalk fresh mass (referred to as sugarcane yield, which corresponds to actual yield) used in the calibration and validation of the models were obtained from rainfed and irrigated commercial sugarcane fields. The spatial distribution of the sites from where sugarcane yield data were obtained can be found in Supplementary Material (Fig. S1). The characteristics of each site are presented in Table 1. Only data from sugarcane harvested with 11–13 months were used in the study. The planting depth was around 15 cm. The number of buds used in planting varied from 12 to 15 m^{-1} and row spacing ranged from 140 to 150 cm. The irrigation method used was subsurface drip. In some sites, irrigation ranged from 500 to 750 mm and was applied only during in the most critical dry periods of the crop cycle (Table 1). In other sites, full irrigation was done, totaling between 1070 and 2000 during the cycle (Table 1). As only APSIM-Sugarcane takes into account the effect of nitrogen (N) on crop growth, a high rate of this nutrient (300 kg N ha^{-1}) was applied 30 days after plating (plant cane) or sprouting (ratoon cane) for avoiding any N stress for sugarcane crop in the simulations with APSIM, which could compromise the comparisons with the other two models (FAO-AZM, DSSAT/CANEGRO). As the cultivars used in each mill varied, the yield data was considered as representing a mix of them.

The weather data (maximum and minimum air temperature, rainfall, solar radiation and/or sunshine hours) were obtained from the stations at the mills or, if not available, from the nearest public weather station. The public weather stations belonged to the National Institute of Meteorology (INMET), Nation Institute for Space Research (INPE), Agronomic Institute of Campinas (IAC), National Water Agency (ANA) and University of São Paulo (ESALQ/USP). When solar radiation data were missing, this variable was estimated using the Angstrom-Prescott method for stations that had sunshine hours data or the Hargreaves method when only air temperature data were available, as recommended by Allen et al. (1998). The soil type was provided by the sugar mills (Table 1).

For the calculation of soil water balance used in the FAO-AZM model, values of soil water holding capacity (SWHC) were obtained, which were based on Driessen and Konijn (1992) and Prado (2014) for one meter of soil depth (Table 1). For DSSAT/CANEGRO and APSIM-Sugarcane, which use more complex soil data (physical and hydraulic properties), RadamBrasil (BRASIL, 1981) and WISE (Batjes, 2009; Gijsman et al., 2007) databases were used to adjust the soil characteristics for each location. The DSSAT root growth factor (SRGF) was based on Vianna and Sentelhas (2016) and on the default values of the WISE database. For APSIM, the fractions of available soil water that can be potentially obtained on the given day from a given layer (K_L) was based on the following values: 0.1, 0.09, 0.08, 0.07, 0.06 and 0.05 mm d^{-1}, respectively, for 0–30, 30–60, 60–90, 90–120, 120–150 cm or deeper layers, like reported by Inman-Bamber et al. (2000).

2.2. Crop simulation models

The sugarcane simulation models used in this study were FAO-AZM, DSSAT/CANEGRO and APSIM-Sugarcane. The simulations were started one year before the planting or sprouting to normalize soil water balances of the models.

The FAO-AZM is a generic mathematical-physiological crop simulation model that was developed originally by Doorenbos and Kassam (1979). It estimates gross photosynthesis for C_3 or C_4 crops and adjusts it to yield through calibration of coefficients related to leaf area index (LAI), harvest index, respiration and stalk water content. Potential yield (Yp) was estimated considering only the interactions between the genotype and solar radiation, photoperiod and mean air temperature during the crop cycle, following Kassam (1977). The harvest index and stalk water content were assumed as 0.80 and 70%, respectively (Doorenbos and Kassam, 1979).

Afterward, Yp was penalized by the crop water deficit, which occurred during different sugarcane crop phases, to estimate the water-limited yield (Yw), according to the following equation:

$$\mathrm{Yw_n} = \prod_{i=1}^{n} \left\{ \mathrm{Yw_{n-1}} \times \left[1 - \mathrm{ky}_i \times \left(1 - \frac{\mathrm{ETr}}{\mathrm{ETc}} \right)_i \right] \right\} \quad (\mathrm{t\ ha^{-1}}) \tag{1}$$

where: ky is the water deficit sensitivity coefficient; ETa is the actual crop evapotranspiration, which was calculated through the crop water balance (Thornthwaite and Mather, 1955), having rainfall, maximum crop evapotranspiration (ETc) and SWHC as inputs; ETc was estimated by multiplying Priestley and Taylor (1972) reference evapotranspiration (ETo) by crop coefficient (kc) for each *i* crop phase. The kc values