CALIBRATION AND TEST OF A SIMPLE AGROMETEOROLOGICAL MODEL FOR ESTIMATING SUGARCANE YIELD

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ABSTRACT: Simulation models linked to a geographic information system (GIS) are efficient tools for determining the spatial yield variabilility, allowing to identify more appropriated regions for each sugarcane varieties according to soil and climate characteristics. Thus, the aims of this study were to calibrate and test an adaptation of the FAO model for estimating the potential and actual sugarcane yields in the State of São Paulo, Brazil, and mapping these yields through a SIG. The FAO model is a relative simple model that considers the climate characteristics for calculating the potential yield and the relationship between yield break and relative water deficit for estimating actual yield. The model inputs are meteorological data as extraterrestrial solar radiation, photoperiod, air temperature, sunshine hours and rainfall. A frost factor was introduced in this model in order to represent the impact on yield caused by low air temperatures. The model performance was evaluated considering the main 50 sugarcane locations of the state, by comparing estimated and observed yields. The results showed that the frost factor improved the yield estimates. The performance of the models resulted in the following statistical indices: R^2 = 0.58, d = 0.83, C = 0.64 and RMSE = 5.0 Mg ha^{-1}.
KEY WORDS: yield estimative, crop simulation models, geographic information system.

CALIBRAÇÃO E TESTE DE UM MODELO AGROMETEOROLÓGICO SIMPLES PARA A ESTIMATIVA DA PRODUTIVIDADE DA CANA-DE-AÇÚCAR

RESUMO: Modelos de simulação acoplados a sistemas de informações geográficas (SIG) são eficientes ferramentas para a determinação da variabilidade espacial da produtividade, permitindo identificar regiões mais apropriadas para cada variedade de cana-de-açúcar de acordo com as características edafoclimáticas de cada região. Assim, os objetivos deste trabalho foram calibrar e testar o modelo da FAO para estimar as produtividades potencial e real da cana-de-açúcar no Estado de São Paulo, e mapear essas produtividades por meio de um SIG. O modelo da FAO é relativamente simples e considera as características climáticas vigentes no ciclo da cultura para calcular a produtividade potencial e para o cálculo da produtividade real o modelo considera a relação entre quebra de produtividade e o déficit hídrico relativo. Os dados meteorológicos utilizados foram radiação solar extraterrestre, fotoperíodo, temperatura do ar, insolação e chuva. Um fator de penalização por ocorrência de geadas foi introduzido ao modelo para representar o impacto de baixas temperaturas na produtividade da cana-de-açúcar. O desempenho do modelo foi avaliado considerando-se as 50 principais localidades produtoras de cana do estado, comparando-se os dados estimados aos observados. Os resultados mostraram que o fator geada melhorou as estimativas. O desempenho do modelo resultou nos seguintes indicadores estatísticos: R^2 = 0,58, d = 0,83, C = 0,64 e RMSE = 5,0 Mg ha^{-1}.

PALAVRAS-CHAVE: estimativa da produtividade, modelo de simulação de culturas, sistemas de informações geográficas.

INTRODUCTION

Crop simulation models applied to a specific region allows to obtain information for planning the agricultural system. However, it is necessary to calibrate such models with the correct parameters in order to reproduce the field conditions and make it an important tool for crop planning, which is essential for the sugarcane sector in Brazil. Furthermore, the spatial yield variability is also important information for determining the crop management practices and for identifying the more appropriate regions for each sugarcane cultivar, according to environmental conditions and crop cycle. The FAO yield simulation model (DOORENBOS; KASSAM, 1979) is a simple way for yield estimation but can be used in several regions and climate conditions for not requiring complex inputs (GOUVEA et al., 2009).
Based in these considerations, the aims of this study were: a) to calibrate and test the FAO model for estimating the potential and actual sugarcane yields in the State of São Paulo, Brazil; b) to map the potential and actual yields with a geographic information system (GIS) in order to show the yield spatial variability in this state.

MATERIAL AND METHODS

The weather data used in this study were: extraterrestrial solar radiation; photoperiod; air temperature; sunshine hours; and rainfall. These dataset was adjusted to 10-day time scale to be applied in the FAO model to estimate the potential and actual sugarcane yields. The daily rainfall data were obtained from 178 rainfall stations from the National Water Agency (ANA), for a period of 31 years (1973 to 2003), distributed in the main sugarcane regions of the State of São Paulo and in the surrounding areas.
Due to the lack of weather data for all the 178 rainfall stations, average air temperature and sunshine hours were estimated using multiple linear models (ALVARES et al., 2012), which were developed with the average datasets from National Institute of Meteorology (INMET).
The simulation in each date of the year were considered from 1973 to 2003, considering a crop cycle of five years, in which plant cane and ratoon cane represented 20% and 80% of the crop area, respectively. For estimating potential yield (PY) the following FAO model (DOORENBOS; KASSAM, 1979) was used:

$$PY = \sum_{i=1}^{m} \left(PPBp \times C_{LAI} \times C_{resp} \times C_{harv} \times C_{wc} \right)$$

where: m is the 10-day period considered, varying according to the type of the crop and cycle; PPBp is the gross photosynthesis for each 10-day period, expressed as dry matter of a standard crop (kg ha^{-1}); C_{LAI} is the correction coefficient for leaf area index; C_{resp} is the correction coefficient for maintenance respiration; C_{harv} is the harvest index; and C_{wc} is the coefficient that represents the water content in the stalks. All correction coefficients are dimensionless. The PPBp and the correction coefficients were determined according to Pereira et al. (2002). The actual sugarcane yield (AY) was obtained by the following equation:

$$AY_n = \prod_{i=1}^{7} \left\{ Ya_{n-1} \times \left[1 - ky_i \times \left(1 - \frac{ETr}{ETc} \right)_i \right] \right\}$$

where: i represents the phenological phases during the crop cycle; AY_{n-1} is the actual crop yield in the previous phenological phase, which in case of the first phenological phase is equal to the potential yield (PY); ETr is the crop evapotranspiration, estimated through the crop water balance, using the Thornthwaite and Mather (1955) method; ETc is the maximum crop evapotranspiration, calculated by the product between reference evapotranspiration (ETo), estimated by Priestley-Taylor method, and the crop coefficient (kc), for each phenological phase along the cycle; ky is the water response factor (ky), obtained from Doorenbos and Kassam (1979). A frost factor (f_{frost}) was introduced in this model in order to represent the low air temperatures impact on sugarcane yield. The model performance was evaluated for the original model and for the model with the frost factor, by considering the coefficient of determination (R^2), agreement index "d", confidence index "C" and root mean square error (RMSE).

For mapping the sugarcane potential and actual yields we used the GIS ArcGis 9.3®, considering the SRTM images (digital elevation model, DEM) which have a spatial resolution from 90 x 90 m. In addition, the maps of potential sugarcane yields were generated according the following steps: 1) the yield (dependent variable) was estimated by multiple linear regression models as a function of geographic coordinates (latitude and longitude) and altitude as independent variables and mapped; 2) the yield bias was mapped by *kriging* method considering the differences between calculated and estimated yields according to agrometeorological and linear regression models, respectively; 3) the final map was obtained by the sum of yield map obtained in step 1 and the bias map obtained in step 2. The same procedure was made for obtaining the actual yield maps, however the layer of potential yield and water deficit were considered in the linear regression model as independent variables.

RESULTS AND DISCUSSION

The leaf area index (LAI) and crop phenology parameters were adjusted in order to fit estimated and observed yields (Table 1). Furthermore, a frost factor was inserted in the model in order to improve its performance. The simulations considered the cycles of plant and ratoon crops, which were weighted to compose the annual potential and actual yields.

Table 1 – Leaf area index (LAI) variation in each phenological phase considering the plant and ratoon cane and frost depletion factor (f_{frost}) according to the probability of frost occurrence (P%).

Phenological Phase	**LAI Plant cane**			**LAI Ratoon cane**
	18 months	**15 months**	**12 months**	**12 months**
25% full canopy	**2.5**	**2.0**	**2.0**	**2.0**
25–50% full canopy	**3.0**	**2.5**	**2.5**	**2.5**
50–75% full canopy	**4.5**	**3.5**	**3.0**	**3.0**

75–100% full canopy	**5.0**	**4.0**	**3.5**	**3.5**
Peak use	**6.0**	**5.0**	**4.5**	**4.0**
Senescence	**5.0**	**4.0**	**4.0**	**3.5**
Ripening	**4.5**	**3.5**	**3.5**	**3.0**
	f_{frost}	**P(%)**	**f_{frost}**	**P(%)**
Frost factor	**1.00**	**0 – 20.0**	**0.80**	**50.1 – 60.0**
	0.98	**20.1 – 30.0**	**0.65**	**60.1 – 70.0**
	0.95	**30.1 – 40.0**	**0.45**	**70.1 – 80.0**
	0.90	**40.1 – 50.0**	**0.20**	**> 80.0**

The frost factor allowed a better performance of the model, as shown in Figure 1. The model performed with reasonable precision and good accuracy, as proved by the statistical coefficients: R^2 = 0.58, d = 0.83, and C = 0.63. The RMSE was 5.0 Mg ha^{-1} and the mean error was 2% (Figure 1).

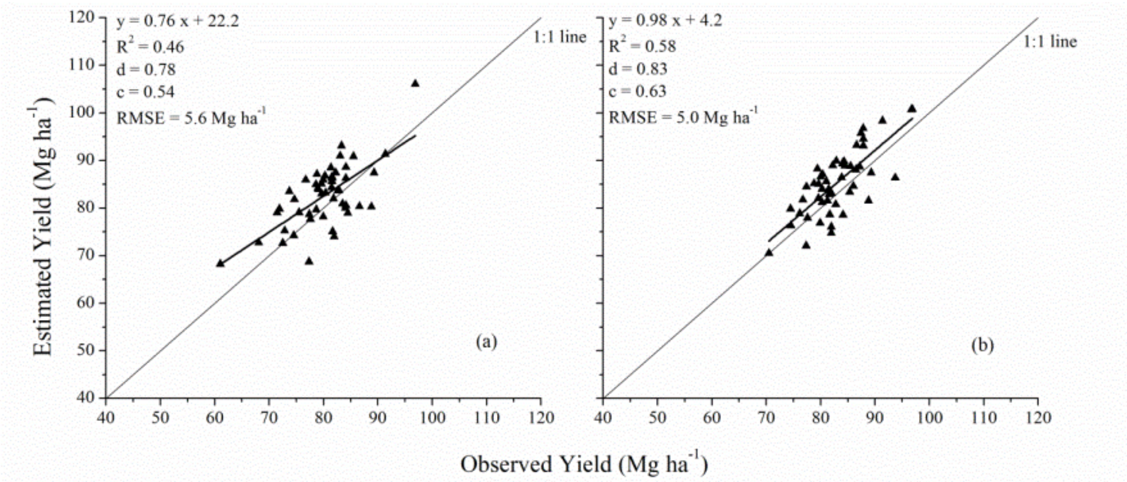

Figure 1 – Relationship between estimated and observed sugarcane yields, considering the original FAO model (1a) and the FAO model with the frost factor (f_{frost}) for the state of São Paulo, Brazil.

The maps were able to determine the variation of PY and AY in the state of São Paulo (Figure 2), identifying the regions were the climatic risk to the crop is higher, allowing to guide crop expansion plans as well as cultivars allocation. Even with a simple methodology, the model showed satisfactory results and has a good potential to be applied for crop planning when properly calibrated. Using the calibrated model considering the frost factor we obtained the estimated yields from State of São Paulo (85 Mg ha^{-1}), which is similar to observed yields published by Brazilian Institute of Geography and Statistics (IBGE) (83 Mg ha^{-1}).

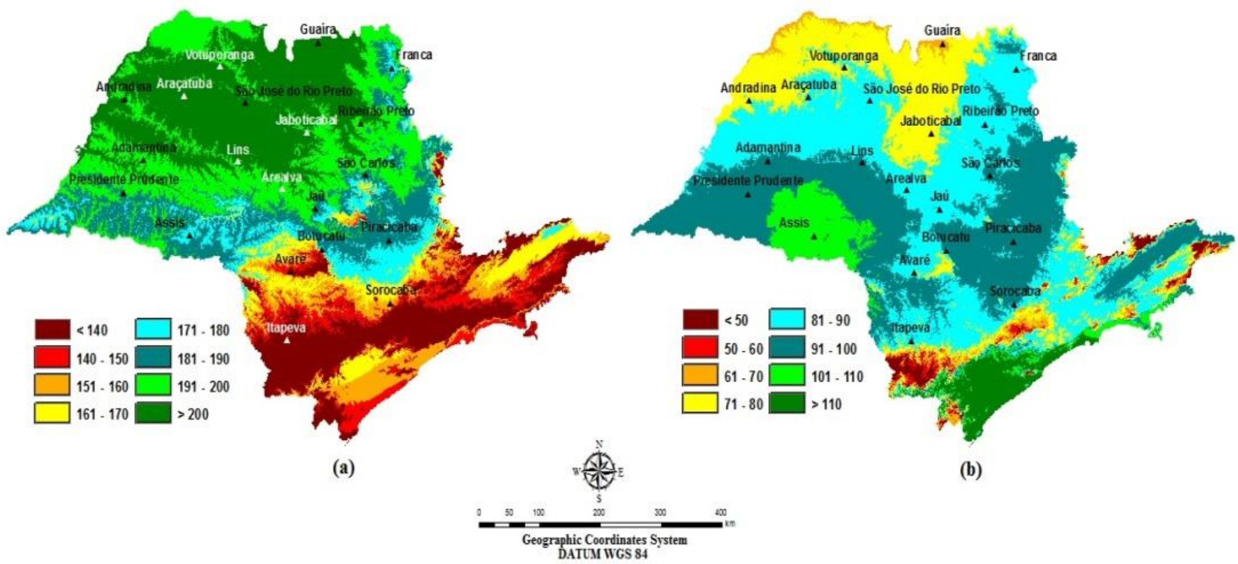

Figure 2 - Spatial variability of the sugarcane potential (Mg ha^{-1}) (a) and actual yields (Mg ha^{-1}) (b) in the State of São Paulo, by considering the depletion of frost factor (f_{frost}).

According to Figure 2a is possible to identify regions where the climate characteristics allow to obtain high yield levels, as showed in north region of São Paulo State with PY that can achieve 200 Mg ha^{-1}, similar value obtained by Maule et al. (2001) with irrigation. The actual yield levels in the main producing regions of the State of São Paulo ranged from 61 to 110 Mg ha^{-1} which is in accordance to the results found by other authors with more complex models (CUADRA et al., 2011).

CONCLUSIONS

The calibration process of the FAO model allowed estimate the potential and actual sugarcane yields in State of São Paulo with satisfactory precision and accuracy, even with a relative simple approach. The linear regression models were an essential method for obtaining the spatial variability of potential and actual yields in State of São Paulo, Brazil. Using these maps, it is possible to have a range of yields in each region according with climate and soil characteristics for planning strategies for management of sugarcane cultivars, in different production environments.

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