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Forecasting sugarcane yields using agro-climatic indicators and Canegro model: A case study in the main production region in Brazil

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ABSTRACT

Timely crop yield forecasts at regional and national level are crucial to manage trade and industry planning and to mitigate price speculations. Sugarcane is responsible for 70% of global sugar supplies, thus making yield forecasts essential to regulate the global commodity market. In this study, a sugarcane forecasting system was developed and successfully applied to São Paulo State, the largest cane producer in Brazil. The system is based on multiple linear regressions relating agro-climatic indicators and outputs of the sugarcane model Canegro to historical yield records. The resulting equations are then used to forecast the yield of the current season using 10-day period updated values of indicators and model outputs as the season progresses. We quantified the reliability of the forecasting system in different stages of the sugarcane cycle by performing cross-validations using the 2000–2013 time series of official stalk yields. Agro-climatic indicators alone explained from 38% of inter-annual yield variability (at State level) during the boom growth phase (i.e., January–April) to 73% during the second half of the harvesting period (i.e., September–October). When Canegro outputs were added to the regressor set, the variability explained increased to 63% for the boom growth phase and 90% after mid harvesting, with the best performances achieved while approaching the end of the harvesting window (i.e. at the beginning of October, SDEP = 0.8 t ha^{-1}, R^2_{cv} = 0.93). It is concluded that the overall performances of the system are satisfactory, considering that it was the first attempt based on information exclusively retrieved from the literature. Further improvements to operationalize the system could be possibly achieved by the use of more accurate inputs possibly supplied by the collaboration with local authorities.

1. Introduction

Sugarcane (*Saccharum* spp. L.) is a semi-perennial crop widespread in tropical and sub-tropical environments. It is grown on about 27 million ha worldwide, for an annual production of 1.89 billion tonnes as fresh cane (FAOSTAT, 2014), corresponding to 70% of global sugar supply (Lakshmanan et al., 2005). Moreover, it is efficiently used for ethanol production (Goldemberg, 2008; Langeveld et al., 2014), contributing for 60% to the global bioethanol demand (Demirbaş, 2005). The sucrose stored in the stalk, which depends on genetic, management and environmental factors, is about 12–15% of the fresh weight (Humbert, 2013).

Brazil is the main sugarcane producing country worldwide, accounting for 40% of global production (FAOSTAT, 2014). The cultivated area in the country sharply increased from 2002 to 2009, mainly due to incentives aimed at replacing or blending gasoline with ethanol in the transport sector (Scarpare et al., 2016). After this period, the global financial crisis and the fall of international sugar prices slowed down the Brazilian sugar sector (Marin, 2016). The State of São Paulo is the most important producer, being responsible for more than half of national sugarcane production (UNICA, http://www.unicadata.com.br/).

Its prominent role in global production places emphasis on the timely estimation of sugarcane yields in Brazil. Indeed, early warning in case of anomalous seasons at regional and national scale allows stakeholders to properly assure imports and regulate the agricultural market (Atzberger, 2013; Bannayan and Crout, 1999). Moreover, the

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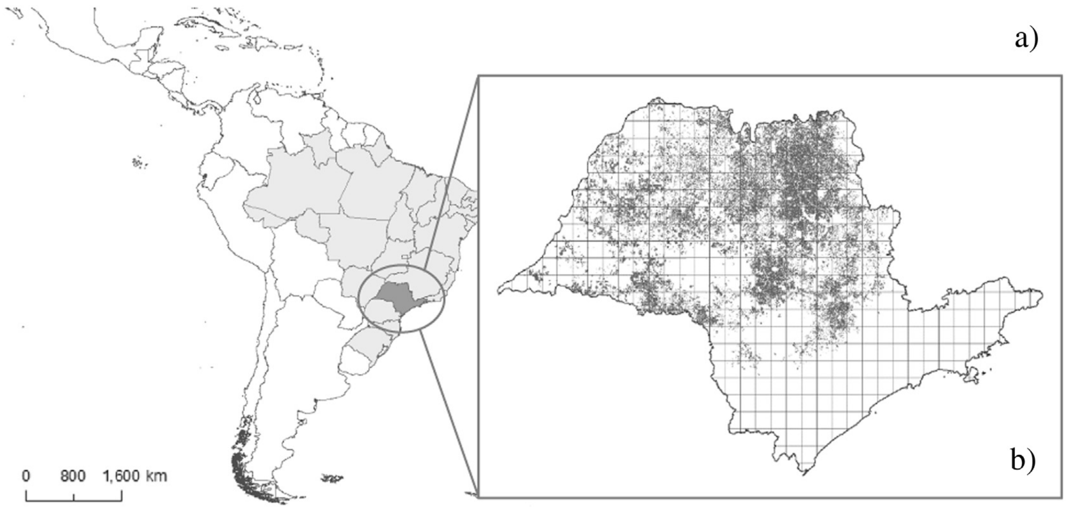

Fig. 1. a) Position of the State of São Paulo in South America and b) 0.25° latitude × 0.25° longitude simulation grid and sugarcane cover map (CANASAT Project; Rudorff et al., 2010).

sugar and ethanol supply chains involve distinct sectors at local (agriculture, transportation, milling, marketing) and national and global (energy, trade) levels. In such a complex scenario, early knowledge on seasonal supplies may support selling strategies and industry competitiveness, besides being a valuable information to plan milling operations and sugar shipments (Everingham et al., 2002). Finally, transparent forecasts made available to the public and early warnings in case of unfavorable conditions can mitigate the volatility of prices that often affect the main food commodities because of unexpected production falls and speculative actions (OECD and FAO, 2011).

These considerations led to the development of a variety of yield forecasting systems in the past decades. The first methods were based on farm surveys and crop scouting (Bannayan and Crout, 1999); however, these methodologies are strongly subjective and suffer from a lack of consistency. Since the 1990s, systems based on information retrieved from agro-climatic indicators, remote sensing and crop simulation models became more common (Bouman et al., 1997). The latter approaches present major advantages regarding coherence and objectiveness, and applicability at the regional to global scales. However, these methods also present some tenacious constraints, that undermine the accuracy of model-based yield forecasting systems: (i) the uncertainty regarding input data at regional scale (i.e., agro-management practices, soil properties, weather data, crop distribution, cultivated varieties), largely depending on the aggregation assumptions (Hoffmann et al., 2016), (ii) the difficulty to simulate all the factors that significantly influence crop yield (e.g. nutrient availability, competing weeds, pests, diseases, extreme weather events), (iii) the uncertainty in parameterizations. In order to reduce the impact of these factors on the forecast uncertainty, the European Commission Joint Research Centre – within the MARS (Monitoring Agricultural ResourceS) activities – supported the development of a forecasting system based on the statistical post-processing of model outputs and time series of official yields (Vossen and Rijks, 1995), operational at the level of the EU and its Member States (https://ec.europa.eu/jrc/en/research-topic/crop-yield-forecasting).

Regarding sugarcane, various systems have been developed to forecast cane yields in the world's main production regions. These systems are based on the estimation of climatic-edaphic parameters (Scarpari and Beauclair, 2004; Suresh and Krishna Priya, 2009), on information retrieved from remote sensing (Everingham et al., 2005; Fernandes et al., 2011; Gonçalves et al., 2012; Mulianga et al., 2013; Nascimento et al., 2009) and on the use of crop simulation models often integrated with climatic outlooks (Everingham et al., 2002, 2005). These methods were mostly tested within small areas or over limited time windows, thus without evidence of their applicability in operational contexts at national level. Notable exceptions are the national-scale systems developed by Bezuidenhout and Singels (2007a,b) in South Africa and by Duveiller et al. (2013) in Brazil. In particular, the system developed in South Africa, based on the Canesim model, provides since the early 2000s operationally monthly forecasts of sugarcane production at mill and industry level.

In this paper we present a yield forecasting system for sugarcane based on agro-climatic indicators and on the Canegro model (Inman-Bamber, 1991; Singels and Bezuidenhout, 2002; Singels et al., 2008) as implemented in the BioMA framework. As a case study, we evaluated the system for the State of São Paulo by quantifying its forecasting reliability in different stages of the sugarcane growth cycle. Compared to existing model-based systems, the approach we propose is resource-efficient in terms of input data needs. Moreover, being based on a process-based model, it is potentially able to better support analysists in interpreting seasonal peculiarities compared to approaches solely based on remote sensing.

2. Methods

2.1. The study area

The State of São Paulo (44°10′/53°5′W, 19°46′/25°18′S) is located along the Atlantic Ocean coast in the south-eastern part of Brazil (Fig. 1a). The State is responsible for 56% of Brazilian sugarcane production, with 369 million tons harvested in the 2015/2016 season (UNICA, 2015). The crop covers about 20% of the State's surface: according to the 2008 CANASAT cover map (Fig. 1b) (CANASAT Project; Rudorff et al., 2010), it is concentrated in the central and north-eastern areas, which presents optimal climatic conditions for sugarcane. The climate is tropical to subtropical, with annual average temperature of 23 °C and cumulated rainfall of 1400 mm according to the historical weather series for the period 1990–2009 (Instituto Nacional de Meteorologia, www.inmet.gov.br/). Rainfall events are concentrated in the north-eastern part of the State from September to March; temperature follows a north-west/south-east decreasing trend, with maximum values recorded during January and February. Sugarcane is usually harvested 12 or 18 months after sprouting both for planted and ratoon crops (i.e., canes resprouting from the stubbles of the previous crop), with the latter covering about 80% of cultivated area (Marin et al., 2016). On average, the ratoon crop is replanted every five years, due to the progressive yield decrease over successive ratoons. Fig. 2 highlights the main growth phases of 12 and 18 months sugarcane compared to monthly average mean temperature and cumulated rainfall in the State of São Paulo. Highest biomass accumu-