Field Crops Research 200 (2017) 28–37

Contents lists available at ScienceDirect

Field Crops Research

journal homepage: www.elsevier.com/locate/fcr

Inter-comparison of performance of soybean crop simulation models and their ensemble in southern Brazil

Rafael Battisti[a], Paulo C. Sentelhas[a,*], Kenneth J. Boote[b]

[a] Department of Biosystems Engineering, ESALQ, University of São Paulo, Piracicaba, SP, Brazil
[b] Agronomy Department, University of Florida, Gainesville, FL, USA

ARTICLE INFO

Article history:
Received 2 May 2016
Received in revised form 2 September 2016
Accepted 4 October 2016
Available online 15 October 2016

Keywords:
Model calibration
FAO- agroecological zone
AQUACROP
DSSAT
APSIM
MONICA

ABSTRACT

Crop simulation models can help scientists, government agencies and growers to evaluate the best strategies to manage their crops in the field, according to the climate conditions. Currently, there are many crop models available to simulate soybean growth, development, and yield, with different levels of complexity and performance. Based on that, the aim of this study was to assess five soybean crop models and their ensemble in Southern Brazil. The following crop models were assessed: FAO – Agroecological Zone; AQUACROP; DSSAT CSM–CROPGRO–Soybean; APSIM Soybean; and MONICA. These crop models were calibrated using experimental data obtained during 2013/2014 growing season in different sites, sowing dates and crop conditions (rainfed and irrigated) for cultivar BRS 284, totaling 17 treatments. The crop variables assessed were: grain yield; crop phases; harvest index; total above-ground biomass; and leaf area index. The calibration was made in three phases: using original coefficients from modelsí default (no calibration); calibrating the coefficients related only with crop life cycle phases; and calibrating all set of coefficients (below and above the soil). The results from the models were analyzed individually and in an ensemble of them. The crop models showed an improvement of performance from no calibration to complete calibration. Crop phases were estimated efficiently, although different approaches were used by the models. The estimated yield had RMSE of 650, 536, 548, 550 and 535 kg ha^{-1}, respectively, for FAO, AQUACROP, DSSAT, APSIM and MONICA, with d indices always higher than 0.90 for all of them. The best performance was obtained when an ensemble of all models was considered, reducing yield RMSE to 262 kg ha^{-1}. The same tendency for ensemble being best was observed for leaf area index. The harvest index was the crop variable with the poorest performance. In general, the results showed that an ensemble of completely calibrated models were more efficient to simulate soybean yield than any single one, which was also observed when testing this procedure with independent data.

1. Introduction

The soybean is a major crop around of world, being source of oil (refined for cooking and biodiesel production), defatted soy flour, soybean meal (animal feeding), isolated protein, and as fresh food used for cooking (Embrapa, 2015). Due to its multiple uses, soybean is the largest crop grown in Brazil, with 30.9 million hectares in the 2014/2015 crop season (CONAB, 2015), while it is the fourth largest crop cultivated in the world, with 111.3 million hectares in 2013 (FAO, 2015).

Soybean grain demand is increasing constantly with population growth, thus it is necessary to improve production, mainly by yield increase, in a sustainable way (Sentelhas et al., 2015). In this context, crop models can help in the assessment of the best strategies to achieve this goal, since they are able to evaluate the best sowing dates (Battisti and Sentelhas, 2014), the effects of climate change on yield (White et al., 2011; Asseng et al., 2013), identify drought tolerance traits (Sinclair et al., 2010; Boote, 2011; Battisti and Sentelhas, 2015), as well as many other possibilities (Tsuji et al., 1998; Wallach et al., 2006).

Crop models differ in the way and level that they simulate dynamic processes, such as water balance and crop growth and development (White et al., 2011), creating uncertainties related to the modelís parameters and structure (Palosuo et al., 2011). For example, FAO-Agroecological zone model is a simple crop model used to evaluate the relationship between crop yield and climate conditions (Doorenbos and Kassam, 1994). Using this model, Battisti and Sentelhas (2015) estimated soybean yield efficiently

* Corresponding author.
E-mail address: pcsentel.esalq@usp.br (P.C. Sentelhas).

http://dx.doi.org/10.1016/j.fcr.2016.10.004
0378-4290/

in Brazil, despite its simple approach. On the other hand, complex crop models consider more details in the description of all crop processes, which increases their possible uses to evaluate crop development and yield, as CROPGRO model, that integrates carbon, nitrogen and water balances on growth processes for estimating soybean yield (Boote et al., 2003). Besides FAO and CROPGRO, AQUACROP (Raes et al., 2012), APSIM (Keating et al., 2003), and MONICA (Nendel et al., 2011) models also stand out as the primary models for simulating growth, development, and yields of different crops, including soybean.

This large range of crop models' structures and parametrizations requires comparative studies of their performance under different conditions (Porter et al., 1993; Jamieson et al., 1998; Bassu et al., 2014; Li et al., 2015). However, as in the majority of the cases there is no "error free" or "best" model performance (Palosuo et al., 2011), recent studies suggested the use of multi-models approach with the final results being an ensemble of them (Palosuo et al., 2011; Asseng et al., 2013; Martre et al., 2015), improving accuracy and reducing uncertainties (Asseng et al., 2013).

Therefore, the aims of this study were: to calibrate five simulation models for soybean crop growth and development under different field conditions in Southern Brazil, and to evaluate their performance when using different levels of calibration and models ensemble approach.

2. Materials and methods

2.1. Field experiments

The soybean development, growth and yield data were obtained from different sites in Southern Brazil. These data were divided into two sets, with first one used to calibrate the crop models and the second for their evaluation (Table 1). For the sites of Frederico Westphalen, RS, Londrina, PR, and Piracicaba, SP, field experiments were carried out during 2013/14, 2014/15 and 2015/16 crop seasons. For Dourados, MS, the results from 2014/15 crop season were obtained from Comunello (2015), while the other results were obtained from experiments conducted by Fundação (2015) in Naviraí, São Gabriel do Oeste, and Antônio João. Details of the locations, sowing dates and crop water management are presented in Table 1, while in the Supplementary material (Fig. A1) is shown the geographic position of each site and their respective Köppen's climate classification, according to Alvares et al. (2013).

The cultivar used in all field trials was BRS 284, maturity group 6.5, with indeterminate growth habit, and non-transgenic. This cultivar was chosen since it is recommended for the region of this study and for having a high potential yield, similar to the majority of the cultivars grown. In the field experiments, fertilization was applied to sustain crop growth without deficiency and was performed according to soil analysis, by applying mainly P and K and using rhizobium inoculation to improve soybean N fixation. The crop management followed EMBRAPAís recommendations, keeping the crop free of pests and diseases (EMBRAPA, 2013).

The row spacing was between 0.45 and 0.50 m, with the plant population between 26 and 32 plants m^{-2}, respectively for highest and lowest latitudes (EMBRAPA, 2013). In the most of locations the soybean was cultivated in no-tillage crop system, except for the experiment in Piracicaba in 2013/2014 crop season, where conventional tillage system was used. During 2013/2014 crop season, the field experiments conducted in Piracicaba (C3) and Dourados (E5) had full irrigation, while in Londrina (C2) the irrigation supplied 75% of crop evapotranspiration. For the other experiments, irrigation was used, when required, only after sowing to guarantee the emergence. The irrigation applied in each site is presented in Supplementary materials (Table A1).

2.2. Weather and soil data

Soil characteristics and weather data are the main inputs from field experiment in the crop models, as well as information about crop management such as sowing date, irrigation, row spacing, plant population and cultivar, as previously described. For Piracicaba, Londrina, Frederico Westphalen and Dourados the weather data were obtained from National Meteorological Institute weather stations located near each experiment (±100 m), while for the other sites the weather data were also obtained from stations of the National Meteorological Institute, but considering those that were in the same municipality. The following daily weather data were used: maximum and minimum air temperature; relative humidity; wind speed at 2 m; incoming solar radiation; and rainfall. Details about climate variability during field experiments are presented in Supplementary material (Table A1).

The main soil characteristics are presented in Table 2. In the experiment C1, C2, C3, E1, E2, E3 and E5, the data required to build the soil profile were measured in the field experiment. For E4, E6, E7, E8 and E9, the data were obtained from RADAM-Brazil Project (1974), providing information on clay, silt and sand contents, drainage, pH, carbon and nitrogen contents, and using pedo-transfer functions from Lopes-Assad et al. (2001) and Reichert et al. (2009) to estimate the water content on the soil. Following this information, the FAO model only requires total soil water holding capacity for the crop. For the MONICA model, the type of soil was defined based on the clay, silt and sand content and on the modelís soil database. For APSIM, DSSAT and AQUACROP, the soil profiles were created based on the curve number that defines water infiltration (Soil Conservation Service, 1972), bulk density, soil saturation, drained upper limit, lower limit and saturated conductivity. Soil analysis was limited to the top 0.50 m, which required extrapolations to a potentially deeper maximum root depth, with each model presenting a different definition for that (Palosuo et al., 2011). As maximum root depth varies according each one of these models, it was one of the parameters adjusted during the calibration process.

2.3. Crop growth and development

For the field experiments identified as C1, C2 and C3 (Table 1), measurements were recorded for total above dry matter, leaf area index and specific leaf area on six dates (at 20 days after emergence, at beginning of flowering, beginning of pod formation, beginning seed formation, full seed and after full maturity). Measurements included grain yield at maturity, harvest index and the date of occurrence of planting, emergence, anthesis, beginning of pod formation, beginning of seed formation and maturity. All this information was used to calibrate the model coefficients. For the evaluation process, the field experiment E1 to E9 data included the yield at maturity and sowing date, while for E1, E2 and E3 the data included only the dates of each crop phase. Details of the methodology of these measurements are shown in Supplementary material (Table A2).

2.4. Crop models

Soybean growth and development were simulated by five crop models, as follows: FAO – Agroecological Zone (Kassam, 1977; Doorenbos and Kassam, 1994; Rao et al., 1988), referred to as FAO; FAO – AQUACROP v. 4.0 (Steduto et al., 2009; Raes et al., 2012), referred to as AQUACROP; Model for Nitrogen and Carbon in Agroecosystems v. 2.11 (Nendel et al., 2011), referred to as MONICA; Crop System Model – CROPGRO – Soybean v. 4.6.1 present in the software Decision Support System for Agrotechnology Transfer (Boote et al., 1998, 2003; Jones et al., 2003), referred to as DSSAT; and Agricultural Production Systems Simulator v. 7.7 (Robertson and Carberry,