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A comparison of the performance of the CSM-CERES-Maize and EPIC models using maize variety trial data

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ABSTRACT

Multiple crop models are now being used in climate change impact studies. However, calibration of these models with local data is still important, but often this information is not available. This study determined the feasibility of using maize variety trial data for the evaluation of the CSM-CERES-Maize and EPIC models. The models were calibrated using observed grain yield from variety trials conducted in Blairsville, Calhoun, Griffin, Midville, Plains, and Tifton, Georgia, USA. The software program GenCALC was used to calibrate the yield component coefficients of CSM-CERES-Maize, while the coefficients for EPIC were manually adjusted. The criteria for evaluating the performance of the two crop models included the slope of linear regression, R^2, d-stat, and RMSE. Following model calibration and evaluation, both models were used to simulate rainfed and irrigated grain yield during 1958 to 2012 for the same six locations that were used for model evaluation. The differences between the simulations of CSM-CERES-Maize and observations were no more than 3% for calibration and no more than 8% for evaluation. However, the differences between the simulations of EPIC and observations ranged from 2% to 23% for calibration and evaluation, which was larger than for the CSM-CERES-Maize model. This analysis showed that calibration of CSM-CERES-Maize was slightly superior than EPIC for some cultivars. Although this study only used observed grain yield for calibration and evaluation, the results showed that both calibrated models can provide fairly accurate simulations. Therefore, it can be concluded that limited data sets from maize variety trials can be used for model calibration when detailed data from growth analysis studies are not readily available.

1. Introduction

"Crop simulation models integrate the current state-of-the art scientific knowledge from many different disciplines, including crop physiology, plant breeding, agronomy, agrometeorology, soil physics, soil chemistry, soil fertility, plant pathology, entomology, economics and many others" (Hoogenboom, 2000). Since agricultural production is determined by weather and climate (Adams et al., 1998), these models have been used extensively to analyze the potential impact of climate change on crop production (Lobell and Asner, 2003; Semenov and Shewry, 2011; White and Hoogenboom, 2010). Coupling crop models and climate models has been widely used in both past and current climate impact analysis (Carbone et al., 2003; Curry et al., 1995; Easterling et al., 1996; Easterling et al., 1997; Parry et al., 2004; Parry et al., 2007; White et al., 2011). Alexandrov and Hoogenboom (2000) combined the CERES v.3.5 simulation model for maize (*Zea mays* L.) and winter wheat (*Triticum aestivum* L.) and the CROPGRO v.3.5 model for soybean (*Glycine* max L.) and peanut (*Arachis hypogaea* L.) with climate projections of Global Circulation Models (GCM) for more than 500 locations in the southeastern region of the USA. Their results concluded that the GCM scenarios projected a decrease in crop yield for the 2020s under the current level of CO_2 and the increased CO_2 tended to increase crop yield. Adaptation options were suggested for changing sowing date, hybrids and cultivar selection, and fertilization to mitigate the potential negative impact of potential warming.

It is well known that the calibration and evaluation of a crop model is extremely important when a crop model is applied for new locations with new varieties, cultivars or hybrids. Model evaluation is not only important for determining the accuracy of the simulations, such as for flowering, maturity and yield, but also to show the possible uncertainties that a crop model could introduce in impact studies. Many studies have developed procedures for the calibration of crop models based on limited observations for numerous applications for a range of crops such as maize, soybean, alfalfa (*Medicago sativa*), grain sorghum (*Sorghum bicolor* (L.) *Moench*), wheat, barley (*Hordeum vulgare* L.), peanut, rice (*Oryza sativa*), cotton (*Gossypium hirsutum L.*), etc. (Balkovič et al.,

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2013; Cabelguenne et al., 1990; Gaiser et al., 2010; Ko et al., 2009; Perez-Quezada et al., 2003; Soler et al., 2007).

In addition to the calibration and evaluation of single model, studies also have shown that different modeling approaches may lead to significant differences in results due to the differences between crop simulation models (Wolf, 2002). The comparison of the performance of different crop models in predicting crop phenology has been studied (Porter et al., 1993, and French and Hodges, 1985) and for grain yield (e.g., Cerrato and Blackmer, 1990), showing that some models performed better than others, which means less uncertainties will be introduced when the models are applied. Recent discussion of uncertainties that crop models could introduce in climate change impact studies emphasizes a comparison of the performance of different crop models (Ceglar et al., 2011; Rötter et al., 2012; Semenov and Stratonovitch, 2010). Newly released cultivars, varieties, and hybrids have not been parameterized for most models and, therefore, need to be calibrated, while the crop models also have improved over time (Holzworth et al., 2015). Therefore, the comparison of the performance among different crop models and the use of multiple crop models to minimize uncertainties has been acted on internationally, such as in The Agricultural Model Intercomparison and Improvement Project (Rosenzweig et al., 2013). In addition to calibration and evaluation of each model, a proper sensitivity test is also important in order to better understand the potential impact of climate change effect on crop growth, development and ultimately yield.

Comprehensive data sets and associated data standards are needed for the comparison of crop models' performance, especially for the more complex dynamic crop growth simulation models (Hunt et al., 2001; Hoogenboom et al., 2012a; White et al., 2013). For instance, Anothai et al. (2008) collected detailed phenological and growth analysis data for the calibration of CSM-CROPGRO-Peanut. However, detailed growth analysis data are normally not available and are also very expensive to obtain with respect to financial resources required for field experimentation and personnel resources for detailed data collection (Kersebaum et al., 2015). Unfortunately for most impact studies, the calibration and evaluation procedures of the crop simulation models have been ignored, and the recommended cultivar coefficients from model designers or previous studies were used, introduction additional uncertainties.

Only a few studies so far have concentrated on multiple model comparisons, such as for barley (Rötter et al., 2012), wheat (Asseng et al., 2013; Liu et al., 2016), maize (Bassu et al., 2014) and potato (Fleisher et al., 2016). There is, therefore, also a need to analyze the uncertainties of maize crop models with recently released maize hybrids. In this study two commonly used maize crop simulation models in both the USA and across the globe were selected. One is CSM-CERES-Maize, which is one module of the Decision Support System for Agrotechnology Transfer (DSSAT), the other one is Environmental Policy Integrated Climate (EPIC) cropping systems model. As defined by White and Hoogenboom (2003), EPIC can be considered a type 2 model with species-specific genetic coefficients but no reference to genotypes, while CSM-CERES-Maize is a type 3 model with genotypic differences represented by cultivar-specific genetic coefficients. The main interest in this study was to compare two models with different sets of genetic coefficients rather than the performance of an ensemble requiring more than two models.

DSSAT is a software package that incorporates independent models for more than 25 different crops with programs that facilitate the evaluation and application of the crop models for different purposes (Hoogenboom et al., 2012b; Jones et al., 2003). The DSSAT crop models simulate growth, development, and yield by considering weather, genetics, soil water, soil carbon and nitrogen, and management for single or multiple seasons and in crop rotations at any location where minimum inputs are provided (Hunt and Boote, 1998; Jones et al., 2003). The minimum inputs contain soil profile, daily weather data (minimum and maximum temperature, precipitation, and solar radiation), crop management (plant population, row spacing, application of irrigation and fertilizer etc.), and a set of cultivar coefficients. The individual crop growth modules of CSM such as CERES and CROPGRO were designed for simulating different crops to provide an accurate description for the development stages of a specific cultivar. The CSM-CERES-Maize is the module that simulates growth, development and yield for maize using a daily time step. Growth stages that are simulated by CSM-CERES-Maize include germination, emergence, end of juvenile, floral induction, 75% silking, beginning grain fill, maturity, and harvest (Jones and Kiniry, 1986; Jones et al., 2003; Ritchie et al., 1998). The physiological day accumulator is a function of temperature and day length; when it reaches the threshold given in the cultivar file, the new growth stages is triggered. The potential growth depends on photosynthetically active radiation and its interception, where the actual biomass production is constrained by stresses such as temperature, nitrogen, and water. It also considers the sensitivity of a crop to the ambient CO_2 concentration.

EPIC was designed to estimate soil productivity as affected by erosion throughout the U.S. (Williams et al., 1989). The components of the EPIC model include weather, hydrology, erosion-sedimentation, nutrient cycling, crop growth, tillage, soil temperature, economics, and plant environment control (Jones et al., 1984a, 1984b; Sharpley et al., 1984; Williams et al., 1984, 1989). Similar to CSM-CERES-Maize, soil profile information, daily weather data, crop management, and a set of cultivar coefficients are the minimum data inputs for EPIC. However, multiple crops are simulated by a single module. The yield is estimated using the harvest index and above-ground biomass. The above-ground biomass in turn is a function of photosynthetically active radiation and leaf area. Leaf area is calculated as a function of heat unit accumulation, crop development states and crop stresses. Unfortunately, this model does not provide the individual predictions and thus outputs for crop development stages.

The goal of this study was to determine the feasibility of using limited maize variety trial data for the evaluation of different crop simulation models using different complexities with respect to genetic coefficients. The first objective was to determine the cultivar coefficients for the two crop models using observed grain yield; the second objective was to determine whether the performance of the two evaluated crop models is comparable in predicting maize grain yield.

2. Materials and methods

2.1. Experimental data collection

In Georgia, variety trials for both rainfed and irrigated maize are conducted at the regional agricultural experimental stations located in Blairsville (34.84°N, 83.93°W), Calhoun (34.34°N, 85.12°W), Griffin (33.26°N, 84.28°W), Midville (32.88°N, 82.22°W), Plains (32.05°N, 84.37°W), and Tifton (31.49°N, 83.53°W) (Table 1). These variety trials are conducted by the University of Georgia (UGA) College of Agricultural & Environmental Science (CAES) Statewide Variety Testing (SWVT) program. In this study data collected from 2003 until 2010 were used (Coy et al., 2003, 2004, 2005, 2006, 2007, 2008, 2009, 2010). Soil profile and soil surface data and generic soil information for these seven locations were obtained from the soil analyses conducted by Perkins et al. (1986, 1979, 1978, 1982, 1983, 1985) and Natural Resources Conservation Service (NRCS) of United States Department of Agriculture (USDA). The soil types were a Bradson clay loam for Blairsville; a Waynesboro loam, an Ethowah loam, a Rome gravelly clay loam, and a Savannah loam for Calhoun; a Pacolet sandy loam and a Cecil sandy loam for Griffin; a Tifton loamy sand and a Dothan loamy sand for Midville; a Faceville sandy loam and a Greensville sandy loam for Plains; and a Tifton loamy sand, a Fuquay loamy sand, and a Dothan loamy sand for Tifton. A soil utility program of DSSAT, SBuild, was used to create the soil inputs based on these local soil profile data.

The daily solar radiation, maximum and minimum air temperature, and precipitation for each location were obtained from the Georgia