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Validation and reliability of the EPIC model to simulate maize production in small-holder farming systems in tropical sub-humid West Africa and semi-arid Brazil

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ABSTRACT

The majority of existing crop growth models has been developed for temperate or subtropical regions and for high input cropping systems. However, climate, soil and management systems are quite different in tropical regions. Therefore, crop growth models in tropical regions require extended testing under a range of climatic, soil and management conditions. Multi-location calibration and validation of the EPIC (Environmental Policy Integrated Climate) model for maize production has been carried out using data sets from 22 sites in the semi-arid and sub-humid tropics in West Africa and North-East Brazil. The data sets originated from field experiments on research stations as well as on-farm trials with various treatments over one to four cropping seasons. The calibration procedure revealed the necessity to distinguish between local and improved varieties and to take into account specific parameterization requirements of hydromorphic soils influenced by groundwater or water-logging. Validation with grain yield data from 141 cropping seasons proved to be satisfactory with a mean error (ME) of 0.01 t ha^{-1} and a mean relative error (MRE) of 4%. However, the coefficient of determination for the regression between simulated and observed maize yields was quite low with a R^2-value of 0.69. Detailed analysis of the validation data set showed that model performance depends partially on soil acidity, with the poorest R^2-value of 0.40 on highly acidic soils with aluminum saturation of more than 35% (Alumi-Haplic Acrisols, Ferralsols and Ferralic Cambisols). When data of the other sites were pooled the R^2-value of the regression between simulated and observed maize yields was 0.79, which means that the model explained about 80% of the variance in crop yield. It is concluded that upscaling of the model to the regional scale requires the quantification of the usage of improved varieties and information about the extent of highly acid soils in the target region.

1. Introduction

In developing countries located in tropical regions, environmental conditions and crop management differ strongly from those found in temperate regions with respect to climatic and soil characteristics, land use practices and fertilizer inputs. Soils are usually heavily weathered and hence of low fertility. Although mean temperature and vapour pressure deficit are low during the growing period, climate conditions are characterized by high mean temperature and high potential evapotranspiration. The rainy season may last less than 6 months with dry spells of variable duration and frequency. There are few crop growth models that have attempted to simulate crop growth under the strongly contrasting environmental conditions observed in the tropics. The earliest results were obtained by the application of the DSSAT (Decision Support System for Agricultural Technology Transfer) system which relies on crop models from the CERES and CROPGRO families (Lal et al., 1993; Thornton et al., 1997). However, most of the studies on the model performance of DSSAT have been done in subtropical or temperate regions like Northern India, Southern US or Turkey (Garcia et al., 2006; Dogan et al., 2007; Soler et al., 2007). Investigations related to tropical environments concluded that further validation on contrasting soil and crop management conditions is required (Asadi and Clemente, 2001). More recent developments like SARRA-H, APSIM or InfoCROP show promising results with respect to model performance for millet, rice, wheat and some leguminous crops (Robertson et al., 2002; Dingkuhn et al., 2003; Aggarwal et al., 2006). The output and fertility

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dynamics of maize–legume fallow systems in Kenya have been well described by simulations with the simulation model WANULCAS at the plot and farm level after having replaced the default pedotransfer functions (PTFs) in the model by PTFs specific to the tropical soils of this region (Walker et al., 2007).

The main objective of this study was to evaluate the potential of the EPIC (Environmental Policy Integrated Climate model, formerly known as Erosion Productivity Impact Calculator) model to simulate maize development and yield under a wide range of climatic and soil conditions that occur in tropical regions. Previous model applications on highly acid soils in Brazil with free aluminum in the soil solution indicated that, the EPIC model (Version 8120), in spite of its capacity to consider aluminum toxicity as a growth constraint, was not able to simulate maize and cowpea production accurately (De Barros et al., 2004b). However, whether the conclusion drawn for this specific site holds also for other sites in tropical semi-arid and sub-humid regions is still an open question. The calibration and validation exercise is based on 15 years of field work focusing on small-holder farming systems in contrasting agro-ecological zones in West Africa and the North-East of Brazil (Gaiser et al., 1994, 1998, 1999, 2003, 2004; Würth et al., 2000; Hilger et al., 2000; De Barros et al., 2001, 2004a, 2007; Herfort et al., 2002; Saboya et al., 2002).

2. Materials and methods

2.1. The EPIC model

There are few crop growth models that are able to simulate maize growth under the strongly contrasting environmental conditions observed in the tropics, considering temperature stress, nutrient deficiencies of nitrogen, phosphorous and potassium, as well as the toxic effects of salts, oxygen deficiency and aluminum toxicity in the rhizosphere which may affect root growth, water uptake and crop development (Table 1). The EPIC model (Williams, 1990) was selected, because it potentially takes into account all relevant soil processes (soil water dynamics, availability of nitrogen, phosphorous and potassium, soil salinity, aluminum toxicity) and is considered therefore to be suitable for application in the tropics. EPIC is a field-scale model designed to simulate drainage areas that are characterized by homogeneous weather, soil, landscape, crop rotation, and management system parameters (Williams, 1990). It operates on a continuous basis using a daily time step and can perform long-term simulations over several decades. A wide range of crop rotations and other vegetative systems can be simulated with the generic crop growth routine used in EPIC. Several tillage systems and other management options like inter- or relay cropping which are widely practised in Sub-Saharan Africa and Latin America can also be simulated with the model. EPIC is continuously updated and in this study the version 3060 was used. This version has an improved submodel for the simulation of C and N turnover (Izaurralde et al., 2006) based on algorithms of the CENTURY model (Parton et al., 1994). The soil organic matter dynamics are crucial for crop growth under low-input farming systems; a farming system common in tropical regions. In the revised approach, simulated C and N compounds in EPIC are stored in either biomass, slow, or passive soil organic matter pools. Direct interaction is simulated between these pools and the soil moisture, temperature, nutrient leaching and nutrient translocation functions. Nutrient leaching from surface litter to deeper soil layers and the effect of soil texture on organic matter stabilization are also both accounted for in the revised code. In addition to the C and N dynamic routine, EPIC is composed of eight major submodels (Williams, 1995):

1. Weather generator.
2. Soil water dynamics and hydrology.
3. Erosion by wind and water.
4. Nutrient (N, P, K) and carbon cycling.
5. Soil temperature.
6. Tillage.
7. Crop growth.
8. Crop and soil management.

There is also a calculator integrated in the model for simple cost-benefit analyses.

For data input the i_EPIC interface (http://www.public.iastate.edu/~tdc/i_epic_main.html) was used.

2.2. Weather data

Due to the fact that spatial and temporal variability of rainfall is very high under tropical sub-humid and semi-arid conditions, only sites were used where daily information for rainfall from a nearby station was available (Tables 2 and 3). In addition to rainfall, maximum and minimum temperatures (°C) were used as inputs, on a daily basis, either from the same station, or from the closest synoptic station. In cases where the latter variables were not available, average monthly values for the year of the experiment were used together with the long-term average standard deviation for maximum and minimum temperature (°C). In all cases the potential ET was calculated according to the method proposed by Hargreaves and Samani (1985), which requires only the minimum and maximum temperatures as input variables.

2.3. Soil data

The soil data were input according to the site data that were available. For each site at least one fully described soil profile with all relevant physical and chemical parameters was available. On

Table 1
Major constraints to crop production in tropical regions as considered by various crop growth models.

Model name (reference)	Climate	Soil water dynamics	Nutrient availability	Toxic elements (Al, salt)	Pests, diseases	Number of crops	Mixed cropping
SORGF (Arkin et al., 1976)	+	+	–	–	–	1	–
SUCROS (Van Keulen et al., 1982)	+	+	–	–	–	1	–
CERES (Ritchie and Otter, 1985; Jones et al., 1986)	+	+	N	–	–	5	–
CENTURY (Metherell et al., 1993)	+	+	N, P, S	–	–	(18/6)	–
SIMRIW (Yoshino et al., 1988)	+	–	–	–	–	1	–
CROPWAT (Smith, 1989)	+	+	–	–	–	30	–
WOFOST (Van Diepen et al., 1989)	+	+	(N, P, K)[a]	–	–	22	–
EPIC (Williams, 1995)	+	+	N, P, K	+	(+)	130	+
QUEFTS (Janssen et al., 1990)	–	–	N, P, K	–	–	>20	–
DSSAT (www.icasanet.org)	+	+	N	–	(+)	28	–
APSIM (McCown et al., 1996)	+	+	N, P	–	(+)	18	+

[a] Nutrient requirements of the crops are related to the nutrient applications prescribed by the user. Nutrient turnover is not included.