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A comparison of four wheat models with respect to robustness and transparency: Simulation in a temperate, sub-humid environment

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ABSTRACT

There is debate over determining the appropriate model complexity to simulate crop development, growth, and yield. An approach that is sometimes suggested is to compare the performance of models using common datasets for ability to reproduce specific sets of observations. However, this narrow-focused approach overlooks the critical heuristic aspects in using models to explore and understand the behavior of cropping systems at the process level. We argue that the key criteria of model evaluation are both transparency and overall robustness. While model robustness (often mislabeled as "validation") is sometimes presented at some level, model transparency has normally been ignored in model comparison studies. The objective of this paper is to examine the transparency and robustness of four wheat (*Triticum aestivum* L.) models that are markedly different in detail: CropSyst and SSM as simpler models and APSIM and DSSAT as more complex models. Data for development, growth and yield of the crop were collected from a wide range of environmental and growth conditions in the Grogan region of Iran. Models parameterization was done according to the guidelines for each model and then model testing and comparison were performed using different datasets. The two simpler models were found to be more robust than the complex models; across all the evaluated crop variables, the coefficient of variation in yield prediction was lower for SSM (8.2%) and CropSyst (14.3%) than APSIM (15.0%) and DSSAT (18.5%). Transparency of the models was mainly gauged by the number of input parameters needed by the models. Simulations using APSIM (292 parameters) and DSSAT (211 parameters) required the definition of about fourfold more parameters than CropSyst (50 parameters) and SSM (55 parameters). The simulation results showed no significant relationship between model performance and parameter number; the lack of transparency sacrificed in complexity was not rewarded by increased robustness in the output.

1. Introduction

Crop models have proliferated to address a number of issues related to the response of plants to their environment, and have been used to address a number of management and genetic issues in cropping improvement. These models have been developed at varying levels of complexity and process reductionism in describing plant development and growth, and hence vary greatly in their requirements for parameterization and input data. A major challenge is to sort out which model is most "suitable" for the objective laid out for a simulation exercise (Asseng et al., 2013). As noted by White et al. (2011) there is widespread debate over the appropriate modeling complexity that models should attempt to describe in simulating crops.

The criteria for defining model "suitability" of a model are necessarily flexible. The first criterion for suitability is to use a model that is appropriate for the objectives of the modeling effort or modeling purpose (Soltani and Sinclair, 2012). Therefore, it is essential to have a clear statement of the objective for the use of the model before attempting to select or develop a model. Model selection needs to be made based on the full scope of the objective for doing simulations.

A second criterion for judging the suitability of a model is its robustness. The robustness is tested by comparing the simulation output from the model against observations. Various statistical approaches can be used to quantify this comparison. Of course, an important feature of robustness is not simply an acceptable prediction of final yield but a realistic representation of the temporal dynamics of the growing crop (Soltani and Sinclair, 2012).

An often overlooked criterion, but a very important one in optimizing the heuristic value of a model is having a high degree of transparency. Transparency reflects whether model parameters,

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flow diagrams and code can be accessible and readily understood by those that were not involved in its development (Van Ittersum et al., 2003; Soltani and Sinclair, 2012). Transparency, therefore, depends to a large extent on the complexity of the model. Transparency is usually facilitated by a minimum number of input coefficients (parameters), and requires that these coefficients are observable and measurable independent of the model. Often, transparency is diminished as the complexity of a model is increased.

Complexity has two aspects. The first aspect is the number of processes that a model simulates, which may be required for different purposes. For instance, a wheat model that simulates growth and yield under both non-limited and limited water conditions is more complex than a model that simulates growth and yield for only optimum conditions; a more complex model will be needed for limited-water conditions. The second aspect is the number of equations/parameters that a model uses to simulate a specific process. A wheat model that requires 100 parameters to simulate potential growth is more complex that a model that uses only 10 parameter to simulate crop growth under the same conditions. In this analysis, complexity is judged based on this second aspect; a complex model relies on more parameters and hence inputs to simulate key processes. A simple or complex crop component (sub-) model, then, can be a part of a complex modeling package that simulates many processes or a simple model that simulates several processes.

Other aspects of transparency involve the extent of model "calibration", availability of technical documentation, accessibility of the model code and its understandability, and agreement of published documents and the model codes. Calibration often involves examining the output of the entire model to guide the selection of the values of various parameters to improve the model fit with observations. 'Calibration' is sometimes incorrectly used as being synonymous with parameterization. Model calibration can be a specific concern because it may reflect the existence of parameters in the model that are either not readily observable or vary in an unknown way. Further, calibration to determine model parameters reduces the model to a complicated framework to empirically match observations. Some models, in fact, include parameters that cannot be measured or determined independent of the model itself; so the calibration of the model necessarily causes the model to become an empirical description of observations.

The objective of this study was to compare the robustness and transparency of four crop models that vary in complexity. The context of this comparison was an ability to simulate the development, growth and yield of wheat (*Triticum aestivum* L.) crops grown over a wide range of environmental and growth conditions in the Grogan region of Iran. Robustness compared various indices of crop behavior between observed and simulated values. Transparency was initially judged simply by the number of parameters that must be known in a model to allow it to be operational. Among the four tested models, two simpler models were tested: CropSyst (Stockle et al., 2003) and SSM (Amir and Sinclair, 1991; Soltani and Sinclair, 2012; Soltani et al., 2013). The two more complex models are APSIM (Keating et al., 2003) and DSSAT (Jones et al., 2003; Hoogenboom et al., 2012).

2. Models

CropSyst, whose development was initiated in the early 1990s (Stockle et al., 1994, 2003), is one of the simplest in representing plant growth processes. A primary objective of CropSyst was to simulate cropping systems with specific focus on crop rotations. The model includes soil water and nitrogen budgets, crop growth and development, crop yield, residue production and decomposition, soil erosion by water, and salinity. The model has been used to study the effect of climate, soils, and management on cropping systems productivity and the environment (Stockle et al., 2003).

A model that incorporates somewhat more detail about the processes involved in crop development, growth and yield formation is the SSM-wheat model (Soltani and Sinclair, 2012; Soltani et al., 2013), which is an up-to-date version of earlier wheat models developed by Sinclair and co-workers (Amir and Sinclair, 1991; Sinclair and Amir, 1992; Sinclair et al., 1993; Wahabi and Sinclair, 2005; Soltani and Sinclair, 2012). The wheat model includes the key physiological process to simulate crop responses to radiation-, water-, and nitrogen-limited conditions. The model was designed as an analytical tool to assist crop and management research under various conditions of crop growth and yield.

The DSSAT (Decision Support System for Agrotechnology Transfer) wheat model is complex. DSSAT was originally developed to facilitate the application of crop models to agronomic research using a systems approach. Its initial development was motivated by a need to integrate knowledge about soil, climate, crops, and management for making better decisions about transferring production technology from one location to others where soils and climate differed (Jones et al., 2003). DSSAT crop simulation models can be used to determine optimum crop management practices (including cultivar, fertilizer, water and tillage), precision agriculture, pest management, climate change and variability, long-term sustainability, environmental pollution, genomics, and education (Jones et al., 2003; Hoogenboom et al., 2012).

Another complex wheat model is APSIM (Agricultural Production systems SIMulator). Like DSSAT, APSIM is challenging in its requirements for undertaking simulations. The APSIM was constructed as a modular modeling framework based on biophysical processes in farming systems with many plant, soil and management modules for a diverse range of crops, pastures and trees, soil processes including water balance, nitrogen and phosphorus transformations, soil pH, erosion, and a full range of management controls. A key objective of the model was to generate economic and ecological outcomes in response to various management practices. APSIM has been applied to a broad range of applications, including support for on-farm decision making, farming systems design for production or resource management objectives, assessment of the value of seasonal climate forecasting, analysis of supply chain issues in agribusiness activities, development of waste management guidelines, risk assessment for government policy making, and as a guide to research and education activity (Keating et al., 2003). The model has also been used to study crop response to weather and climatic risk (Keating et al., 2003; Hammer et al., 2010).

In this paper, therefore, these four wheat models were challenged to simulate the growth, development, and yield of wheat crops grown in many seasons in the Grogan region of Iran. Data were collected from a number of published records in this specific area that included a range of experimental treatments. Simulations were done using each of the four models. The models were compared specifically based on the objective criteria of robustness of results and transparency in the use of the model.

3. Materials and methods

3.1. Experimental data

Experimental studies listed in Table 1 were used as the source of information for parameterization and evaluation of different wheat models; no specific wheat model guided experimental protocol. These studies were designed to collect data on wheat development, growth, and yield formation under a wide range of environmental and growth condition in Gorgan region, Iran. Gorgan has mild