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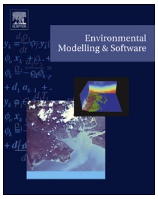

Accuracy, robustness and behavior of the STICS soil–crop model for plant, water and nitrogen outputs: Evaluation over a wide range of agro-environmental conditions in France

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ABSTRACT

Soil–crop models are increasingly used as predictive tools to assess yield and environmental impacts of agriculture in a growing diversity of contexts. They are however seldom evaluated at a given time over a wide domain of use. We tested here the performances of the STICS model (v8.2.2) with its standard set of parameters over a dataset covering 15 crops and a wide range of agropedoclimatic conditions in France. Model results showed a good overall accuracy, with little bias. Relative *RMSE* was larger for soil nitrate (49%) than for plant biomass (35%) and nitrogen (33%) and smallest for soil water (10%). Trends induced by contrasted environmental conditions and management practices were well reproduced. Finally, limited dependency of model errors on crops or environments indicated a satisfactory robustness. Such performances make STICS a valuable tool for studying the effects of changes in agro-ecosystems over the domain explored.

Software availability

STICS is a free software, available by downloading at http://www6.paca.inra.fr/stics_eng together with a set of default parameters covering general parameters and specific plant parameters.

1. Introduction

Soil–crop models are recognized as powerful tools for assessing the interacting effects of management practices, soils and climate on the environment and agricultural production (Therond et al., 2011). They are increasingly used as predictive tools for assessing yield and environmental impacts of agriculture, not only at the field scale and over a cropping season but also at larger spatial scales from the regional one (Gabrielle et al., 2006; Ledoux et al., 2007;

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Leenhardt et al., 2006; Moreau et al., 2012; Therond et al., 2011) to the global one (De Gryze et al., 2011; Gervois et al., 2008; Osborne et al., 2007) and at longer time scales ranging from decades (Beaudoin et al., 2008; Berntsen et al., 2006) to century, as in climate change impact studies (Asseng et al., 2013; Bassu et al., 2014; Ducharne et al., 2007; Lenz-Wiedemann et al., 2010). The use of soil–crop models at large spatial scales and/or over long periods for predictive purposes increases the necessity to be able to simulate the functioning of a wide diversity of agro-systems, sometimes over heterogeneous areas, with a reasonable confidence. In that context, there is a strong need to produce solid evaluations of models performances in various agro-environmental situations.

Model improvement and validation is a continuous process (Boote et al., 1996) resulting from new model developments, usage and tests by the scientific community. Quite often, when the model is applied to specific conditions in order to address a local research issue, parameters are first (re)-calibrated ('*ad hoc* modeling' in Affholder et al., 2012) to improve fitting to available observations (Jamieson et al., 1998; Jégo et al., 2011, 2010; Popova and Kercheva, 2005). While such a local calibration step may be useful to address a particular research question on a given site, it cannot be used to broaden the scientific validity of the model (Sinclair and Seligman, 2000). The evaluation of the prediction potential of a model actually entails assessment of model performance without a local re-parameterization step, and using situations (sites, years) as independent as possible from the ones used for its calibration. It is also essential to evaluate the model over its intended domain of use, which may represent a wide diversity of agro-environmental conditions and output variables (Wallach et al., 2014). Most environmental models have been tested several times in a range of contexts when applied by different researchers. Examples include evaluation on a few distinct geographical sites (Beheydt et al., 2007; Frolking et al., 1998; Sahu et al., 2010), on different climatic areas (Rötter et al., 2012) or spread all over a region (Casper and Vohland, 2008; Loaiza Usuga and Pauwels, 2008) or state (Tong and Mauzerall, 2006). Such studies often focus only on a few particular output variables. Some soil–crop models evaluations focused on their ability to simulate the growth of different crops (Annandale et al., 2004; Lenz-Wiedemann et al., 2010) sometimes grown at different sites (Brisson et al., 2002). Some studies have tested the effect of crop managements and crop varieties on the model performance (Li et al., 2011; Zhang, 2010), others evaluated that performance at the catchment scale over several years (Beaudoin et al., 2008). Published evaluations of soil–crop models performed simultaneously on a wide range of agronomic situations including a gradient of conditions for several input variables at the same time (e.g. crops, climates, soils and management practices) and for different outputs concerning plant components and soil water and nitrogen dynamics remains scarce (Kersebaum et al., 2007; Nendel et al., 2011). In addition, trying to combine a wide range of agro-environmental conditions, multiple outputs and independent data for evaluation is very data intensive and may require compromises in the way the evaluation is performed.

Finally, a thorough model evaluation should also rely on a combination of assessment methods including multiple complementary statistical criteria (Bellocchi et al., 2010; Loague and Green, 1991; Rivington et al., 2005) but also robustness analyses (Confalonieri et al., 2010) and "behavioral tests" (Sinclair and Seligman, 2000) that indicate whether the model behaves in accordance with differences observed among contrasted type of conditions. This last step is part of the 'qualitative model evaluation' recommended in a recent methodological review on the evaluation of environmental models (Bennett et al., 2013).

In this study, our objective was to conduct a global evaluation of the new version 8.2.2 of the STICS generic soil–crop model (Brisson et al., 1998) combining i) a large diversity of climates, soils, plants, management practices and multiple outputs and ii) the use of the standard parameters of the model (i.e. with no attempt to recalibrate them to better fit our database or specific situations) as supplied to users. Nevertheless, we focused on situations which were both well documented and with a good knowledge of the context of application. Several aspects of model evaluation were addressed. The first set of questions concerns the accuracy of predictions: what is the global accuracy of predictions when the model is used over a wide range of conditions, with its standard set of parameters? The second set of questions relates to the ability of the model to produce reliable information about the effects we want to analyze: is the model able to reproduce the trends related to variations in crops, climate, soils and management? Is it capable of capturing the main features of the temporal dynamics of the variables of interest? Finally it is also important to study in more details model errors response to environmental factors to check the robustness of the model, i.e. are the errors homogeneous over the wide range of conditions tested? If we could identify some specific conditions (a particular crop or type of soil for example) that favor larger errors, it would help to better know the domain of validity of the model and to define where to focus efforts for improving it.

2. Materials and methods

2.1. The STICS model

STICS is a soil–crop model which has been developed at INRA since 1996 (Brisson et al., 1998, 2002, 2003, 2008) and which software and documentation are freely available on the web at http://www6.paca.inra.fr/stics_eng. It simulates the carbon (C), water and nitrogen (N) balances of the soil–crop system and can estimate simultaneously agricultural and environmental variables (e.g. crop yield, N content of harvested organs, soil water and mineral N contents, N leaching and soil organic carbon dynamics) by taking into account the impact of weather, soil, crop and management practices (e.g. nutrient and organic fertilization, irrigation, soil tillage and residues management). It was conceived as a generic model able to adapt easily to various kind of crops and environmental conditions. The specificity of each crop is defined using ecophysiological options (for example photoperiod action and/or cold requirements on crop phenology) and plant parameters. Plant parameters include both specific and cultivar parameters. Default values for a number of species and cultivars are supplied with the model. Cultivar parameters are grouped in a particular section of these plant files allowing to define several cultivars in a given plant file. Crop parameters can be used without further modification but it remains possible for users to adapt them or to define a new cultivar so as to better meet specific conditions. The description of the physical and biological processes occurring in the soil–crop system mostly relies on a unique set of general parameters. Although that set of general parameters is also opened to modifications by users, changes are not encouraged to preserve model consistency. Finally, there is a very limited set of soil and crop management input parameters that are site specific and are the only ones that must be filled in by the users. Daily weather variables must also be provided to the model, as well as initial values for some state variables (as initial soil water and mineral N content). A description of all parameters is available in the documentation downloadable together with the model. In this work we used the latest available version of the STICS model (v8.2.2) where new developments were made to tackle important societal issues such as climate change, nitrate pollution, N_2O emissions or energy crops (Bergez et al., 2014).

2.2. Dataset and methodology for simulation

We built a test dataset by compiling data from previous well documented studies carried out with STICS, all conducted in France in a wide range of contexts (Table 1). It resulted in a total of 1809 units of simulation ('*usm*', which generally corresponds to the growth cycle of a given plant, or a bare soil period, on a given soil and with given practices and climate, i.e. a single treatment.site.year) which can be run individually. Continuous simulation of crop rotations was not considered in this study.

All *usm* were run again, keeping the original site specific input parameters (soil and crop management), daily weather variables and initializations but using the unique set of general parameters and the plant files (including cultivars) delivered with the latest version of the model (v8.2.2). The methodology for the estimation of site specific input parameters was variable between *usm*, because these studies were conducted independently, over more than 15 years, and by research groups having different skills either more plant oriented or soil oriented. Using current values for