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Simulation of winter wheat yield and its variability in different climates of Europe: A comparison of eight crop growth models

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A B S T R A C T

We compared the performance of eight widely used, easily accessible and well-documented crop growth simulation models (APES, CROPSYST, DAISY, DSSAT, FASSET, HERMES, STICS and WOFOST) for winter wheat (*Triticum aestivum* L.) during 49 growing seasons at eight sites in northwestern, Central and south-eastern Europe. The aim was to examine how different process-based crop models perform at the field scale when provided with a limited set of information for model calibration and simulation, reflecting the typical use of models for large-scale applications, and to present the uncertainties related to this type of model application. Data used in the simulations consisted of daily weather statistics, information on soil properties, information on crop phenology for each cultivar, and basic crop and soil management information.

Our results showed that none of the models perfectly reproduced recorded observations at all sites and in all years, and none could unequivocally be labelled robust and accurate in terms of yield prediction across different environments and crop cultivars with only minimum calibration. The best performance regarding yield estimation was for DAISY and DSSAT, for which the RMSE values were lowest (1428 and 1603 kg ha^{-1}) and the index of agreement (0.71 and 0.74) highest. CROPSYST systematically underestimated yields (MBE – 1186 kg ha^{-1}), whereas HERMES, STICS and WOFOST clearly overestimated them (MBE 1174, 1272 and 1213 kg ha^{-1}, respectively). APES, DAISY, HERMES, STICS and WOFOST furnished high total above-ground biomass estimates, whereas CROPSYST, DSSAT and FASSET provided low total above-ground estimates. Consequently, DSSAT and FASSET produced very high harvest index values, followed by HERMES and WOFOST. APES and DAISY, on the other hand, returned low harvest index values. In spite of phenological observations being provided, the calibration results for wheat phenology, i.e. estimated dates of anthesis and maturity, were surprisingly variable, with the largest RMSE for anthesis being generated by APES (20.2 days) and for maturity by HERMES (12.6).

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The wide range of grain yield estimates provided by the models for all sites and years reflects substantial uncertainties in model estimates achieved with only minimum calibration. Mean predictions from the eight models, on the other hand, were in good agreement with measured data. This applies to both results across all sites and seasons as well as to prediction of observed yield variability at single sites – a very important finding that supports the use of multi-model estimates rather than reliance on single models.

1. Introduction

Decision making and planning in agriculture increasingly makes use of various model-based decision support tools, particularly in relation to changing climate issues. The crop growth simulation models applied are mostly mechanistic, i.e. they attempt to explain not only the relationship between parameters and simulated variables, but also the mechanism of the described processes (Challinor et al., 2009; Nix, 1985; Porter and Semenov, 2005).

Even though most crop growth simulation models (hereafter referred to as crop models) have been developed and evaluated at the field scale, and were not originally meant for assessing large areas, it has become common practice to apply them in assessing agricultural impacts and adaptation to climate variability and change, from the field to a (supra-) national scale (e.g. Parry et al., 2005; Rosenberg, 2010). We hypothesize that many large-scale crop model applications that assess climate impacts and adaptation options for crops involve huge uncertainties related to the model parameters and model structure. For example, the models applied have often not been thoroughly calibrated for the conditions of the application; they have not been evaluated for their capacity to capture the effect of climatic variability on yield, either under the conditions for which the model was developed or for the conditions of the application. Moreover, most model users are not familiar with the range of model limitations and specificities for their proper application.

Comparison of different modelling approaches and models can reveal the uncertainties related to crop growth and yield predictions, including also the uncertainty related to model structure, which is the most difficult source of uncertainty to quantify (Chatfield, 1995). Comparisons can help to identify those parts in models that produce systematic errors and require improvements (see e.g. Porter et al., 1993). Since the 1980s, there have been many studies comparing different mechanistic crop models with respect to their performance in predicting yield and yield variability in response to climate and other environmental factors (Diekkrüger et al., 1995; Eitzinger et al., 2004; Ewert et al., 2002; Jamieson et al., 1998; Kersebaum et al., 2007; Wolf et al., 1996), and many comparisons have been made for wheat models (e.g. Goudriaan et al., 1994; Landau et al., 1998; Meinke et al., 1998; Porter et al., 1993). However, for more than a decade, neither at the European nor at a global level has there been a comparison involving more than just a handful of the major accessible crop models (see Goudriaan et al., 1994), at least not for those that are most widely used for assessing impacts of climate variability and changes in field (cereal) crops.

The aim of this study was (1) to examine how different process-based crop models perform at the field scale when provided with limited information for model calibration and simulation, reflecting the typical situation in which these models are applied to large areas, and (2) to present and discuss the different sources of uncertainty involved in this kind of model application. To this end, eight crop models were run for 49 growing seasons at eight different study sites across Europe: in the Czech Republic, Denmark, Germany, Slovakia and Turkey. Winter wheat (*Triticum aestivum* L.) was used as the test crop as it is Europe's dominant cereal crop.

2. Material and methods

2.1. Models

The eight crop simulation models included in the comparison were APES, CROPSYST, DAISY, DSSAT, FASSET, HERMES, STICS and WOFOST. Details of these models can be obtained from the references gathered in Table 1. Table 2 provides an overview of the various modelling approaches applied regarding the major processes that determine crop growth and development.

All the eight models are applicable to winter wheat and they are capable of simulating crop phenology, total above-ground and root biomass, leaf area, grain yield, and field water balance components in daily time steps. However, they clearly differ with respect to their complexity and algorithms applied.

The eight crop simulation models can be grouped in terms of the detail with which they treat the following major crop growth processes (see also Table 2):

(1) *Leaf area development and light interception.* Most of the models simulate leaf area dynamics dependent on crop phenological stage, acknowledging that e.g. temperature and light affect differently the leaf expansion at different stages (Spitters, 1990). APES, CROPSYST and DSSAT are simpler in this respect. They base their leaf area calculations on a specific leaf area at emergence and biomass partitioning factors, or apply a forcing function with an exogenously defined maximum leaf area index (LAI) (Ewert, 2004). LAI in the FASSET model is primarily driven by nitrogen uptake in the vegetative period (Olesen et al., 2002a).

(2) *Light utilization.* DAISY, HERMES and WOFOST contain detailed descriptions of leaf photosynthesis, respiration, development-stage-dependent dry matter allocation patterns and scaling up of dry matter increase at canopy level (e.g. van Ittersum et al., 2003). Other models apply a simpler approach, using the radiation use efficiency (RUE) concept (Monteith and Moss, 1977).

(3) *Crop phenology.* Most of the models included have detailed phenological sub-routines that consider more than two phases in describing relationships between temperature and crop development. They include the effect of temperature, day length and vernalisation, the latter being important for winter wheat (see e.g. Mirschel et al., 2005; Slafer and Rawson, 1996). STICS is the only model in which water and nutrient stress could affect development rate, but that feature was not activated in this study. WOFOST and FASSET exclude the effect of vernalisation.

(4) *Soil moisture dynamics.* Apart from the fact that the eight crop models deal with the soil profile at different degrees of resolution (e.g. different number of soil layers and soil characteristics considered), they use either a simpler capacity or tipping bucket approach (seven models out of eight), or a more detailed Richards approach for soil water movement (DAISY) (van Ittersum et al., 2003). Models also require different numbers and types of weather variables, mostly depending on the evapotranspiration formulae applied (Penman–Monteith, Priestley–Taylor, Turc, etc.). Their assumptions regarding root distribution over depth and related water uptake vary (Wu and Kersebaum, 2008).