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Development and test of a crop growth model for application within a Global Change decision support system

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ABSTRACT

When examining potential impacts of Global Change on water resources on the regional scale, spatial and temporal changes in crop water and nitrogen demand are of fundamental significance. State-of-the-art crop growth models are powerful tools to assess the response of crops to altered environmental conditions and cultivation practices. In this paper, the process-based, object-oriented and generic DANUBIA crop growth model is presented. To evaluate the performance of the model, a validation analysis is carried out by comparing modelled data with various field measurements of sugar beet, spring barley, maize, winter wheat and potato crops. Model performance statistics show that crop growth is efficiently simulated. The closest agreement between measured and modelled biomass and leaf area index is achieved for sugar beet and winter wheat. Additionally, the response of the model to changed nitrogen availability caused by cultivation practices is analysed and reveals good results. The results suggest that the model is a suitable tool for numerically assessing the consequences of Global Change on biomass production, water and nitrogen demand, taking into account the complex interplay of water, carbon and nitrogen fluxes in agro-ecosystems.

1. Introduction

Plants function as an interface for the exchange of water and carbon between atmosphere and terrestrial biosphere. Since stomatal control of water vapour and carbon dioxide fluxes governs the processes of transpiration and photosynthesis, vegetation plays a vital role in the water, carbon and nitrogen cycle, controlling their fluxes and balances in manifold ways on all temporal and spatial scales. The interaction of the water, carbon and nitrogen cycles in the soil–plant–atmosphere system is further complicated in agro-ecosystems through the interference of human activity. The choice of crop and the specific management procedures involved have profound and large-scale eco-hydrological impacts. In view of the vast land surface area covered by crops, agro-ecosystems play a key role with respect to managing water as well as carbon and nitrogen fluxes, particularly in the context of Global Change. To mitigate the adverse effects of the projected changes, effective strategies for an adaptive land use and water resource management are required.

In the project GLOWA-Danube, a team of experts from diverse disciplines collaborates with water resources stakeholders to develop integrative strategies to secure sustainable water management in the Upper Danube Basin (~80 000 km^2). The Global Change decision support system (DSS) DANUBIA is developed embracing key environmental and socio-economic processes for simulating water fluxes (Mauser and Ludwig, 2002; Ludwig et al., 2003). A significant feature of DANUBIA is a crop growth model which addresses the reaction of various crops to altered growing conditions and cultivation practices.

A crop growth model within a Global Change DSS like DANUBIA has to fulfil several requirements. The dynamic interplay of water, carbon and nitrogen fluxes in agro-ecosystems has to be taken into account. The model has to be responsive to meteorological as well as pedological conditions, to atmospheric CO_2 concentration and to managerial options. Furthermore, applying site-specific calibration is unfeasible for large-scale application. Consequently, a process-based modelling approach is mandatory. Transpiration and photosynthesis have to be coupled to depict stomata reactions and the particularity of C_4 photosynthesis has to be considered. Since modelled yield is an important determinant for future land use plans and because of various feedback mechanisms, the influence of environmental conditions on the allocation of carbon and nitrogen within the plant has to be accounted for. In addition, leaf area development and senescence should be modelled on the basis of the interaction of leaf carbon and nitrogen dynamics. The most relevant crops in the study area have to be included and extensibility in terms of additional crops should be easily possible. Within the DSS, modelled data for export to the other models during runtime have to be provided and the interfaces for import and export parameters must be implemented.

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Numerous studies on the impact of Global Change on biomass production have been published (e.g. Olesen et al., 2000; Alexandrov et al., 2002; Wolf, 2002; Wessolek and Asseng, 2006; Krysanova et al., 2007) and a multitude of crop growth models exists. Here, only a selection of those models comprising various crops can be mentioned. The DSSAT cropping system model (Hoogenboom et al., 2003) includes models of 17 different crops, among these the CERES-Maize, -Wheat and -Barley models (Jones and Kiniry, 1986; Ritchie and Godwin, 2000), and was developed primarily to assess options for crop management. Over the last 20 years, the DSSAT suite of models has been widely validated and used (Jones et al., 2003). Examples for other models embracing a set of crops are: AGROSIM (Wenkel and Mirschel, 1995), APSIM (Keating et al., 2003), CropSyst (Stöckle et al., 2003) and STICS (Brisson et al., 2003), LINTUL and SUCROS, both developed by the Wageningen modelling group (e.g. van Ittersum et al., 2003), as well as the EPIC plant growth model, developed by scientists of the US Department of Agriculture (Williams et al., 1989). These are all generic crop models. The EPIC model has shown its applicability particularly in the context of erosion studies. It is an integral part of SWAT (Arnold et al., 1998) and SWIM (Krysanova et al., 1998, 2000; Hesse et al., 2008). An example for integrating crop growth models with hydrological models and remote sensing data for regional applications is PROMET-V (Schneider, 2003).

Most of the models were initially not intended for use in Global Change research. Consequently, the process descriptions of plant development and growth are primarily appropriate for present climate conditions. Recently, many crop models have been upgraded to simulate the direct effect of atmospheric CO_2 concentration on plants. For example, in EPIC the concept of radiation use efficiency (absorbed radiation is converted to biomass via a crop-specific factor) is extended by an empirically derived factor accounting for the effect of CO_2. The use of, e.g. EPIC in Global Change studies is widely accepted. However, except for specific versions of the LINTUL and SUCROS models (van Ittersum et al., 2003), the applicability of these models for comprehensively assessing Global Change effects is limited, since a suitable biochemically based modelling approach for photosynthesis is lacking. This process-based approach on the leaf scale is necessary to comprehensively simulate the effect of CO_2 on plant growth. Models for gas exchange based on the biochemical approach by Farquhar et al. (1980) are published, e.g. by Friend (1995) and Humphries and Long (1995). This biochemical approach is widely employed in studies of natural ecosystems (e.g. Falge, 1997; Friend et al., 1997; White et al., 1999; Reichstein, 2001; Garcia-Quijano and Barros, 2005; Lucht et al., 2006). Wang et al. (2005) modified the BIOME-BGC (BioGeochemical Cycles, e.g. White et al., 2000) model to account for winter wheat and maize crops, presenting a study for the North China Plain. However, to our knowledge only two models which are applicable for several crops include the biochemical approach of modelling photosynthesis: *ecosys* (Grant, 2001) and GECROS (Yin and van Laar, 2005). In contrast to the other models mentioned above, these two models use the "functional balance" theory (Brouwer, 1962) for the allocation of carbon and nitrogen, which is also one prerequisite for comprehensively modelling the effects of Global Change.

Additional requirements set by the research objective of developing a plant growth model applicable under Global Change conditions and reactive to management options are (i) the computational efficiency of the model to enable large-scale spatially distributed modelling and (ii) the provision of expandable interfaces to other natural science models (hydrology, meteorology, soil, etc.) as well as to actor models (particularly farming actors).

To fulfil the requirements listed above, the DANUBIA crop growth model was developed by combining and extending the models GECROS (Yin and van Laar, 2005) and CERES (Jones and Kiniry, 1986; Ritchie and Godwin, 2000). GECROS (Genotype-by-Environment interaction on crop growth Simulator) is the most recent of the Wageningen crop growth models. It is a generic model and incorporates the current knowledge of interacting ecophysiological processes. CERES (Crop Environment Resource Synthesis) comprises well established, widely used and extensively validated models for different crops and is characterized by a detailed modelling of plant processes in the rooted soil system. Within the given context, the choice of this hybrid modelling approach combines the advantages of the GECROS and CERES models. Because high performance computers are available and affordable and parallel computing techniques are applied, the use of a complex, state-of-the-art crop growth model for large-scale applications of a DSS like DANUBIA is not hampered by limited computational power anymore.

In order to prove the suitability of the DANUBIA crop growth model as a tool for assessing the response of crops to Global Change, the objectives of this study are (i) to describe the model in terms of its framework, its design, its main simulated processes, its input data and crop-specific parameters, (ii) to provide evidence for the capability of the model to simulate plant growth, including yield formation, water and nitrogen uptake and (iii) to demonstrate the model's sensitivity to soil nitrogen availability. To evaluate the accuracy of the model, a validation analysis is carried out. Modelled results for various crops are compared with measurements of biomass, leaf area index, crop nitrogen content as well as soil nitrogen and water content on the field scale. Additionally, the response of the model to two different fertilizer treatments is analysed. A complete description of the model can be found in Lenz (2007).

2. Model development and description

2.1. Modelling framework

The DANUBIA crop growth model is one of many models included in the integrative simulation and DSS DANUBIA (Barth et al., 2004). Within DANUBIA, models describing natural science processes of, e.g. hydrology, glaciology and plant growth interact with socio-economic models representing the decisions of actors from sectors such as tourism, agro-economy and water supply (see, e.g. Barthel et al., 2008). The DANUBIA crop growth model simulates the water, carbon and nitrogen fluxes within crops as well as the energy balance at leaf level. Its main import data are (i) meteorological drivers, (ii) soil data and (iii) farming practices. The main export data are (i) agricultural yield, (ii) soil layer-specific root characteristics, (iii) soil layer-specific water and nitrogen uptake rates, (iv) canopy characteristics such as leaf temperatures, leaf area and canopy height, (v) phenological development stage and (vi) amounts of crop carbon and nitrogen recirculated to soil.

In DANUBIA, the soil compartment is considered to be composed of a user-defined number of horizontal layers, assuming homogeneous characteristics within each soil layer. Each layer is described by a set of constant soil characteristics (e.g. thickness, soil texture) and dynamic attributes like temperature, root length density, water and nitrogen content. In this study, three soil layers (30 cm each) are considered. For a detailed description of the DANUBIA soil hydrology and nitrogen model (SOIL-SNT), see Klar et al. (2008). Information on farming practices are provided by an agro-economic model. In turn, the agricultural yield is simulated and exported by the crop growth model to determine future agricultural land use plans (see Apfelbeck et al., 2007). The modelled phenological development stage is used for adapting dates of management activities. DANUBIA is raster-based and suitable for modelling large watersheds. The spatial resolution of each grid cell is typically 1 km^2 but can be adjusted for smaller watersheds.