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Evaluation of crop yield simulations of an eco-hydrological model at different scales for Germany

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ABSTRACT

A prerequisite for integrated crop model applications is the evaluation at the desired spatial and temporal scale. Here, we analysed the eco-hydrological model SWIM simulating crop yields. Historic simulations for winter wheat and silage maize from 1991 to 2010 were used to examine the model performance at the county level in reproducing the county statistics for crop yields. The focus laid on the replication of mean yield levels and interannual crop yield variability. Simulations of silage maize performed better than simulations of winter wheat with R^2-values for interannual yield variability of 0.72 and 0.26 respectively at the national level. In particular, silage maize showed a tendency to perform better in areas of lower soil water availability. The reasons for the clear superiority of silage maize were supposedly the short growing season, the lower susceptibility to pests and diseases and, hence, the direct translation of water stress into yield reductions. This signal was less evident for winter wheat and was additionally superposed of climate induced biotic and abiotic stresses – primarily originating in the cold season - which were not implemented in the model. Overall, the simulation bias seemed to originate rather from unconsidered processes than from uncertainties of input data or in model parameterisation.

1. Introduction

High-yielding high-input systems (e.g. Germany) were identified as regions where weather variability has a relatively high explanatory power for yield volatility (Reidsma and Ewert, 2008; Ray et al., 2015; Conradt et al., 2016). To understand and assess the complex interactions between biophysical and human induced crop growth factors or to predict the response of crop growth to climate change, mechanistic crop models are employed which are run independently or embedded in more complex modelling frameworks such as eco hydrological models (e.g. SWIM, Krysanova et al. (1998)) or integrated assessment models (Ewert et al., 2015).

Originally, such crop models had been developed for plot scale applications assuming homogeneous environmental conditions (Hansen and Jones, 2000; van Ittersum et al., 2003; Challinor et al., 2009). However, the application spectrum of crop models has expanded substantially ever since (Ewert et al., 2015), accompanied by the increased computational capacities. Crop models are now employed at all scales, at the field and farm level, at regional, national and global scale (Tan and Shibasaki, 2003; Stehfest et al., 2007; Srinivasan et al., 2010; Balkovič et al., 2013; Nendel et al., 2013; Rosenzweig et al., 2014; Hoffmann et al., 2015; Zhao et al., 2015b; Soltani et al., 2016; Müller et al., 2017). Crop model estimations are used as inputs to economic agricultural models (Adams et al., 1990; Bowes and Crosson, 1993; Rosenzweig and Parry, 1994; Parry et al., 2005; Rosenzweig et al., 2013), form an integral part of Integrated Assessment Models (Ewert et al., 2015) and support decision makers who require crop simulations at the regional scale (Hansen and Jones, 2000; Priya and Shibasaki, 2001; Rötter et al., 2011) to design spatially explicit integrated policies (Ewert et al., 2011, 2015). Nevertheless, despite this wide application range, plot scale crop models still form the basis of all simulation exercises (Dhakhwa et al., 1997; Izaurralde et al., 1999; Saarikko, 2000; Priya and Shibasaki, 2001; Tan and Shibasaki, 2003; Parry et al., 2005; Liu et al., 2007). A major challenge is ensuring the representativeness of plot scale results for larger regions either by the extrapolation and upscaling of parameters and model assumptions (Müller et al., 2017) or the aggregation of input data (Hansen and Jones, 2000; Hoffmann et al., 2015; Zhao et al., 2015a,b). “Gridded” model applications run

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crop models at a defined raster of points for which input data are provided (Hoffmann et al., 2015; Müller et al., 2017). These rasters usually reflect data availability rather than the actual mosaic landscape heterogeneity. Moreover, the lateral hydrological fluxes of surface and subsurface runoff which form an integrative ecosystem component and impact on the soil water availability of the vegetation are missed out. Eco-hydrological models are designed to overcome this deficit. They integrate regional scale water processes with soil characteristics and plant dynamics at the catchment scale.

The integration of crop simulation approaches into hydrological models has frequently been reported (Arnold et al., 1998; Krysanova et al., 1998; Klocking et al., 2003; Liu et al., 2009; Albano et al., 2017). However, only a few studies have addressed multi-criteria model evaluation, and simultaneously addressed crop yields and hydrological aspects (Krysanova et al., 1999; Huang et al., 2006; Luo et al., 2008; Srinivasan et al., 2010). Vegetation dynamics induce an essential feedback-mechanism for hydrological fluxes in terms of root water uptake and subsequent transpiration. And although the overarching importance of vegetation dynamics on water circulation (modelling) has widely been recognised (Chen, 2015) the multiple range of evaluation criteria of eco-hydrological models have not been exploited yet. An explicit evaluation of crop yield dynamics adds an extra dimension of evaluation aspects to constrain overall model performance. However, in respect to the fundamental importance of vegetation dynamics for evapotranspiration and the latter being one of the most uncertain factors in spatial hydrological modelling (Conradt et al., 2012) and crop modelling (Cammarano et al., 2016), the explicit evaluation of the performance of vegetation dynamics within hydrological models has been widely neglected.

In this study, we used a simplified version of the well-established crop modelling approach of the Erosion Productivity Impact Calculator (EPIC) (Williams et al., 1989) embedded in the spatially explicit Soil Water Integrated Model (SWIM) (Krysanova et al., 1998) to simulate regional crop yields for Germany. In contrast to other crop modelling studies, we use a model here that was pre-calibrated and evaluated at hydrological gauge stations for all main catchments of Germany (Huang et al., 2010). By using a hydrologically calibrated model, the degrees of freedom for additional parameter changes are restricted to those with minor effects on hydrological processes.

We explored simulated inter-annual yield fluctuations for the 20-year period of 1991–2010 for a representative winter crop, namely winter wheat (WW) *Triticum aestivum* L., and a representative summer crop, namely silage maize (SM), *Zea mays* L.. WW and SM are the main winter and summer crops grown in Germany in terms of area coverage and gross yields (Statistisches Bundesamt, 2012). We deliberately chose two crops with different growing seasons also to rationalise model performance based on the comparison between the respective simulations.

Just recently, several crop modelling studies for Germany were published (Nendel et al., 2013; Kersebaum and Nendel, 2014; Hoffmann et al., 2015; Zhao et al., 2015b; Soltani et al., 2016). These studies presented the evaluation of interannual yield variability simulations as a precondition for the assessment of, e.g., scaling issues, but, apart from Nendel et al. (2013), omitted a thorough discussion on the performance of the applied crop models at the regional scale.

Previous studies with SWIM have only peripherally addressed the performance of integrated vegetation dynamics at the regional scale and only for selected regions (Krysanova et al., 1998, 1999). Post (2006) evaluated the yield simulations of SWIM at three long-term sites in Germany. Mean yields were met quite satisfactorily but the simulation of a winter wheat long-term trial (1954–2002) revealed problems matching interannual yield variability. A number of studies used various versions of EPIC around the globe simulating mean yields and year-to-year yield variability of different crops (Kiniry et al., 1990; Rosenberg et al., 1992; Moulin and Beckie, 1993; Easterling et al., 1996; Roloff et al., 1998; Brown and Rosenberg, 1999; Izaurralde et al., 1999; Huang et al., 2006; Luo et al., 2008; Srinivasan et al., 2010). Overall, these studies agreed that EPIC is well suited to simulate mean crop yields, however, it has difficulties in replicating interannual yield variability.

The aim of our study is to provide a comprehensive and transparent evaluation of crop yield simulations for the whole territory of Germany within the framework of an eco-hydrological model, thereby establishing a reference for modelling efforts to consider crop yields and water household at the water shed scale under German conditions (food-water-nexus).

2. Data and methods

2.1. The eco-hydrological model SWIM

SWIM is a process-based, time continuous, semi-distributed watershed model which describes the impact of land use and land management on hydrological fluxes at the landscape scale in conjunction with plant growth dynamics and soil organic carbon and nitrogen turnover. It can be regarded as robust and well evaluated for hydrological conditions of German river-catchments (Krysanova et al., 1998, 1999; Hattermann et al., 2005a, b; Huang et al., 2010). SWIM integrates the heterogeneous landscape by simulating homogeneous landscape units (i.e. hydrotops) of up to several hectare sizes at which site-scale crop growth processes and yields are simulated.

2.2. The plant growth module of SWIM

The plant growth module of SWIM is essentially based on the EPIC crop model (Williams et al., 1984), similar to SWAT (Arnold et al., 1998). The main features are the description of potential plant biomass growth using the Beer's law equation (Monsi and Saeki, 1953) in conjunction with Monteith's approach (Monteith, 1977) of photosynthetic active radiation and plant specific biomass-energy conversion factors. Plant water uptake (and evaporation) is driven by the potential atmospheric demand (Ritchie, 1972). This was calculated by the Turc/Ivanov approach which was adapted for Germany following DVWK (1996) with the monthly adjustments suggested by Glugla and König (1989) and land use adjustment factors taken from ATV-DVWK (2002). Potential transpiration rates depend on the LAI and the overall atmospheric demand while actual soil water supply in the active rooting zone determines and limits actual transpiration. Daily potential biomass growth and LAI development are limited by factoring in the minimum stress factor (ranging from zero to one with one expressing no stress) of water and temperature. Water stress is the proportion of potential atmospheric demand and actual plant-available water in the rooting zone. The temperature stress factor is a function of the crop specific base and optimum temperature, and daily mean temperature (Krysanova et al., 1998). It approaches one at optimum temperature and decreases rapidly above this temperature. Yield is the product of aboveground biomass and a plant specific harvest index.

In contrast to previous SWIM applications, we slightly modified the standard crop growth calculations as described by Krysanova et al. (1998) by (i) introducing hydrotop-specific dynamic harvest dates, (ii) including a modification factor for potential plant biomass increase depending on day length and (iii) coupling phenology dynamics, i.e. leaf-area-index (LAI) with the biomass development via the plant specific leaf area and the respective biomass allocation fraction into leaves (for more details refer to S1).

2.3. Input data

The general soil map of Germany "BÜK 1000" with a resolution of 1:1 000 000 (Hartwich et al., 1995), the digital elevation model provided by the NASA Shuttle Radar Topography Mission (SRTM), the CORINE 2000 land cover map (CEC, 1995; Bossard et al., 2000), and