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Simulating the impact of flooding on wheat yield – Case study in East China

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ABSTRACT

In order to account for the waterlogging damage to crop yield, a process-based regional crop model for wheat was modified to represent surface hydrology and the waterlogging stress. Two schemes of differing complexity were investigated, the first a simple generic scheme that could be easily modified for other crops, while the second approach requires detailed field studies to measure an array of required parameters for each crop growth stage. Using simulations of wheat yield in south-east China as a test case, both waterlogging schemes can capture the yield reduction in wet years such as in 1991 and 1998. Although the more complex waterlogging scheme gives the highest correlations with observed wheat yield, the difference to the simple scheme is marginal, and much smaller than the improvement relative to the default model in which waterlogging is neglected. Thus for areas subject to intense rainfall, even adding a simple scheme can capture the zero-order impact of waterlogging and improve yield simulations significantly.

1. Introduction

Floods, and less dramatic but more frequently occurring waterlogging, can cause crop losses and large economic costs. Excessive rainfall and associated waterlogging is estimated to reduce by about 12–20% the wheat yield in southeastern China, Southern Australia, Britain, USA and other South and East Asian countries (Hu et al., 2004). According to China's statistics year book, from 1978 to 2008 China's average crop area hit by flood damage was 12.19 million hectares per year (CSY, 2009) causing great economic losses. For example the agricultural losses due to floods from 1998 to 2004 were 51.16 billion RMB/a, accounting for 0.8% of China's GDP (Huang, 2009). In China one of the highest impact events was the summer of 1998, which caused more than 30 billion dollars in economic losses (Kundzewicz and Takeuchi, 1999).

Besides the direct catastrophic effect of floods, waterlogging resulting from heavy rainfall is also an important constraint on crop production. Waterlogging occurs when soil water cannot penetrate and diffuse quickly in poorly drained soils due to excess irrigation or rainfall. Excess water damages crops both above and below ground due to oxygen depletion (Kozdroj and van Elsas, 2000) and can also result in insect infestations and plant diseases (Ashraf and urRehman, 1999). Crop yield can thus be significantly reduced under waterlogging conditions (Cannell et al., 1980; Collaku and Harrison, 2002). Watson et al. (1976) found that intermittent and continuous waterlogging of 6 weeks can result in a reduction of wheat grain yields by 40% and 53%, respectively. The damage of floods and waterlogging to agricultural production projected may even increase under future climate (McCarthy et al., 2001; Reilly et al., 2001), with the possibility of intensive precipitation increasing in some climate model projections (Kundzewicz and Schellnhuber, 2004). Recent studies have demonstrated higher and more intense precipitation increasing in some parts of the world, with Kostopoulou and Jones (2005) reporting an increase in heavy rainfall events in the central Mediterranean region, while in South Africa, Siberia, central Mexico, Japan and the northeastern part of the USA, a similar increase in heavy precipitation has been respectively reported by Easterling et al. (2000), Frauenfeld and Davis (2003) and Groisman et al. (2004, 2005).

China's climate is diverse with severe winters and hot summers in the northwest, and with monsoonal rains affecting the rest of the country (Prieler, 1999). Across China, there are floods in southern China, while droughts affect northern China, aggregating the instability of water resources. The focus of this study is wheat yield in southeastern China, since crops are frequently damaged by floods and waterlogging. Floods in 1991 resulted in a 12 billion kilogram reduction in food crop production in Anhui and

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Jiangsu provinces of southeast China (Huang and Zhou, 2002). Li and Tompkins (2012) noted that for the regions of Jiangsu, Anhui and Zhejiang provinces, located in southeast China, crops damaged by floods and waterlogging is so frequent that it leads to a negative relationship between rainfall and crop yield. This is in contrast to the north of the country, where rainfall agriculture combined with lower rainfall amounts leads to greater sensitivity to drought and a positive precipitation–yield relationship.

One of the main tools for predicting and projecting crop yields over lead times of months to decades are dynamic crop models, which attempt to explicitly represent the equations that describe the phenology of the plant growth for the crop of interest. Commonly used examples include DSSAT (Jones et al., 2003), APSIM (McCown et al., 2003), CropSyst (Stöckle et al., 2003), AquaCrop (Steduto et al., 2008), SARRAH (Sultan et al., 2005), WOFOST (Bouman et al., 1996), and the General Large Area Model for annual crops (GLAM, Challinor et al., 2004). Despite the risk of increased crop losses due to flooding and waterlogging under climate change, the impact of waterlogging is sometimes neglected in dynamic crop models. The GLAM model, used in this study, is one such example that does not presently account for such effects despite its emphasis on modeling the impact of climate on yield over regional scales. For example, the model has been used to assess the impact of warming on wheat yield at the regional level in China (Li et al., 2010) and to investigate how the temporal and spatial scales of climate variables affect the forecast skill of GLAM for rainfed wheat in China (Li and Tompkins, 2012).

When waterlogging is included, the schemes are often simple, using functions that are independent of plant growth stage. For example, in AquaCrop the root transpiration is reduced when the water content in the root zone is above a critical value, similar to the approach also used in the WOFOST/CGMS model. The WOFOST model was originally designed to assess the potential crop production at the regional level in tropical countries (van Keulen and Wolf, 1986; van Diepen et al., 1988; van Keulen and Diepen, 1990). The model also was applied to assess the impacts of climate change on crop yield (Supit et al., 2012; Alexandrov and Eitzinger, 2005) and forecast regional crop yield in European countries (de Wit et al., 2010). The waterlogging routine of WOFOST is initially described by van Diepen (Supit et al., 1994). In the WOFOST/CGMS model, the reduction factor was introduced to reduce the transpiration rate due to waterlogging when the soil moisture content is greater than a critical value for aeration, and it maximum reduction occurs after four successive days of anaerobic conditions (Supit et al., 1994). For some crops such as winter wheat, field studies have been conducted that attempt to detail the impact of waterlogging during each specific growth stage of the plant (Hu et al., 2004). The potential impact of such growth-stage specific approaches in crop yield simulations is poorly understood.

The aim of this study is to assess two methods for incorporating the impact of waterlogging implemented into GLAM crop model for wheat. The first is a simple linear scheme, while the second uses detailed field measurements to parameterize the impact as a function of plant growth stage. In the following section the data used for the study is outlined and the modifications made to the default model to include these two new waterlogging schemes into the crop model are detailed. The impact of both schemes is then tested using simulations of wheat yield over southeast China.

2. Materials and methods

2.1. The crop model

The dynamical model used in the study is the GLAM, which is a process-based, regional crop model using a daily time step for simulations of yield. The model input climate data requirements are the daily rainfall, the minimum and maximum temperature and solar radiation. The spatial scale of most dynamic crop models is generally smaller than the spatial scale of the climate model output and they often rely on detailed field-scale parameters that are difficult to obtain over regional scales. Recognizing their limitation, the general large-area model for annual crops (GLAM) has been designed to operate at the spatial scale of global and regional climate models (Challinor et al., 2004), with the motivation to address the requirement to simulate crop yields directly at a regional level. The GLAM model has been successfully used to simulate groundnut yield over large areas in India (Challinor et al., 2004) and wheat yield at a regional level in China by Li et al. (2007, 2010), who reported a good agreement between simulated and observed wheat yields in many regions. However, Li and Tompkins (2012) reported a poor performance of the model over the southeastern region of China, which they attributed to the neglect of waterlogging in the model.

The GLAM model explicitly simulates the processes of leaf canopy and root growth, biomass accumulation and ultimately crop yield in response to spatial and temporal weather and climate variability. Yield reduction due to nutrient limitation, pests, diseases and suboptimal field management is not directly modeled, but it is represented by a calibration scale factor referred to as the yield gap parameter (YGP). This is the ratio between the observed yield to the simulated potential yield, averaged over the multi-year simulation period. Note that the YGP only includes the effect of waterlogging and flooding in terms of its impact on the long-term mean yield in a region, and cannot account for year to year variability, since this would confound the main purpose of GLAM, namely to simulate explicitly the year to year variability of yield due to climate variation. Thus flooding and waterlogging requires explicit representation in the model physics and cannot be accounted for statistically using the YGP. In the experiments presented in this work, the YGP is calculated once for the default model and then this YGP is applied to all further experiments the include the new waterlogging schemes. In this way the direct impact of waterlogging on yield can be assessed and the experiments directly compared, which would not be possible if the YGP were recalculated for each experiment.

2.2. Default surface hydrology of GLAM

While GLAM is documented in Challinor et al. (2004), little previous detail has been provided for the hydrological treatment of the model. The GLAM model explicitly simulates daily soil water balance, which is used to simulate plant drought stress in the present implementation presented here. The vertical column of the soil, assumed to be 252 cm thick, is divided into 25 equal-thickness vertical layers. Precipitation P in each time step is divided into components of infiltration of water F_0 into the soil and run-off, R, which is modified in this work to improve the simulation of saturated and waterlogged conditions.

In the default GLAM model the division of precipitation into infiltration and runoff is driven by the specification of runoff (USDA-SCS, 1964; Choudhury et al., 1998):

$$R = \frac{P^2}{P + K_{sat}} \tag{1}$$

where R is the runoff, P is the precipitation and K_{sat} is the saturated hydraulic conductivity of soil. According to Suleiman (1999), the factor K_{sat} is defined

$$K_{sat} = K_{ks} \times \left(\frac{\theta_{sat} - \theta_{dul}}{\theta_{dul}} \right)^2 \tag{2}$$