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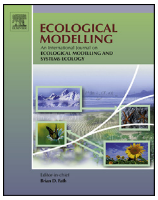

Assimilating remote sensing information into a coupled hydrology-crop growth model to estimate regional maize yield in arid regions

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ABSTRACT

Regional crop yield prediction is a significant component of national food policy making and security assessments. A data assimilation method that combines crop growth models with remotely sensed data has been proven to be the most effective method for regional yield estimates. This paper describes an assimilation method that integrates a time series of leaf area index (LAI) retrieved from ETM+ data and a coupled hydrology-crop growth model which links a crop growth model World Food Study (WOFOST) and a hydrology model HYDRUS-1D for regional maize yield estimates using the ensemble Kalman filter (EnKF). The coupled hydrology-crop growth model was calibrated and validated using field data to ensure that the model accurately simulated associated state variables and maize growing processes. To identify the parameters that most affected model output, an extended Fourier amplitude sensitivity test (EFAST) was applied to the model before calibration. The calibration results indicated that the coupled hydrology-crop growth model accurately simulated maize growth processes for the local cultivation variety tested. The coefficient of variations (CVs) for LAI, total above-ground production (TAGP), dry weight of storage organs (WSO), and evapotranspiration (ET) were 13%, 6.9%, 11% and 20%, respectively. The calibrated growth model was then combined with the regional ETM+ LAI data using a sequential data assimilation algorithm (EnKF) to incorporate spatial heterogeneity in maize growth into the coupled hydrology-crop growth model. The theoretical LAI profile for the near future and the final yield were obtained through the EnKF algorithm for 50 sample plots. The CV of the regional yield estimates for these sample plots was 8.7%. Finally, the maize yield distribution for the Zhangye Oasis was obtained as a case study. In general, this research and associated model could be used to evaluate the impacts of irrigation, fertilizer and field management on crop yield at a regional scale.

1. Introduction

Crop growth and yield data are critical for informing national food security and agricultural operation and management. A range of factors, including increasingly augmented populations, reduced cropland acreage and water resources, environmental deterioration, and global climate change, significantly affect agricultural production and threaten food security. Therefore, accurate regional crop growth monitoring and yield prediction are vital for the sustainable development of agriculture. In the past decades, crop growth monitoring and crop yield predictions have moved away from conventional techniques, such as agro-meteorological model forecasting and the establishment of relationships between remote sensing spectral vegetation indexes and field measurements, in favour of more integrated approaches (e.g. Dente et al., 2008; de Wit et al., 2012; Fang et al., 2011; Liang and Qin, 2008; Ma et al., 2013; Xu et al., 2011). For instance, operational systems for regional crop monitoring and yield forecasting now usually rely on an integrated analysis of weather data, crop simulation model results and satellite observations.

Using the biophysical principles of plant growth, crop growth models can provide detailed estimates of crop states, including phenological status, leaf area index (LAI) and yield for specific crop types. The most commonly used crop growth model, WOFOST,

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has been applied to evaluations of production potential, optimized crop management, and yield gap quantification for various crops (Van Laar et al., 1997; Bouman et al., 2001; Wolf, 2002) in addition to studies of the effects of environmental variability and climatic change on crop production (Kropff et al., 1996; ten Berge et al., 1997; Tsuji et al., 1998; Matthews and Stephens, 2002). However, in WOFOST, the soil water balance is calculated using a "tipping bucket" approach within three compartments (i.e. a root zone, a transmission zone, and a groundwater zone) under water-limited conditions. This approach oversimplifies simulations of the hydrologic cycle in crop growth models (Eitzinger et al., 2004; Priesack et al., 2006). In reality, variation in available soil moisture is a main driver of variation in crop yield (Rodriguez-Iturbe et al., 2001; Shepherd et al., 2002; Anwar et al., 2003; Patil and Sheelavantar, 2004), and accurate estimates of soil moisture are critical for understanding crop status and yield. To enhance the ability of the WOFOST model to simulate the hydrologic cycle, model coupling is needed. Linkages between models have recently received attention from researchers. For example, Casanova and Judge (2008) coupled a land surface process (LSP) model with a widely used crop-growth model (DSSAT) to estimate energy and moisture fluxes in dynamic vegetation. Maruyama and Kuwagata (2010) linked land surface and crop growth models to estimate the effects of growing season changes on the energy balance and water use in rice paddies. Van den Hoof et al. (2011) coupled the Land Environment Simulator (JULES) and a crop-growth model (SUCROS) to evaluate the hydrological cycle and vegetation effects on energy, water, and carbon fluxes.

Crop models are very useful in evaluating crop growth and yield at the field scale, but their implementation at a regional scale is restricted by input data availability at the corresponding scale, which results in models that may not produce results with adequate accuracy for practical applications (Chipnashi et al., 1999; Moulin and Guerif, 1999; Mignolet et al., 2007). To overcome the difficulties inherent to these modelling approaches, the integration of remote sensing observations and crop growth models has been recognized as an important approach for monitoring crop growth conditions and estimating yield at a regional scale (Dente et al., 2008; de Wit et al., 2012; Fang et al., 2011; Liang and Qin, 2008; Ma et al., 2012; Xu et al., 2011). In recent years, extensive efforts have been made to integrate crop growth models with remote sensing information based on the "assimilation strategy" (Chen et al., 2012; Revill et al., 2013). Satellite data can provide a synoptic overview of actual growing conditions and can be used to diagnose discrepancies from normal conditions. For example, a Normalized Difference Vegetation Index (NDVI; Rouse and Haas, 1973) profile of the current year could be compared to the average historic profile for a given crop (Kogan, 1998; Liu and Kogan, 2002). Moreover, satellite data can be used to complement crop model simulation results by including, for example, the impacts of fire, frost, or drought during sensitive crop stages.

In general, the integration of remote sensing observations and crop growth models is often achieved through data assimilation. There are two basic strategies for data assimilation: (1) recalibration/re-initialization methods and (2) sequential assimilation algorithms, such as the EnKF. The recalibration/re-initialization approach commonly uses optimization algorithms to re-initialize or re-parameterize a crop growth model by adjusting initial conditions or input parameters to minimize the merit function between remotely sensed biophysical parameters and simulated parameters (Dente et al., 2008; Fang et al., 2011; Ma et al., 2013). However, this method cannot incorporate dynamic changes, such as state variable updates or dynamic crop growth simulations. For sequential assimilation algorithms, a primary assumption is that improvements in a state variable made in the previous step can enhance the estimation accuracy in the next step. Because this approach can combine many types of observations taken at discrete time steps, the state variables can be continually updated and more accurately simulated. In particular, the EnKF, which is a sequence filter algorithm that combines a probabilistic approach with sequential data assimilation, can account for sequential uncertainty in remotely sensed observations (Curnel et al., 2011; Dorigo et al., 2007; Quaife et al., 2008) and nonlinear structural characteristics in crop growth models (de Wit and Van Diepen, 2007; Vazifedoust et al., 2009). Several EnKF assimilation schemes with different degrees of complexity and integration have been developed and evaluated during the last decade (Curnel et al., 2011; de Wit and Van Diepen, 2007; Vazifedoust et al., 2009; Jin et al., 2010).

In this study, we present a novel method for estimating regional maize yield that assimilates LAI values derived from remote sensing imagery into a coupled hydrology-crop growth model (which links the WOFOST and HYDRUS models) using an EnKF. This method can ultimately be used to estimate crop yields at a regional scale.

2. Material and methods

2.1. Study area

We applied our coupled model to the agricultural system in the Zhangye Oasis (Fig. 1), an arid region in the middle reaches of the Heihe River basin, northwest China. This area has a typical temperate continental climate, with mean annual precipitation and potential evaporation ranging from 60 to 280 mm and 1000 to 2000 mm, respectively. This agricultural system, which primarily cultivates maize and wheat, employs a highly developed irrigation system that was constructed in the last few decades. The main water resource for irrigation in this area originates from the Heihe River and the groundwater.

2.2. Observation data

In 2008, the Watershed Allied Telemetry Experimental Research (WATER) program (Li et al., 2009), part of the Chinese Academy of Sciences' Action Plan for Western Development, was applied to this region to study the ecological and hydrological processes of agricultural systems (methodological information for this program can be found at http://westdc.westgis.ac.cn/data). The primary biophysical, biochemical, meteorological and hydrological parameters used in our study were obtained through this program, predominantly from the Yingke station (38°51′N, 100°25′ E, altitude 1519 m a.s.l.). Research at this agro-ecological station focused on eco-hydrological processes during maize growth periods and provided data (interval: 30 min) on regional meteorology, physical soil properties, and soil moisture dynamics. Meteorological data included net radiation, solar radiation, maximum air temperature, minimum air temperature, precipitation, wind speed, atmospheric pressure, and relative humidity.

The status of maize was intensively monitored throughout its entire growth period, which lasted from April 20, 2008 through September 22, 2008. The sowing date, emergence date and harvest date were April 20, May 6, and September 22, respectively. Data on LAI were measured once every 15 days using a LAI-2000 Plant Canopy Analyzer (LI-COR Inc., Lincoln, NE, USA). The dry weight of storage organs (WSO), dry weight of total above-ground biomass (TAGP) and crop height were sampled every 15 days during crop growth. Data on latent flux were measured by an eddy covariance system (EC) (Li7500 & CSAT3, Cambell Scientific, USA) that was installed here for long-term use at a height of 2.85 m. The correction of EC data was produced with revised EdiRE software from the University of Edinburgh (Xu et al., 2008). Nitrogen (329 kg ha^{-1}),