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Research paper

Improving maize growth processes in the community land model: Implementation and evaluation

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ABSTRACT

Earth system models (ESMs) are essential tools to study the impacts of historical and future climate on regional and global food production, as well as to assess the effectiveness of possible adaptations and their potential feedback to climate. Several current ESMs have the capabilities to simulate crop growth. However, some critical crop growth processes (e.g. flowering and other reproductive processes) and their responses to environmental extremes (e.g. heat stress) are not yet represented in most of these models. In this paper, an improved maize growth model was implemented in the Community Land Model version 4.5 (CLM4.5) by modifying the maize planting scheme, incorporating the phenology scheme adopted from the APSIM model (Agricultural Production Systems sIMulator), adding a new carbon allocation scheme into CLM4.5, and improving the estimation of canopy structure parameters including leaf area index (LAI) and canopy height. Unique features of the new model (CLM-APSIM) include more detailed phenology stages, an explicit implementation of the impacts of various abiotic environmental stresses (including nitrogen, water, temperature and heat stresses) on maize phenology and carbon allocation, as well as an explicit simulation of grain number. Evaluation of results at 7 AmeriFlux sites located in the US Corn Belt show that the CLM-APSIM model performs better than the original CLM4.5 in simulating phenology (LAI and canopy height), surface fluxes including gross primary production (GPP), net ecosystem exchange (NEE), latent heat (LH), and sensible heat (SH), and especially in simulating the biomass partition and maize yield. The CLM-APSIM model corrects a serious deficiency in CLM4.5-related to CLM4.5's underestimation of aboveground biomass (i.e. overestimation of belowground biomass) and overestimation of Harvest Index, which lead to a reasonable yield estimation with wrong mechanisms. Moreover, 13-year simulation results from 2001 to 2013 at the three Mead sites (US-Ne1, Ne2 and Ne3) show that the CLM-APSIM model can more accurately reproduce maize yield responses to growing season climate (temperature and precipitation) than the original CLM4.5 when benchmarked with the site-based observations and USDA county-level survey statistics. The CLM-APSIM model is thus more suitable than its predecessor models in terms of simulating abiotic environmental stresses on maize yield. This new model provides an improved tool to attribute maize yield change to various processes under historical and future climate, as well as to assess and design effective climate adaptation strategies for sustainable agricultural production.

1. Introduction

Global food security is under continuing pressure from increased population and climate change (Rosenzweig et al., 2014). Maize (*Zea mays* L.) is the most important staple food and feed crop in the world according to the total production. The Midwest Corn Belt of the United States produces more than 45% of global maize production. However, maize yield in this area is projected to decrease with increasing vapor

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Table 1
Strengths and weaknesses of CLM4.5 and APSIM models in crop growth simulation.

Model	Strength	Weakness
CLM4.5	• Sophisticated soil and canopy hydrology • Two-stream approximation of canopy radiative transfer • Physical-based stomatal conductance, photosynthesis, and respiration • Explicit calculation of energy balance and canopy temperature • More process-driven CO_2 fertilization effects • Can be coupled in climate model (CESM)	• Missing critical crop phenology stages (e.g. flowering) and reproductive processes (e.g. grain number formation) • Lack of stage-dependent stress simulation • Linear accumulation of thermal time
APSIM	• More detailed crop phenology stages • Stage-dependent stress simulation • Piece-wise linear response of thermal time • More detailed management practices	• RUE-based calculation of NPP and no explicit simulation of photosynthesis and respiration • Lack of resolving energy balance • Simplified soil hydrology

pressure deficit (VPD) (Lobell et al., 2014), droughts (Ort and Long 2014; Lobell et al., 2014) and extreme high temperatures (Schlenker and Roberts 2009) under climate change. For example, previous empirical studies have shown that maize yield would be suppressed sharply when exposed to higher temperature (Schauberger et al., 2017; Schlenker and Roberts 2009). However, the yield-to-temperature relationship is an integral of the effects from several temperature-sensitive processes on crop growth and development (Lobell et al., 2013). Therefore, parsing the overall temperature effects to crop yield into different processes is of great value to understand and potentially mitigate the climate change impact on the global food production (Peng et al., 2016).

Process-based models are major tools to study the impacts of historical and future climate on regional and global food production, to assess the effectiveness of possible adaptations and their potential feedback to climate and to attribute different pathways through which climate can impact crop yields. There are two main classes of process-based crop models currently used to study crop responses to climate: (1) agronomy crop models and (2) crop models in the framework of earth system models (ESMs) (see Table 1 for an example of the differences in specific models from these two classes). Agronomy crop models have been developed by agronomists to simulate field-level crop growth and yield. Widely used agronomy crop models include APSIM (Agricultural Production Systems sIMulator) (Keating et al., 2003; Holzworth et al., 2014), DSSAT (Decision Support System for Agrotechnology Transfer) (Jones et al., 2003), EPIC (Erosion Productivity Impact Calculator or Environmental Policy Integrated Climate) (Williams et al., 1989), Hybrid-Maize (Yang et al., 2017; Yang et al., 2004), CropSyst (cropping systems simulator) (Stöckle et al., 2003; Stöckle et al., 2014), etc. They usually include detailed phenology development schemes with many explicit stress terms and field management schemes. However, most of these models use empirical light use efficiency (LUE) or radiation use efficiency (RUE) to simulate the net primary production (NPP), which lumps the photosynthesis and respiration processes together. Thus, in these models, acclimation to temperature for both photosynthesis and respiration and processes related to CO_2 fertilization effect are not mechanistically simulated. Moreover, most agronomy crop models do not solve the energy balance at the soil-crop-atmosphere interface. Consequently, soil and leaf temperatures are not explicitly simulated; instead, they use air temperature to drive crop phenology development and to quantify heat stress effects on crop growth and yield. As recent studies have recognized the importance of canopy temperature in assessing heat stress impact on crop yield (Stefan et al., 2014; Levis 2014; Webber et al., 2015), the lack of simulated soil and leaf temperature in agronomy crop models significantly limits their utility for assessing and attributing crop yield responses under climate change. Furthermore, agronomy crop models do not fully simulate the surface flux exchanges at sub-daily time scale and are not coupled with climate models or earth system models. Therefore they cannot be utilized to assess the feedback impact of agriculture management on the broader climate system.

In contrast, crop models that are embedded in the land surface models (LSMs), the land component of ESMs, numerically and explicitly solve the surface water, energy and carbon balances, and are ready to run synchronously coupled to ESMs to simulate the two-way feedbacks between climate and agricultural systems. Simple crop models and basic management practices were introduced into LSMs/ESMs relatively recently (Kucharik 2003; Levis et al., 2012; Drewniak et al., 2013; Osborne et al., 2015; Liu et al., 2016; Song et al., 2013). However, the crop phenology representations in these LSM-based crop models tend to be much simpler than in the agronomy crop models, and the phenology-stage-dependent stresses in ESM crop models are largely missing. Due to these drawbacks, current ESM crop models tend to perform not as well in simulating energy and carbon fluxes in agricultural ecosystems as in other ecosystems (Lokupitiya et al., 2016), nor have similar performance in simulating crop yield as agronomy crop models. Thus, combining the strengths of both agronomy crop models and ESM crop models can provide a direct and promising way to improve crop modeling capabilities to study climate change impacts on crop yield and the potential feedbacks.

The Community Land Model (CLM) (Oleson et al., 2013; Lawrence et al., 2011) is the land component of Community Earth System Model (CESM) (Hurrell et al., 2013). The original parameterization scheme for cropping system management in CLM (Levis et al., 2012; Drewniak et al., 2013) is a heritage of the Agro-IBIS ecosystem model (Kucharik 2003). The maize phenology in CLM is simulated through a 3-phase algorithm (see section 2.1 for more detail) adopted from Agro-IBIS, which is a significant simplification of the real maize growth stages. Previous studies found that the crop phenology scheme is critical for accurate simulation of the agriculture ecosystem carbon exchange, and that the original maize module in CLM4.0 overestimates the leaf area index (LAI) and gross primary production (GPP) in the early growing season due to earlier estimation of leaf emergence (Chen et al., 2015). In addition, except for water and nitrogen stresses on photosynthetic capability, no other stresses are considered in the maize module of CLM. In particular, the high temperature and drought stresses on phenological development and the reproductive processes are not captured in current CLM and these processes have been found to have large impacts on maize yield and the simulation of future maize production (Deryng et al., 2014).

Among many agronomy crop models, APSIM model (Keating et al., 2003; Brown et al., 2014; Holzworth et al., 2014; McCown et al., 1996) is one of the most widely used and also one of the most advanced agronomy crop models, with the capability to simulate growth and yield for a range of crop types including maize. The maize module in APSIM (APSIM-Maize) was developed from a combination of the approaches used in two derivatives of CERES-Maize model (Jones et al., 1986): the CM-KEN (CERES-Maize adapted in Kenya) (Keating and Wafula 1992) and CM-SAT (CERES-Maize for semi-arid tropical environment) (Carberry et al., 1989), with some additional features (such as the modified nonlinear response of thermal time to temperature) from the maize model of Wilson et al. (1995). In recent years, the APSIM crop model has been widely used in the United States (Archontoulis et al., 2014; Jin et al., 2017; Jin et al., 2016b; Jin et al.,