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Comparing crop growth and carbon budgets simulated across AmeriFlux agricultural sites using the Community Land Model (CLM)

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A B S T R A C T

Improvement of process-based crop models is needed to achieve high fidelity forecasts of regional energy, water, and carbon exchanges. However, most state-of-the-art Land Surface Models (LSMs) assessed in the fifth phase of the Coupled Model Inter-comparison project (CMIP5) simulated crops as unmanaged C_3 or C_4 grasses. This study evaluated the crop-enabled version of one of the most widely used LSMs, the Community Land Model (CLM4-Crop), for simulating corn and soybean agro-ecosystems at relatively long-time scales (up to 11 years) using 54 site-years of data. We found that CLM4-Crop had a biased phenology during the early growing season and that carbon emissions from corn and soybean were underestimated. The model adopts universal physiological parameters for all crop types neglecting the fact that different crops have different specific leaf area, leaf nitrogen content and vcmax25, etc. As a result, model performance varied considerably according to crop type. Overall, the energy and carbon exchange of corn systems were better simulated than soybean systems. Long-term simulations at multiple sites showed that gross primary production (GPP) was consistently over-estimated at soybean sites leading to very large short and long-term biases. A modified model, CLM4-CropM', with optimized phenology and calibrated crop physiological parameters yielded significantly better simulations of gross primary production (GPP), ecosystem respiration (ER) and leaf area index (LAI) at both short (hourly) and long-term (annual to decadal) timescales for both soybean and corn.

1. Introduction

Land surface models (LSMs) serve as important tools for studying the interactions between the atmosphere and ecosystems, understanding biophysical feedback processes, and predicting future climate. Most state-of-the-art LSMs assessed in the fifth phase of the Coupled Model Inter-comparison project (CMIP5), however, did not include process-based crop models with comprehensive physiology and phenology. The first attempt to incorporate explicit crop simulations into a land surface model was made early this century by Tsvetsinskaya et al. (2001), in which the Biosphere-Atmosphere Transfer Scheme (BATS) was modified to include plant growth functions for corn. The modified model showed improved simulation of seasonal phenology and significant changes in surface sensible (20%–35%) and latent (30%–45%) heat fluxes, especially during dry years in central and eastern Nebraska and eastern Kansas. Since then, the development and evaluation of land surface models (LSMs) with prognostic agricultural schemes became an active and important topic of inquiry (Tsvetsinskaya et al., 2001; Kucharik, 2003; Bondeau et al., 2007; Osborne et al., 2007; Stehfest et al., 2007; Gervois et al., 2008; Lokupitiya et al., 2009; Levis et al., 2012; Song et al., 2013; Wu et al., 2015; Chen et al., 2015).

Kucharik and Brye (2003) incorporated phenology, carbon allocation, and a corn-specific parameterization into the Integrated Biosphere Simulator (IBIS). The model was further developed to include other crops such as soybean, winter and spring wheat and was renamed Agro-IBIS. Its ability to simulate crop yields, water and energy balances, and impacts of climate change on agro-ecosystems in the United States were investigated at multiple sites and scales (Donner and Kucharik, 2003; Kucharik and Twine, 2007; Kucharik, 2003; Twine et al., 2013, 2004; Twine and Kucharik, 2009; Webler et al., 2012; Xu et al., 2016).

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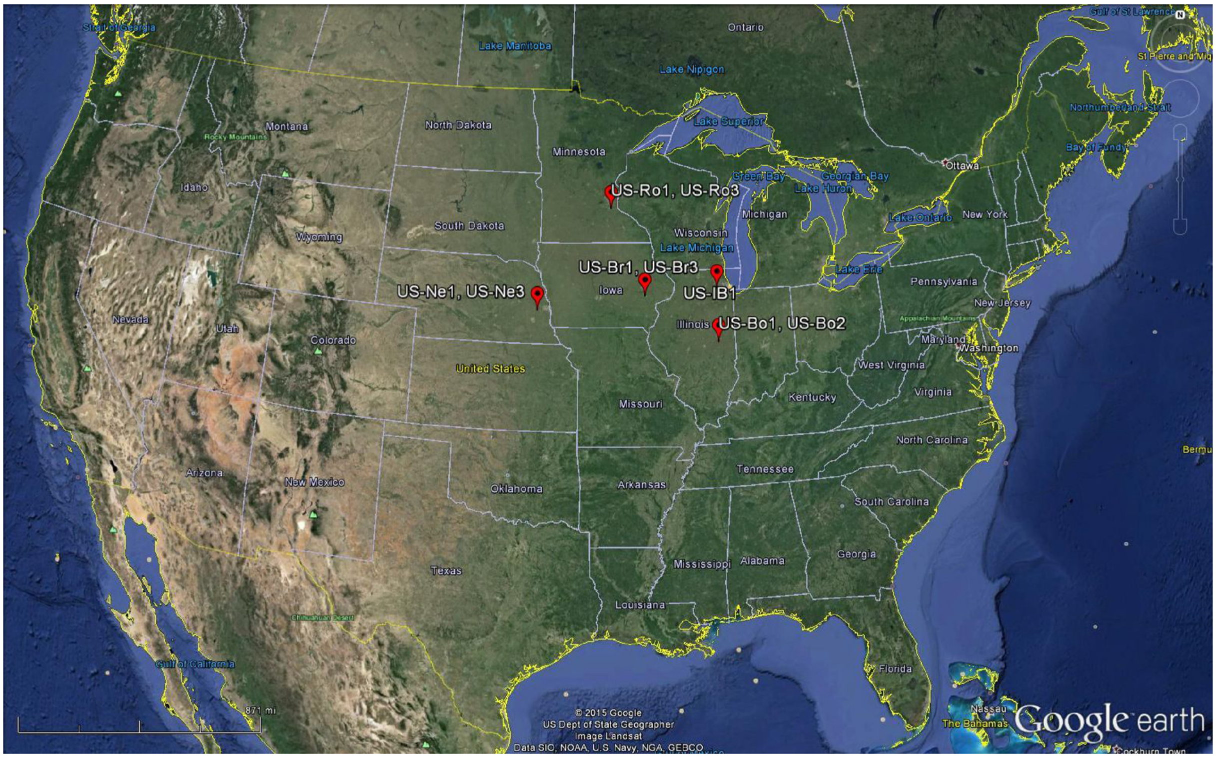

Fig. 1. Nine AmeriFlux crop sites within the US Corn Belt.

Recently, the Community Land Model (CLM), which is the land component of the widely used Community Earth System Model (CESM) (Oleson et al., 2010) adopted the prognostic crop scheme from Agro-IBIS into CLM (called CLM4-Crop). CLM4-Crop has the potential to provide better spatial and temporal information on climate-crop interactions and improved weather and climate prediction (Levis et al., 2012). For example, when CLM4-Crop was coupled to an atmospheric model (i.e. the Community Atmosphere Model, version 4 [CAM4.0] (Neale et al., 2010)), forecasted precipitation during the peak growing season was significantly improved over Midwestern North America. However, recent efforts have examined the phenology and the seasonality of net ecosystem CO_2 exchange (NEE) related to cropping systems over multiple years at three AmeriFlux sites and demonstrated high sensitivity of energy balance and carbon simulations to biases in phenology (Levis et al., 2012; Chen et al., 2015). Further improvements in CLM4-Crop to advance its carbon forecast capability are therefore urgently needed.

While LSMs that incorporate prognostic crop schemes are important for achieving realistic simulations of weather and climate and increasing our capacity to develop sound policies regarding the impacts of climate change on agricultural systems and the potential impacts of land management on climate (Levis et al., 2012), few studies have quantified the accuracy of the simulations at multiple sites and over relatively long time scales (> 10 years). Factors like plant biophysical properties, soil properties and climate vary considerably among sites (Fulton et al., 1996; Mzuku et al., 2005; Loescher et al., 2014; Mourtzinis et al., 2015). An important consideration, therefore, is the evaluation of these models across a broad range of sites to determine if the parameterizations are sufficiently general, while also providing acceptable performance across space and time. Evaluation of models over relatively long timescales can be used to help identify model deficiencies. For example, the ability of models to capture long-term variations in plant phenology and energy and carbon fluxes remains an important challenge (Piao et al., 2013; Richardson et al., 2007; Schwalm et al., 2010; Wang et al., 2012). Depending on the inter-annual variation of climate, it is suggested that 10–20 years of meteorological forcing data are generally necessary for reliable estimates of mean yield potential of crops and its inter-annual variability (Van Wart et al., 2015). Flux observations from networks such as AmeriFlux are just now providing long-term records approaching these important timescales and provide an opportunity for decadal-scale model assessment.

Here, we examine the performance of two versions of CLM4-Crop (CLM4-Crop and CLM4-CropM) at 9 agricultural sites with a focus on the ability of the model to capture seasonal and inter-annual variations in leaf area index (LAI), NEE, ER, and GPP. We use a total of 54 site-years of data to diagnose some of the key model deficiencies in CLM4-Crop and address the following questions:

1 Is the new phenology scheme able to simulate inter-annual variations in early growing season crop phenology at multiple sites across a climate gradient?
2 Are biases in simulated phenology across sites random, or are there systematic deficiencies that can be addressed with model calibration?
3 How well do the models perform under different climate conditions and does the new phenology scheme improve simulations for certain climate conditions?
4 Do the models adequately capture the long-term (> 10 years) dynamics of NEE for cropland?

2. Methods

2.1. Meteorology and biological data

The models were evaluated at nine AmeriFlux sites in the US Corn Belt located within latitude and longitude ranges of 40–45 °N and 88–97 °W, respectively (Fig. 1). These sites represent cropland systems in the northern (US-Ro1, US-Ro3), western (US-Ne1, US-Ne3), southern (US-Bo1, US-Bo2) and central (US-IB1, US-Br1, US-Br3) US Corn Belt. Climate and cropping information for these sites are provided in Table 1.