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Uncertainty in simulating gross primary production of cropland ecosystem from satellite-based models

Wenping Yuan[a], Wenwen Cai[a], Anthony L. Nguy-Robertson[b], Huajun Fang[d],*, Andrew E. Suyker[b], Yang Chen[a], Wenjie Dong[a], Shuguang Liu[c], Haicheng Zhang[a]

[a] State Key Laboratory of Earth Surface Processes and Resource Ecology, Beijing Normal University, Beijing 100875, China
[b] School of Natural Resources, University of Nebraska, Lincoln, NE 68583-0978, USA
[c] State Engineering Laboratory of Southern Forestry Applied Ecology and Technology, Central South University of Forestry and Technology, Changsha, Hunan 410004, China
[d] Key Laboratory of Ecosystem Network Observation and Modeling, Institute of Geographical Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing 100101, China

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ABSTRACT

Accurate estimates of gross primary production (GPP) for croplands are needed to assess carbon cycle and crop yield. Satellite-based models have been developed to monitor spatial and temporal GPP patterns. However, there are still large uncertainties in estimating cropland GPP. This study compares three light use efficiency (LUE) models (MODIS-GPP, EC-LUE, and VPM) with eddy-covariance measurements at three adjacent AmeriFlux crop sites located near Mead, Nebraska, USA. These sites have different crop-rotation systems (continuous maize vs. maize and soybean rotated annually) and water management practices (irrigation vs. rainfed). The results reveal several major uncertainties in estimating GPP which need to be sufficiently considered in future model improvements. Firstly, the C4 crop species (maize) shows a larger photosynthetic capacity compared to the C3 species (soybean). LUE models need to use different model parameters (i.e., maximal light use efficiency) for C3 and C4 crop species, and thus, it is necessary to have accurate species-distribution products in order to determine regional and global estimates of GPP. Secondly, the 1 km sized MODIS fPAR and EVI products, which are used to remotely identify the fraction of photosynthetically active radiation absorbed by the vegetation canopy, may not accurately reflect differences in phenology between maize and soybean. Such errors will propagate in the GPP model, reducing estimation accuracy. Thirdly, the water-stress variables in the remote sensing models do not fully characterize the impacts of water availability on vegetation production. This analysis highlights the need to improve LUE models with regard to model parameters, vegetation indices, and water-stress inputs.

1. Introduction

Approximately, 12% of Earth's ice-free land surface is cultivated cropland (Wood et al., 2000) and up to 33% and 20% of this land surface in Europe and the United States, respectively, is arable (Ramankutty et al., 2008). Crop gross primary production (GPP) contributes approximately 15% of global carbon dioxide fixation (Malmstrom et al., 1997). There is broad agreement that global crop vegetation production is and will be significantly affected by climate change (Parry et al., 2004; Schmidhuber and Tubiello, 2007; Wheeler and von Braun, 2013). Therefore, crop vegetation production monitoring and forecasting are important for agricultural management (Mulla, 2013), food security (Meroni et al., 2014), yield estimates (Ines et al., 2013) and carbon cycle research (Gitelson et al., 2014; Li et al., 2014).

Numerous approaches have been developed to model vegetation primary production in various cropping systems (Li et al., 2013; Cai et al., 2014). Monteith (1972, 1977) remarked that throughout a wide range of crops and environmental conditions, the ratio of absorbed light to carbon assimilation over the growing season is relatively constant. Then a production efficiency model that estimated crop growth from absorbed photosynthetically active radiation (APAR) and maximal light use efficiency (LUE_{max}) was introduced (Running et al., 2004). Subsequent studies further improved the model by expressing LUE_{max} as a function of one or more factors: light climate, temperature, water, and nutrient stress (Gamon et al., 1997; Xiao et al., 2004; Suyker and Verma, 2012).

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* Corresponding author.
E-mail addresses: yuanwpcn@126.com (W. Yuan), fanghj@igsnrr.ac.cn (H. Fang).

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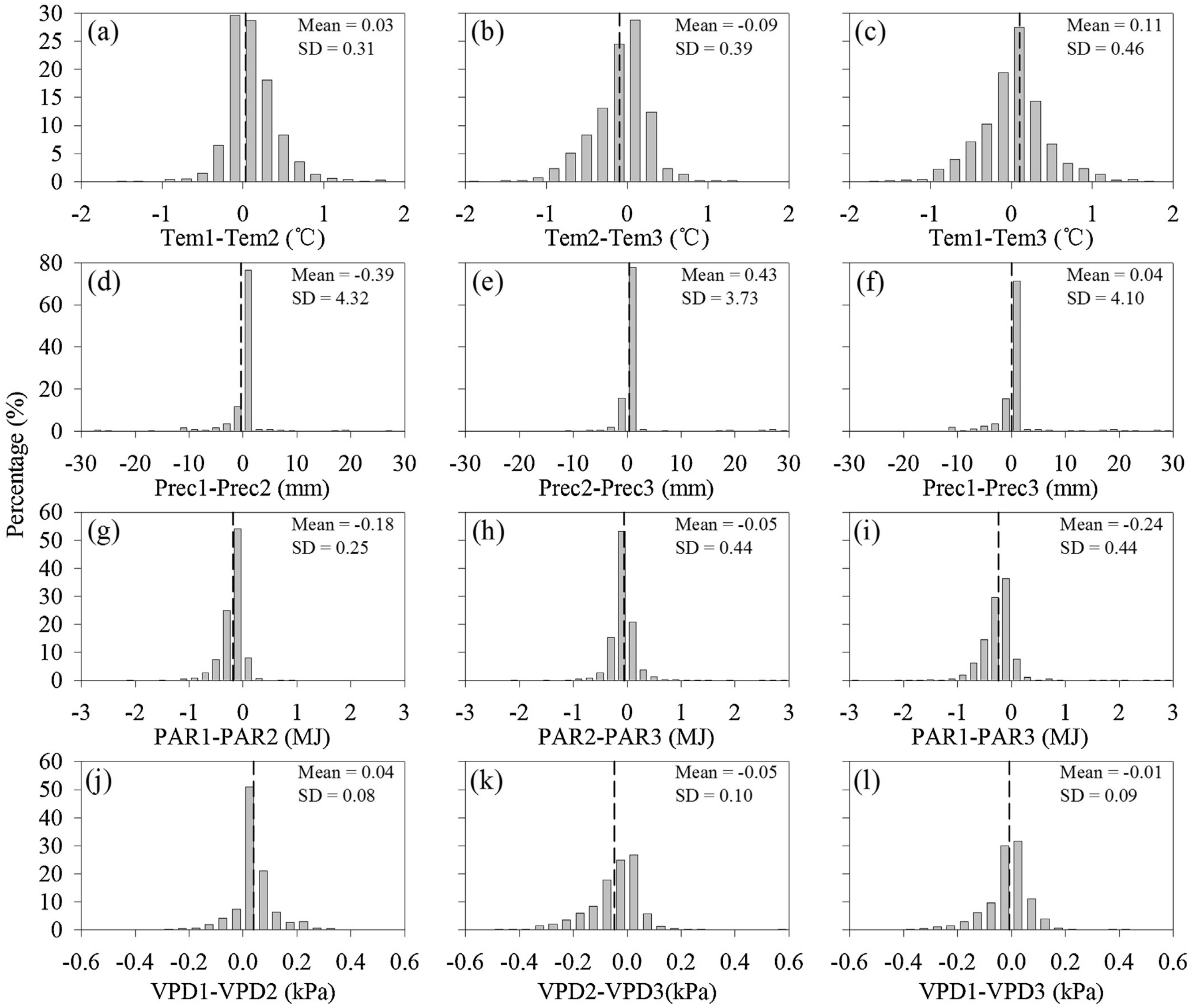

Fig. 1. Histogram of daily difference of four climate variables among three sites. Tem, Prec, PAR and VPD indicate air temperature, precipitation, photosynthetically active radiation and vapor pressure deficit, respectively. The numbers in the *x*-axis label represent the site, and 1–3 represent US-NE1, US-NE2 and US-NE3, respectively. Mean and SD in the figures indicate the mean value and standard deviation of differences through all days.

However, global and regional NPP or GPP estimates of cropland ecosystems still have large uncertainties among different methods (Cramer et al., 1999). For example, carbon balance studies of European croplands have found that cropland net primary production (NPP) estimates range from 490 to 846 g C m^{-2} year^{-1} using various methods (Ciais et al., 2010). Accurate estimates of vegetation production are critical as they are inputs into other models (i.e., crop yield) and can reduce the accuracy of these models. For example, crop yield estimates based on MODIS GPP data collected over the Midwestern United states were underestimated due to the absence of including the impact of irrigation (Xin et al., 2013). Even small biases in GPP models can accumulate in long-term studies and this can lead to erroneous conclusions in forecasting climate change (Richardson et al., 2012).

The goal of this study is to determine uncertainties in estimating vegetation production from MODIS imagery acquired over cropland ecosystems. These estimates will be compared with 4 years of continuous eddy covariance (EC) measurements from three AmeriFlux sites located in Nebraska, U.S.A. The specific objectives were to determine the accuracy of light use efficiency models in estimating vegetation production by (a) crop type, maize vs. soybean, (b) water management practices, irrigated vs. rainfed, and (c) model approaches, MODIS-GPP vs. EC-LUE vs. VPM.

2. Models and data

2.1. Study sites and eddy flux measurements

In this study, three adjacent AmeriFlux eddy covariance towers were selected, which were located within 1.6 km of each other at the University of Nebraska-Lincoln Agricultural Research and Development Center near Mead, Nebraska, USA. They have similar climatic conditions (Fig. 1). US-Ne1 (41.1651°N, 96.4766°W) was planted as continuous maize and was equipped with a center pivot irrigation system. US-Ne2 (41.1649°N, 96.4701°W) and US-Ne3 (41.1797°N, 96.4397°W) were both planted as a maize–soybean rotation, with maize planted in odd years. Similar to US-Ne1, US-Ne2 was irrigated using center-pivot irrigation. US-Ne3 relied entirely on rainfall for moisture. The soil characterize in these three sites is very similar (Table 1). More details about the crop manage-