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Multi-scale evaluation of light use efficiency in MODIS gross primary productivity for croplands in the Midwestern United States

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ABSTRACT

Satellite remote sensing provides continuous observations of land surfaces, thereby offering opportunities for large-scale monitoring of terrestrial productivity. Production Efficiency Models (PEMs) have been widely used in satellite-based studies to simulate carbon exchanges between the atmosphere and ecosystems. However, model parameterization of the maximum light use efficiency (ε^*_{GPP}) varies considerably for croplands in agricultural studies at different scales. In this study, we evaluate cropland ε^*_{GPP} in the MODIS Gross Primary Productivity (GPP) model (MOD17) using in situ measurements and inventory datasets across the Midwestern US. The site-scale calibration using 28 site-years tower measurements derives ε^*_{GPP} values of 2.78 ± 0.48 gC MJ^{-1} (± standard deviation) for corn and 1.64 ± 0.23 gC MJ^{-1} for soybean. The calibrated models could account for approximately 60–80% of the variances of tower-based GPP. The regional-scale study using 4-year agricultural inventory data suggests comparable ε^*_{GPP} values of 2.48 ± 0.65 gC MJ^{-1} for corn and 1.18 ± 0.29 gC MJ^{-1} for soybean. Annual GPP derived from inventory data (1848.4 ± 298.1 gC m^{-2} y^{-1} for corn and 908.9 ± 166.3 gC m^{-2} y^{-1} for soybean) are consistent with modeled GPP (1887.8 ± 229.8 gC m^{-2} y^{-1} for corn and 849.1 ± 122.2 gC m^{-2} y^{-1} for soybean). Our results are in line with recent studies and imply that cropland GPP is largely underestimated in the MODIS GPP products for the Midwestern US. Our findings indicate that model parameters (primarily ε^*_{GPP}) should be carefully recalibrated for regional studies and field-derived ε^*_{GPP} can be consistently applied to large-scale modeling as we did here for the Midwestern US.

1. Introduction

Characterization of the spatial and temporal patterns in terrestrial gross primary production (GPP) and net primary production (NPP) is essential to understand and quantify the carbon exchange between the atmosphere and terrestrial ecosystems (Beer et al., 2010; Lobell et al., 2002). Satellite remote sensing provides spatially continuous and temporally repetitive observations of land surfaces, and has become increasingly important for monitoring vegetation photosynthetic activities over large geographic regions. In satellite-based studies, Production Efficiency Models (PEMs) have been widely employed to estimate terrestrial productivity (Field et al., 1995; Goetz et al., 1999; Gower et al., 2001; Potter et al., 1993; Prince and Goward, 1995; Running et al., 2000, 2004).

The underlying theory behind a variety of PEMs is that vegetation GPP/NPP is linearly related to the amount of photosynthetically active radiation (PAR) absorbed by the canopy:

$$GPP = \varepsilon^*_{GPP} \times f(\varepsilon) \times PAR \times FPAR \quad (1)$$

where the ε^*_{GPP} (gC MJ^{-1}) value for the GPP calculation is the maximum light use efficiency (LUE) when the environment is not limiting for plant carbon uptake; *PAR* (MJ) is the photosynthetically active radiation incident on the canopy; *FPAR* (dimensionless) is the fraction of incident PAR absorbed by the canopy; and $f(\varepsilon)$ (dimensionless) is a scalar that accounts for the effects of environmental stress and is formulated differently in various PEMs.

However, parameterization of ε^*_{GPP}, a key component in these models, differs widely for croplands in studies at different scales. Typical ε^*_{GPP} in site-scale studies range from 2.40 to 4.24 gC MJ^{-1} for C4 crops and 1.41 to 1.96 gC MJ^{-1} for C3 crops (Chen et al.,

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2011; Kalfas et al., 2011; Lindquist et al., 2005; Singer et al., 2011; Turner et al., 2002), while ε^*_{GPP} in many large-scale modeling efforts are about 0.604–1.08 gC MJ^{-1} for croplands (Bradford et al., 2005; Heinsch et al., 2003; Lobell et al., 2002; Zhao and Running, 2010). Note that the ε^*_{GPP} values prescribed in many large-scale biogeochemical models are only approximately half of those in a number of small-scale studies. The discrepancy regarding the ε^*_{GPP} values at different scales may result in biased GPP estimates for croplands. In a recent study, GPP estimates derived from sun-induced chlorophyll fluorescence datasets were approximately 50–75% higher than results from state-of-the-art carbon cycle models, like the MODIS (Moderate Resolution Imaging Spectroradiometer) GPP/NPP product (Guanter et al., 2014). Bandaru et al. (2013) found that modeled NPP in Illinois and Iowa were 2.4 and 1.1 times greater than the MODIS GPP/NPP product for corn and soybean, respectively. However, model evaluation did not identify significant biases in other biomes (Sjöström et al., 2013; Turner et al., 2006), which implies that the differences between field and satellite LUE estimates are the most pronounced in croplands (Garbulsky et al., 2010).

Given the importance of the LUE in modeling cropland productivity, there is a need to investigate reasons for the inconsistent ε^*_{GPP} values in studies at different scales. Most validation efforts for MODIS GPP have been made using eddy covariance data from flux tower measurements, and some studies suggest increasing the ε^*_{GPP} values in models to estimate cropland GPP (Chen et al., 2011; Zhang et al., 2008). On the other hand, some large-scale modeling studies identified overestimations of crop productivity in comparison with statistical inventory data when applying field-derived ε^*_{GPP} values (Lobell et al., 2002; Ruimy et al., 1994; Turner et al., 2006). However, two recent studies that incorporate fine-resolution land use maps and coarse-resolution MODIS data recommend applying field-estimated LUE values for large-scale cropland modeling (Bandaru et al., 2013; Xin et al., 2013).

The objective of this paper is to evaluate cropland ε^*_{GPP} in the MOD17 model at different scales. We perform model calibrations across the Midwestern US using both independent in situ measurements and regional statistical datasets. This would help generate multiple lines of evidence to determine appropriate ε^*_{GPP} values for cropland GPP estimates.

2. Materials and methods

2.1. The MODIS GPP (MOD17) model

Among a variety of PEMs (Cramer et al., 1999; Wu et al., 2010; Yang et al., 2013), we employed the MOD17 model (Running et al., 2004) developed by the Numerical Terradynamic Simulation Group (NTSG) at the University of Montana (UMT). The MOD17 model is used to provide GPP/NPP estimates from MODIS data at 8-day and yearly time steps. In addition to Eq. (1), this model uses the following equations to down-regulate the influences of environmental factors on light use efficiency:

$$f(\varepsilon) = TMIN_s \times VPD_s \quad (2)$$

where $TMIN_s$ and VPD_s are the attenuation scalars for the daily minimum temperature (TMIN) and daily vapor pressure deficit (VPD). These values are calculated with the following simple linear ramp functions:

$$TMIN_s = \frac{TMIN - TMIN_{\min}}{TMIN_{\max} - TMIN_{\min}} \quad (3)$$

$$VPD_s = \frac{VPD_{\max} - VPD}{VPD_{\max} - VPD_{\min}} \quad (4)$$

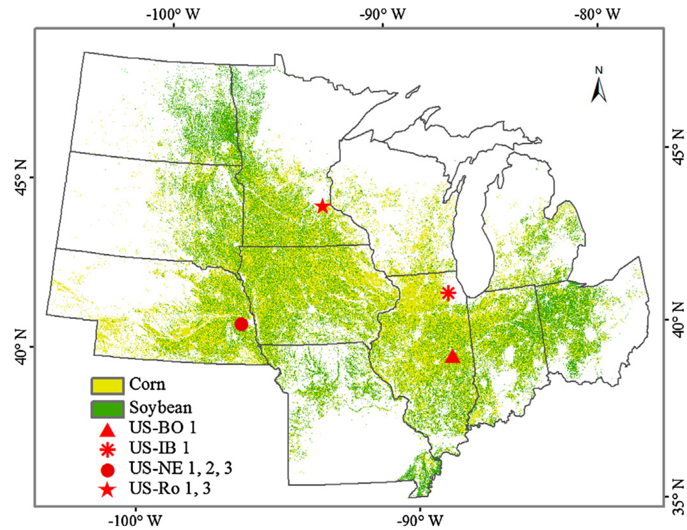

Fig. 1. Study site locations in the Midwestern US. The corn and soybean maps are shown for 2011 and are derived from the NASS Cropland Data Layer datasets. Site codes are specified in Table 1.

where $TMIN_{\max}$ and $TMIN_{\min}$ are daily minimum temperatures at $\varepsilon_{GPP} = \varepsilon^*_{GPP}$ and $\varepsilon_{GPP} = 0$, respectively; and $VPD_{\max}$ and $VPD_{\min}$ are daylight vapor pressure deficits at $\varepsilon_{GPP} = 0$ and $\varepsilon_{GPP} = \varepsilon^*_{GPP}$, respectively.

The MOD17 model prescribes specific parameters in a Biome-Properties-Look-Up-Table (BPLUT) for each biome category. For cropland in MOD17 Collection 5.1, the ε^*_{GPP}, $TMIN_{\min}$, $TMIN_{\max}$, $VPD_{\min}$, and $VPD_{\max}$ are defaulted as 1.044 gC MJ^{-1}, −8.00 °C, 12.02 °C, 650 Pa, and 4300 Pa, respectively (Zhao and Running, 2010). FPAR data are derived from the upstream MOD15 products (Myneni et al., 2002). Meteorological data such as air temperature, VPD, and incident shortwave radiation come from National Center for Environmental Prediction – Department of Energy (NCEP-DOE) Reanalysis II datasets (http://www.esrl.noaa.gov/psd/data/gridded/data.ncep.reanalysis2.html).

2.2. Flux tower site data

We analyzed seven agricultural sites in the Midwestern US (Fig. 1; Table 1) that had Level 4 products available in the AmeriFlux database (http://ameriflux.ornl.gov/). These flux tower sites are operated under different management practices (crop rotations and rainfed/irrigation) and are representative of the widespread agricultural environment in the study area. The AmeriFlux Level 4 products consist of gap-filled meteorological variables and GPP estimates. Missing data due to unsuitable micrometeorological conditions or equipment failures are gap-filled using the marginal distribution sampling method (Reichstein et al., 2005). Flux tower GPP estimates are calculated as the difference between the measured net ecosystem exchange and the estimated ecosystem respiration. Required meteorological variables in the MOD17 model were processed from the half-hour to 8-day datasets to be consistent with the MODIS data.

According to previous studies (Bandaru et al., 2013; Chen et al., 2011), we extracted time series of satellite-derived parameters from Terra/MODIS products for the pixels containing the tower sites. The used Terra/MODIS products included the 8-day 500 m surface reflectance product (MOD09A1), the 8-day 1000 m FPAR/LAI product (MOD15A2), and the 8-day 1000 m vegetation productivity product (MOD17A2). Observations during cloudy conditions within the study period are identified by quality assurance data and gap-filled using linear functions