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Effects of the partitioning of diffuse and direct solar radiation on satellite-based modeling of crop gross primary production

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ABSTRACT

Modeling crop gross primary production (GPP) is critical to understanding the carbon dynamics of agro-ecosystems. Satellite-based studies have widely used production efficiency models (PEM) to estimate cropland GPP, wherein light use efficiency (LUE) is a key model parameter. One factor that has not been well considered in many PEMs is that canopy LUE could vary with illumination conditions. This study investigates how the partitioning of diffuse and direct solar radiation influences cropland GPP using both flux tower and satellite data. The field-measured hourly LUE under cloudy conditions was 1.50 and 1.70 times higher than that under near clear-sky conditions for irrigated corn and soybean, respectively. We applied a two-leaf model to simulate the canopy radiative transfer process, where modeled photosynthetically active radiation (PAR) absorbed by canopy agreed with tower measurements ($R^2 = 0.959$ and 0.914 for corn and soybean, respectively). Derived canopy LUE became similar after accounting for the impact of light saturation on leaf photosynthetic capacity under varied illumination conditions. The impacts of solar radiation partitioning on satellite-based modeling of crop GPP was examined using vegetation indices (VI) derived from MODIS data. Consistent with the field modeling results, the relationship between daily GPP and PAR × VI under varied illumination conditions showed different patterns in terms of regression slope and intercept. We proposed a function to correct the influences of direct and diffuse radiation partitioning and the explained variance of flux tower GPP increased in all experiments. Our results suggest that the non-linear response of leaf photosynthesis to light absorption contributes to higher canopy LUE on cloudy days than on clear days. We conclude that accounting for the impacts of solar radiation partitioning is necessary for modeling crop GPP on a daily or shorter basis.
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1. Introduction

Agricultural land, one of the largest terrestrial biomes, occupies nearly 40% of the global land surface (Foley et al., 2005). Argo-ecosystems by assimilating atmospheric carbon dioxide through photosynthesis play a vital role in the terrestrial carbon cycle (Lobell et al., 2002). The total photosynthetic rates of carbon fixation by crops, termed crop gross primary production (GPP), are closely related to food productivity and influence agricultural commodity prices and human livelihood (Hertel et al., 2010; Xin et al., 2013). Accurate modeling of crop GPP is useful for a broad range of applications, such as yield prediction, water resource management, vegetation monitoring, drought mitigation, and global climate change studies (Gray et al., 2014; Guanter et al., 2014; Wagle et al., 2015; Yu et al., 2014).

Satellite remote sensing has become increasingly important in characterizing the spatial and temporal patterns of vegetation GPP (Ma et al., 2014; Xiao et al., 2010). A number of satellite-based studies have applied production efficiency models (PEM) to estimate crop GPP (Field et al., 1995; Monteith, 1977; Potter et al., 1993; Prince and Goward, 1995; Running et al., 2000a; Yan et al., 2009). PEM assumes that crop yields under non-stressed conditions can be expressed as a product of photosynthetically active radiation (PAR) absorbed by the canopy and an optimal light use efficiency (LUE) (Monteith, 1977). Limiting factors, such as temperature and water availability, are often integrated in a multi-constrained model to account for the impacts of environmental stresses on the LUE. Because satellite-derived vegetation indices

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(VIs) are closely related to the fraction of absorbed photosynthetically active radiation (FPAR; Myneni et al., 2002), PEM provide simple solutions to monitoring large-scale cropland GPP with satellite data. A global vegetation GPP product is now produced based on PEM and moderate resolution imaging spectroradiometer (MODIS) data (Running et al., 2004; Zhao and Running, 2010). Evaluation efforts have been made to quantify the impacts of various factors, such as the upstream data quality, spatial variability, satellite observation footprint, vegetation bidirectional reflectance distribution function (BRDF), and model parameterization, on MODIS GPP estimates (Sjöström et al., 2013; Turner et al., 2002; Xin et al., 2015a; Zhang et al., 2014b). Recent studies have also attempted to estimate regional and global GPP using satellite data at finer spatial and temporal resolutions (Cai et al., 2014; Gitelson et al., 2012; Sakamoto et al., 2011).

Many satellite-based studies on cropland GPP modeling have not explicitly considered the impacts of direct and diffuse solar radiation partitioning on LUE (Gu et al., 2003; Mercado et al., 2009). Direct and diffuse solar radiations undergo different radiative processes within canopies (Li et al., 1995; Myneni et al., 1990; Ni-Meister et al., 2010). Shaded leaves only receive diffuse radiation and down-scattered direct beam radiation, but sunlit leaves intercept additional direct beam radiation from the sky. Due to the non-linear responses of leaf photosynthesis to light absorption, sunlit leaves are often near light saturation, even though the photosynthetic rates of shaded leaves typically have linear relationships with light interception (Bonan, 2002). The underlying mechanism of leaf-level photosynthesis indicates that solar radiation partitioning could influence radiation absorption and canopy GPP (Li and Fang, 2015). Consistently, field studies have observed a higher LUE on overcast days when diffuse radiation dominates than on clear days when direct beam radiation dominates (Cheng et al., 2015; Huang et al., 2014), and the efficiency of forest carbon uptake increases under cloudy conditions (Gu et al., 1999). Comparisons of multiple PEM models have also found underestimated daily GPP during cloudy days (Yuan et al., 2014). Recent studies that apply different values of light use efficiency to sunlit and shaded leaves showed improvements on vegetation GPP modeling (He et al., 2013; Wang et al., 2014). Although canopy radiative transfer models that consider diffuse and direct solar radiation separately could simulate canopy photosynthesis well (Pury and Farquhar, 1997; Xin et al., 2015b), satellite-based studies favor straightforward models, such as PEM, for GPP estimation without solving the complex radiative transfer processes (Ma et al., 2014; Zhang et al., 2015). Given these findings in the literature, there is a need to investigate how and to what extent the partitioning of direct and diffuse solar radiation influences PEM-based GPP modeling.

The objectives of this study are to: (1) simulate and understand the relationships between crop GPP and absorbed photosynthetically active radiation (APAR) under varied illumination conditions using flux tower measurements and a two-leaf canopy model, and (2) develop a method to account for the effects of diffuse and direct solar radiation on satellite-based modeling of crop GPP.

2. Study materials

We studied three agricultural flux tower sites (US-Ne1, US-Ne2, and US-Ne3) at the University of Nebraska–Lincoln Agricultural Research and Development Center in Nebraska (Table 1). US-Ne1 and US-Ne2 are irrigated fields with center-pivot watering systems, and US-Ne3 is a rainfed field relying on natural precipitation (Peng et al., 2013). US-Ne1 is planted with continuous maize, while US-Ne2 and US-Ne3 are cultivated in maize-soybean rotations. More details on the study sites can be found in Suyker et al. (2005) and

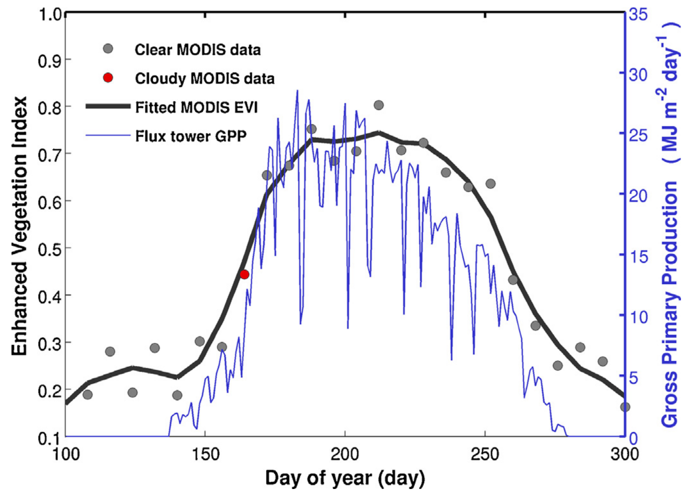

Fig. 1. An example shown for processed daily times series of MODIS Enhanced Vegetation Index (EVI) and flux tower Gross Primary Production (GPP). Data are shown for the US-Ne1 site in 2009.

Verma et al. (2005). The contrasting management practices in terms of crop rotation and irrigation make these three sites ideal to study the impacts of the partitioning of diffuse and direct solar radiation on crop GPP modeling.

Eddy covariance flux tower data were downloaded from the AmeriFlux website (http://ameriflux.ornl.gov/). For each site, 8-year (from 2002 to 2009) AmeriFlux Level 2 gap-filled data were obtained for analysis. The data screening and gap-filling procedures involve a series of quality control steps, which can be found in details from the AmeriFlux website. The used data include crop GPP estimates that were derived by the eddy covariance technique (Baldocchi, 2003) and meteorological data such as temperature, vapor pressure deficit, incoming PAR, incoming diffuse PAR, and absorbed PAR. Flux tower GPP were calculated as the differences between the net ecosystem exchange (NEE) and ecosystem respiration (Re). Crop leaf area index (LAI) was measured by a LICOR 3100 leaf area meter using a destructive sampling approach (Suyker and Verma, 2012). There are 256 records of crop LAI measurements during our study period for all three sites. The hourly solar zenith angle was derived as a function of the day of the year, the solar time in a day, the latitude and the longitude (Allen et al., 1998). Hourly datasets were further processed to daily and 8-day time steps to investigate the influence of diffuse radiation ratio on satellite-based GPP modeling at varied time intervals.

The satellite data of MODIS 8-day surface reflectance products (MOD09A1) were obtained from the Land Processes Distributed Active Archive Center (LPDAAC; https://lpdaac.usgs.gov/). We extracted a time series of surface reflectance from MOD09A1 for the 500 m pixels containing the tower sites (Xin et al., 2015a). Two widely used VIs, namely the Normalized Difference Vegetation Index (NDVI) and the Enhanced Vegetation Index (EVI), were then derived from surface reflectance of corresponding spectral bands. Satellite-derived NDVI has been used to model vegetation FPAR and LAI for more than three decades (Asrar et al., 1984; Tucker et al., 2005). EVI by reducing influences of soil background reflectance and residual atmospheric attenuation has shown better correlations with the green chlorophyll content of vegetation than NDVI (Huete et al., 2002; Kalfas et al., 2011). To minimize noise inherent in MODIS data, we screened cloudy observations using the quality control data in MOD09A1 and applied a Savitzky–Golay filter to time series of vegetation indices (Li et al., 2014). The smoothed time series of vegetation indices on an 8-day basis were interpolated into a daily basis. Fig. 1 shows an example for the US-Ne1 site in 2009 to illustrate our processing of both daily flux tower GPP

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