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Spatially-explicit monitoring of crop photosynthetic capacity through the use of space-based chlorophyll fluorescence data

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ABSTRACT

Plant functional traits such as photosynthetic capacity are critical parameters for terrestrial biosphere models. However, their spatial and temporal characteristics are still poorly represented. In this study, we used satellite observations of sun-induced fluorescence (SIF) to estimate top-of-canopy photosynthetic capacity (maximum carboxylation rate, V_{cmax} at a reference temperature of 25 °C) for crops, which was in turn utilized to simulate regional gross primary production (GPP). We first estimate the key parameter, V_{cmax}, in the widely-used FvCB photosynthesis model using field measurements of CO_2 and water fluxes during 2007–2012 at seven crop eddy covariance flux sites over the US Corn Belt. The results showed that satellite far-red SIF retrievals have a stronger link to V_{cmax} at the seasonal scale ($R^2 = 0.70$ for C4 and $R^2 = 0.63$ for C3 crop) as compared with widely-used vegetation indices. We calibrate an empirical model linking V_{cmax} with SIF that was used to estimate spatially and temporally varying crop V_{cmax} for the US Corn Belt region. The resulting V_{cmax} maps are used together with meteorological data from MERRA reanalysis data and vegetation structural parameters derived from the satellite-based spectral reflectance data to constrain the Soil-Canopy Observation of Photosynthesis and Energy (SCOPE) balance model in order to estimate regional crop GPP. Our results show a substantial improvement in the seasonal and spatial patterns of cropland GPP when compared with crop yield inventory data. The evaluation with tall tower atmospheric CO_2 measurements further supports our estimation of spatiotemporal V_{cmax} from space-borne SIF. Considering that SIF has a direct link to photosynthetic activity, our findings highlight the potential to infer regional V_{cmax} using remotely sensed SIF data and to use this information for a better quantification of regional cropland carbon cycles.

1. Introduction

Current estimates of terrestrial carbon uptake are still highly uncertain, making the projection of future atmospheric CO_2 concentration unreliable (Friedlingstein et al., 2014). Terrestrial biosphere models (TBMs) have long been used to model vegetation photosynthesis (gross primary productivity, GPP) and respiration (e.g., Sitch et al., 2003; Oleson et al., 2013). In TBMs, photosynthetic carbon uptake is a key process that is generally simulated using the C3 and C4 photosynthesis model (FvCB model) developed by Farquhar et al. (1980) and Collatz et al. (1992). One of the most important parameters in the FvCB photosynthesis model is plant photosynthetic capacity, usually represented by the leaf-level maximum carboxylation rate (V_{cmax}, $\mu mol\ CO_2 \cdot m^{-2} \cdot s^{-1}$) and maximum electron transport rate (J_{max}, $\mu mol\ CO_2 \cdot m^{-2} \cdot s^{-1}$) normalized to a reference temperature 25 °C (Bonan et al., 2011). Even though V_{cmax} is known to display significant variations in space and time in response to environmental controls, TBMs typically assume it to be constant in time for a given plant functional types (PFT) or to vary according to empirical relationships with leaf nitrogen (e.g., Wullschleger, 1993; Kattge et al., 2009; Bonan et al., 2011). Its spatial-temporal variation is considered to be a significant source of uncertainty in TBMs (Bonan et al., 2011).

There is growing interest in developing approaches to estimate photosynthetic capacity from space in order to constrain TBMs at broad scales. A particular interest is to accurately map the spatial and temporal variability of key parameters within TBMs. Leaf and canopy

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optical properties are linked to photosynthetic activity through leaf pigments and absorbed photosynthetically active radiation. Remotely-sensed reflectance has been shown to be useful for estimation of photosynthetic capacity due to its relationship to total chlorophyll content (Gamon et al., 1995). Established remote sensing of vegetation reflectance, especially vegetation indices, has been used to infer information regarding V_{cmax} (Houborg et al., 2013; Zhou et al., 2014; Alton, 2017). Recent work also showed the potential of hyperspectral data to estimate V_{cmax} and its variations (Serbin et al., 2012, 2015; Ainsworth et al., 2014).

The recent availability of satellite observations of sun-induced fluorescence (SIF) provides a new perspective to map vegetation photosynthetic activity (e.g., Frankenberg et al., 2011; Guanter et al., 2012; Joiner et al., 2012, 2013, 2016; Köhler et al., 2015). Recent research showed the potential of SIF as a proxy for GPP from leaf to ecosystem scale (e.g., Meroni et al., 2008; Damm et al., 2010, 2015; Guanter et al., 2012; Rossini et al., 2015). A close relationship between far-red SIF and GPP at seasonal time scales was found by a number of recent studies from satellite and field observations of SIF (e.g., Frankenberg et al., 2011; Guanter et al., 2012, 2014; Joiner et al., 2014; Yang et al., 2015). Using retrievals from the GOSAT-FTS instrument, a high linear correlation exists between far-red SIF and GPP from data-driven models on a yearly basis (Frankenberg et al., 2011). A biome-dependent linear relationship between SIF and GPP was observed at a monthly time scale (Guanter et al., 2012). Continuous field measurements of SIF also showed a strong correlation with GPP estimated from flux towers (Yang et al., 2015).

By combining satellite-based SIF retrievals from GOME-2 with the process model SCOPE (Soil Canopy Observation, Photochemistry and Energy fluxes), Zhang et al. (2014) estimated seasonally-varying V_{cmax}. They used SIF at the site scale along with leaf-level chlorophyll content (Cab) and leaf area index (LAI) from ancillary observations. SCOPE was used to derive an empirical relationship between seasonal V_{cmax} and simulated canopy SIF. The resulting relationship was then applied to satellite SIF data to estimate V_{cmax} at a seasonal scale for several crop flux sites in the US Corn Belt. However, several issues must to be addressed in order to apply the approach in Zhang et al. (2014) at a regional scale. For example, the SCOPE model is designed for the site level; it employs complicated radiative transfer processes (van der Tol et al., 2009) that hamper estimation of V_{cmax} over larger areas owing to the required computational resources. In addition, several studies have shown that the SIF-V_{cmax} relationship varies substantially between different SCOPE versions, implying that this relationship within SCOPE is not yet stable (Koffi et al., 2015; Verrelst et al., 2015; van der Tol et al., 2016). Koffi et al. (2015) showed that the sensitivity of canopy SIF to V_{cmax} in a later version of SCOPE is only 2/3 of that in Zhang et al. (2014). We similarly find that SIF is less sensitive to V_{cmax} using an updated version of SCOPE (Fig. S1). This indicates that changes and limitations (model representation errors) of the fluorescence model in SCOPE also contributes uncertainty. To derive spatially explicit maps of V_{cmax} from SIF over larger areas, one may alternatively investigate the sensitivity of SIF to V_{cmax} from ground-based measurements. Eddy covariance flux measurements have enabled estimates of V_{cmax} through inversions of the FvCB model from CO_2 and water fluxes (Reichstein et al., 2003; Braswell et al., 2005; Wang et al., 2007, 2009; Wolf et al., 2006; Alton, 2017).

Chlorophyll fluorescence is generally considered as a direct proxy for electron transport and hence photosynthesis (Genty et al., 1989). Leaf-level chlorophyll fluorescence is intrinsically linked to photochemical efficiency and can be used to calculate electron transport rate (ETR or J_{max}) and overall photosynthetic capacity (Weis and Berry, 1987; Genty et al., 1989). The link between chlorophyll fluorescence and ETR was confirmed at the canopy level by the ground measurements at Harvard Forest (Yang et al., 2015). Empirically, the two photosynthetic capacity parameters (V_{cmax} and J_{max}) have a strong linear relationship (Wullschleger, 1993; Beerling and Quick, 1995; Kattge et al., 2009) and this relationship is not affected by leaf nitrogen content (Walker et al., 2014). Meanwhile, V_{cmax} has been shown to have a strong link to leaf chlorophyll content (Cab) (Houborg et al., 2013; Croft et al., 2017) that also has a strong relationship to SIF (Rascher et al., 2015; Yang et al., 2015). Hence, SIF should have an indirect link with V_{cmax} through its direct link to Cab and photosynthesis.

Spatially-resolved estimates of V_{cmax} are important for the parameterization of TBMs intended to work at regional and global scales. Previous work (Zhang et al., 2014; Guan et al., 2016) highlighted the potential to estimate V_{cmax} using fluorescence model and satellite SIF data at the site level. However, such approaches present some inherent limitations to produce temporally- and spatially-explicit estimates of V_{cmax}, especially regarding the availability of model inputs and computation time.

In this study, we evaluate the ability of satellite-based SIF data to map V_{cmax} at a reference temperature 25 °C in a spatially explicit way for the TBMs. An empirical model linking SIF observations to V_{cmax} is derived from space-based SIF data and in-situ V_{cmax} estimated from in-situ CO_2 and water fluxes. We then applied the resulting empirical model to regional spaceborne SIF observations in the Midwest US crop area to map seasonal V_{cmax} and its uncertainties. The US Midwest crop area is an ideal test bed for this purpose, as US agriculture is usually practiced at a large and homogeneous scale, as needed for the available space-based SIF retrievals, and there are consistent and continuous yield data archived in the public domain.

2. Materials and methods

2.1. Flux tower sites and dataset

We use seven crop flux tower sites located in the Midwestern US corn-belt (Table 1 and Fig. S2). Sites have been selected on the basis of landscape homogeneity within the GOME-2 grid and on data availability in the period of interest (2007–2012). To determine landscape homogeneity, we used the MODIS products for land cover type (MCD12C1, Friedl et al., 2010), and EVI (MOD13C2, Huete et al., 2002) with spatial resolution of 0.05°. We selected those sites for which > 90% of the GOME-2 pixel area around these flux tower sites

Table 1
Information on the AmeriFlux flux tower sites used in this study[a].

Site ID	Lat.	Long.	Study period	Max (LC)	meanEVI	sdEVI	Crop rotations
US-Br1	41.9749	−93.6903	2007–2011	83%	0.5049	0.0506	Corn at even years and soybean at odd years
US-IB1	41.8593	−88.2227	2007–2008	98%	0.4431	0.0780	Corn at even years and soybean at odd years
US-Ne1	41.1651	−96.4766	2007–2012	95%	0.5641	0.0627	Continuous corn
US-Ne2	41.1649	−96.4701	2007–2012	95%	0.5608	0.0704	Corn except in 2008
US-Ne3	41.1797	−96.4397	2007–2012	95%	0.5731	0.0719	Corn at odd years and soybean at even years
US-Ro1	44.7143	−93.0898	2007–2012	98%	0.4912	0.0953	Corn at odd year and soybean at even year
US-SFP	43.2408	−96.9020	2008–2009	98%	0.5568	0.0349	Continuous corn

[a] LC indicates Land Cover class, EVI is the MODIS EVI, Max (LC) is the percent of dominant vegetation cover within the GOME-2 pixel, and sdEVI is the standard deviation of EVI within the GOME-2 pixel.