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Consistency between sun-induced chlorophyll fluorescence and gross primary production of vegetation in North America

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ABSTRACT

Accurate estimation of the gross primary production (GPP) of terrestrial ecosystems is vital for a better understanding of the spatial-temporal patterns of the global carbon cycle. In this study, we estimate GPP in North America (NA) using the satellite-based Vegetation Photosynthesis Model (VPM), MODIS images at 8-day temporal and 500 m spatial resolutions, and NCEP-NARR (National Center for Environmental Prediction-North America Regional Reanalysis) climate data. The simulated GPP (GPP_{VPM}) agrees well with the flux tower derived GPP (GPP_{EC}) at 39 AmeriFlux sites (155 site-years). The GPP_{VPM} in 2010 is spatially aggregated to 0.5 by 0.5° grid cells and then compared with sun-induced chlorophyll fluorescence (SIF) data from Global Ozone Monitoring Instrument 2 (GOME-2), which is directly related to vegetation photosynthesis. Spatial distribution and seasonal dynamics of GPP_{VPM} and GOME-2 SIF show good consistency. At the biome scale, GPP_{VPM} and SIF shows strong linear relationships ($R^2 > 0.95$) and small variations in regression slopes (4.60–5.55 g C m^{-2} day^{-1}/mW m^{-2} nm^{-1} sr^{-1}). The total annual GPP_{VPM} in NA in 2010 is approximately 13.53 Pg C $year^{-1}$, which accounts for ~11.0% of the global terrestrial GPP and is within the range of annual GPP estimates from six other process-based and data-driven models (11.35–22.23 Pg C $year^{-1}$). Among the seven models, some models did not capture the spatial pattern of GOME-2 SIF data at annual scale, especially in Midwest cropland region. The results from this study demonstrate the reliable performance of VPM at the continental scale, and the potential of SIF data being used as a benchmark to compare with GPP models.

1. Introduction

Carbon dioxide fixed through photosynthesis by terrestrial vegetation is known as gross primary production (GPP) at the ecosystem level. Increased carbon uptake during the past decades helped offset growing CO_2 emissions from fossil fuel burning and land cover change and mitigate the increase of atmospheric CO_2 concentration and global climate warming (Ballantyne, Alden, Miller, Tans, & White, 2012). A variety of approaches have been used to estimate GPP of terrestrial ecosystems, and they can be grouped into four categories: 1) process-based GPP models; 2) satellite-based production efficiency models (PEM); 3) data-driven GPP models upscaled from eddy covariance data; and 4) models based on sun-induced chlorophyll fluorescence (SIF) (Fig. 1). However, large uncertainty still remains regarding the spatial distribution and seasonal dynamics of GPP, which limits our capability to address scientific questions related to the increasing seasonal amplitude and interannual variation of atmospheric CO_2 (Forkel et al., 2016; Graven et al., 2013; Poulter et al., 2014). An accurate estimation of GPP at regional and global scales is essential for a better understanding of the underlying mechanisms of ecosystem-climate interactions and ecosystem response to extreme climate events, such as drought, heat wave, and flood, etc. (Beer et al., 2010; Yu et al., 2013; Zhang et al., 2016).

Many process-based biogeochemical models employ the enzyme kinetics theory, most well-known as encapsulated by Farquhar, Caemmerer, and Berry (1980) and its modification for C4 plants (Collatz, Ribas-Carbo, & Berry, 1992). Some process-based models employ the light-use-efficiency (LUE) concept to estimate GPP (Zeng, Mariotti, & Wetzel, 2005). These models also take multiple

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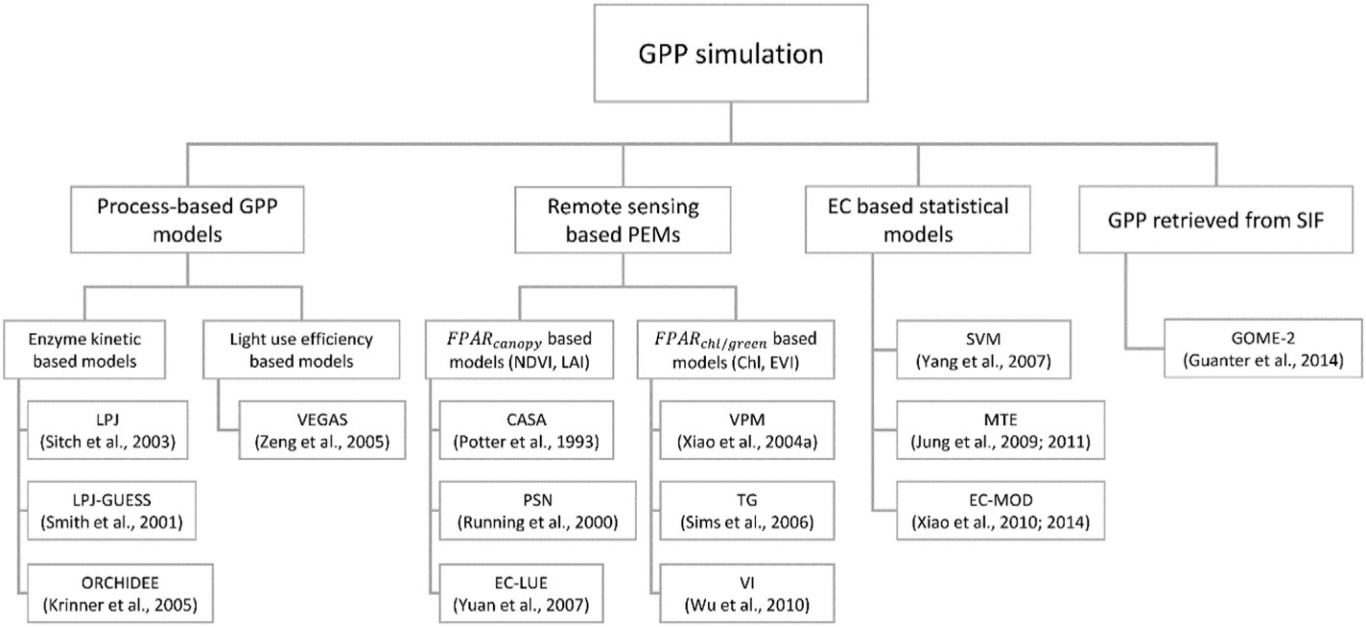

Fig. 1. A list of different approaches and models (as examples) to estimate gross primary production (GPP) of vegetation.

ecological processes into consideration so that they can be coupled with general circulation models (GCMs) to predict feedbacks related to the global warming and CO_2 fertilization (Booth et al., 2012; Keenan et al., 2012; Piao et al., 2013; Xia et al., 2014). However, these models are often run at coarse spatial resolution and the simulation results vary enormously even with the same set of meteorological input datasets (Coops, Ferster, Waring, & Nightingale, 2009).

The remote sensing based PEMs estimate GPP as the product of the energy absorbed by plants (absorbed photosynthetically active radiation, APAR) and LUE that converts energy to carbon fixed during the photosynthesis process (Monteith, 1972). These models can be further divided into two subcategories (Dong et al., 2015a; Xiao et al., 2004a). The $FPAR_{canopy}$ based models, including the Carnegie Ames Stanford Approach (CASA) (Potter et al., 1993), the MODIS GPP algorithm (Photosynthesis, PSN) (Running et al., 2004; Zhao, Heinsch, Nemani, & Running, 2005), and the EC-LUE model (Yuan et al., 2007), use the radiation absorbed by vegetation canopy. The $FPAR_{chl/green}$ based models use radiation absorbed by chlorophyll or green leaves and include the Vegetation Photosynthesis Model (VPM) (Xiao et al., 2004a; Xiao et al., 2004b), Greenness and Radiation (GR) model (Gitelson et al., 2006), and the Vegetation Index (VI) model (Wu, Niu, & Gao, 2010b).

The eddy covariance (EC) technique provides estimates of GPP by partitioning measured net ecosystem CO_2 exchange (NEE) between land and the atmosphere into GPP and ecosystem respiration (R_e) (Baldocchi et al., 2001). Over the past decades, the EC technique has been widely applied to measure NEE of various biome types throughout the world, and a large amount of GPP data (GPP_{EC}) has been accumulated (Baldocchi, 2014; Baldocchi et al., 2001). A number of statistical models have been developed to upscale GPP_{EC} from individual sites to the regional scales (Jung, Reichstein, & Bondeau, 2009; Jung et al., 2011; Xiao et al., 2010; Xiao et al., 2014; Yang et al., 2007). These algorithms, such as model tree ensembles (MTE) or regression tree approaches, build a series of rules through data mining that relate *in situ* flux observations to satellite-based indices and climate data.

Sun-induced chlorophyll fluorescence (SIF), a byproduct of the vegetation photosynthesis process, has been recently retrieved using multiple satellite platforms/instruments such as the Greenhouse gases Observing SATellite (GOSAT) (Frankenberg et al., 2011; Guanter et al., 2012; Joiner et al., 2011; Joiner et al., 2012), the Global Ozone Monitoring Instrument 2 (GOME-2) (Joiner et al., 2013), and the Orbiting Carbon Observatory-2 (OCO-2) (Frankenberg et al., 2014). Recent field studies and theory suggest that SIF contains information from both APAR and LUE that is complementary to vegetation indices such as the normalized difference vegetation index (NDVI) (Guanter et al., 2013; Rossini et al., 2015; Yang et al., 2015). A simple regression model based on space-borne SIF has been developed to estimate cropland GPP (Guanter et al., 2014). Zhang et al. (2014) have also shown the potential of SIF data to improve carbon cycle models and provide accurate projections of agricultural productivity (Guan et al., 2015).

Over the past several years, a number of studies have run the VPM with *in situ* climate data at various eddy flux tower sites. The resulting GPP_{VPM} was evaluated with GPP_{EC} at different ecosystem types, including forests (Xiao et al., 2004a, 2004b, 2005), croplands (Kalfas, Xiao, Vanegas, Verma, & Suyker, 2011; Wagle, Xiao, & Suyker, 2015), savannas (Jin et al., 2013), and grasslands (He et al., 2014; Wagle et al., 2014). Wu, Munger, Niu, and Kuang (2010a) compared GPP from four models driven by remotely sensed data at the Harvard forest site and found that VPM performed best in terms of capturing the seasonal dynamics of GPP. Yuan et al. (2014) compared seven LUE based models at 157 eddy flux sites and showed that VPM had a moderate rank of performance. Dong et al. (2015a) used four EVI-based models to estimate GPP of grasslands and croplands under normal and severe drought conditions, and reported that VPM performed better than other models in capturing the impacts of drought on GPP. This was mostly because VPM uses Land Surface Water Index (LSWI) that is sensitive to water stress (Wagle et al., 2014, 2015), while the other three models lack a water stress scalar. Recently, simulations of VPM on the regional scale, driven by regional climate data, have been carried out in the Tibetan Plateau (He et al., 2014) and China (Chen et al., 2014), where only limited GPP_{EC} data are available for model calibration and validation.

In this study, we aim to assess the feasibility and performance of the VPM model in estimating GPP across North America (NA) and explore the relationship between SIF and GPP_{VPM} at continental scale. The selection of the NA as study area is based on two facts: (1) large uncertainties exist in the GPP estimates from various models (ranging from 12.2 to 32.9 Pg C year^{-1}) (Huntzinger et al., 2012); and (2) a large number of