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Comparison of four EVI-based models for estimating gross primary production of maize and soybean croplands and tallgrass prairie under severe drought

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ABSTRACT

Accurate estimation of gross primary production (GPP) is critical for understanding ecosystem response to climate variability and change. Satellite-based diagnostic models, which use satellite images and/or climate data as input, are widely used to estimate GPP. Many models used the Normalized Difference Vegetation Index (NDVI) to estimate the fraction of absorbed photosynthetically active radiation (PAR) by vegetation canopy ($FPAR_{canopy}$) and GPP. Recently, the Enhanced Vegetation Index (EVI) has been increasingly used to estimate the fraction of PAR absorbed by chlorophyll ($FPAR_{chl}$) or green leaves ($FPAR_{green}$) and to provide more accurate estimates of GPP in such models as the Vegetation Photosynthesis Model (VPM), Temperature and Greenness (TG) model, Greenness and Radiation (GR) model, and Vegetation Index (VI) model. Although these EVI-based models perform well under non-drought conditions, their performances under severe droughts are unclear. In this study, we run the four EVI-based models at three AmeriFlux sites (rainfed soybean, irrigated maize, and grassland) during drought and non-drought years to examine their sensitivities to drought. As all the four models use EVI for FPAR estimate, our hypothesis is that their different sensitivities to drought are mainly attributed to the ways they handle light use efficiency (LUE), especially water stress. The predicted GPP from these four models had a good agreement with the GPP estimated from eddy flux tower in non-drought years with root mean squared errors (RMSEs) in the order of 2.17 (VPM), 2.47 (VI), 2.85 (GR) and 3.10 g C m^{-2} day^{-1} (TG). But their performances differed in drought years, the VPM model performed best, followed by the VI, GR and TG, with the RMSEs of 1.61, 2.32, 3.16 and 3.90 g C m^{-2} day^{-1} respectively. TG and GR models overestimated seasonal sum of GPP by 20% to 61% in rainfed sites in drought years and also overestimated or underestimated GPP in the irrigated site. This difference in model performance under severe drought is attributed to the fact that the VPM uses satellite-based Land Surface Water Index (LSWI) to address the effect of water stress (deficit) on LUE and GPP, while the other three models do not have such a mechanism. This study suggests that it is essential for these models to consider the effect of water stress on GPP, in addition to using EVI to estimate FPAR, if these models are applied to estimate GPP under drought conditions.

1. Introduction

Photosynthesis of terrestrial ecosystems is a critical process in regulating carbon dioxide exchange between land and atmosphere and providing fundamental ecosystem services (food, wood, biofuel, bio-energy materials) (Beer et al., 2010). Gross primary production (GPP) from photosynthesis has been well understood at leaf and canopy levels;

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however, ecosystem level estimation of GPP has not yet been well investigated (Asaf et al., 2013; Barman, Jain, & Liang, 2014). Since the 1990s, the eddy covariance method has been used as an important tool to measure heat, water, and CO_2 exchanges as well as trace green-house gases (Baldocchi, 2014). The observed net ecosystem CO_2 exchange (NEE) at the ecosystem scale is partitioned into GPP and ecosystem respiration (R_e, including both autotrophic and heterotrophic respiration components) (Desai et al., 2008; Papale et al., 2006; Reichstein et al., 2005). However, due to the limited number of flux tower sites and their footprints, estimation of GPP at the regional and global scales still relies on model simulation. The GPP data derived from eddy covariance flux towers (GPP_{EC}, hereafter) provides important validation data for evaluation of GPP estimates from different models.

A number of satellite-based diagnostic models use vegetation indices (VI) derived from optical sensors and climate data to estimate GPP at the site, regional, and global scales (Song, Dannenberg, & Hwang, 2013). Most of these satellite-based models, built upon the Monteith's production efficiency concept (Monteith, 1972, 1977), estimate GPP and net primary production (NPP) as a product of photosynthetic active radiation (PAR), the fraction of PAR absorbed by vegetation canopy (FPAR) and light use efficiency (ε) ($GPP = FPAR \times PAR \times \varepsilon$). These models can be divided into two groups, dependent upon their approaches to estimate absorbed PAR ($APAR = PAR \times FPAR$) (Xiao, Zhang, Hollinger, Aber, & Moore, 2005) (Fig. 1). One group models, such as the Global Production Efficiency Model (GloPEM) (Prince, 1995), Carnegie–Ames–Stanford Approach (CASA) model (Potter, 1999; Potter et al., 1993), and Photosynthesis (PSN) model (Running, Thornton, Nemani, & Glassy, 2000; Zhao, Heinsch, Nemani, & Running, 2005), use the FPAR at the canopy level ($FPAR_{canopy}$). These models often use the Normalized Difference Vegetation Index (NDVI) to estimate $FPAR_{canopy}$. Vegetation canopy is comprised of both photosynthetic (chlorophyll or green leaves) and non-photosynthetic components of vegetation. The other group models used the FPAR at the chlorophyll or green leaf level ($FPAR_{chl}$ or $FPAR_{green}$) (Gitelson et al., 2006; Sims et al., 2006; Wu, Niu, & Gao, 2010; Xiao, Zhang, et al., 2004; Zhang, Middleton, Cheng, & Landis, 2013; Zhang et al., 2006, 2009) (Fig. 1). The Vegetation Photosynthesis Model (VPM) is the first GPP model that uses $FPAR_{chl}$ (Xiao, Hollinger, et al., 2004; Xiao, Zhang, et al., 2004) and the Enhanced Vegetation Index (EVI) (Huete et al., 2002) was used to estimate $FPAR_{chl}$ in VPM. Gitelson, Peng, Arkebauer and Schepers (2014), Gitelson, Vina, Ciganda, Rundquist and Arkebauer (2005), Gitelson et al. (2006) proposed the concept of the fraction of absorbed PAR by green leaves ($FPAR_{green}$) in crops. The Vegetation Index (VI) model (Wu, Niu, & Gao, 2010) used EVI as proxies of both LUE and $FPAR_{green}$ which simplified the model structure. Several other models also used EVI to estimate GPP directly through a statistical modeling approach (Sims et al., 2008; Wu, Chen, & Huang, 2011), including the Temperature and Greenness (TG) model (Sims et al., 2006, 2008) and the Greenness and Radiation (GR) model (Gitelson et al., 2006) which considered EVI as the proxies of $FPAR_{green}$ and $FPAR_{chl}$, respectively. As these four models use EVI to estimate FPAR, they are referred as EVI-based model thereafter.

To better understand the global carbon-cycle feedback to climate change, it is critical to estimate GPP variability due to climate variation (e.g., drought), as it dominates the global GPP anomalies (Barman et al., 2014; Zscheischler et al., 2014). Previous studies have shown that EVI-based VPM, TG, GR, and VI models perform well in forest, grassland and cropland ecosystems under non-drought condition (Gitelson et al., 2006; Kalfas, Xiao, Vanegas, Verma, & Suyker, 2011; Sims et al., 2008; Wu, Gonsamo, Zhang, & Chen, 2014; Wu, Munger, Niu, & Kuang, 2010; Wu et al., 2011; Xiao et al., 2005). The performances of these models in agricultural and grassland ecosystems under drought conditions are still unclear (Mu et al., 2007; Schaefer et al., 2012). Drought affects (1) light absorption through changes in leaf chlorophyll content and leaf area index, and (2) LUE through increased water and

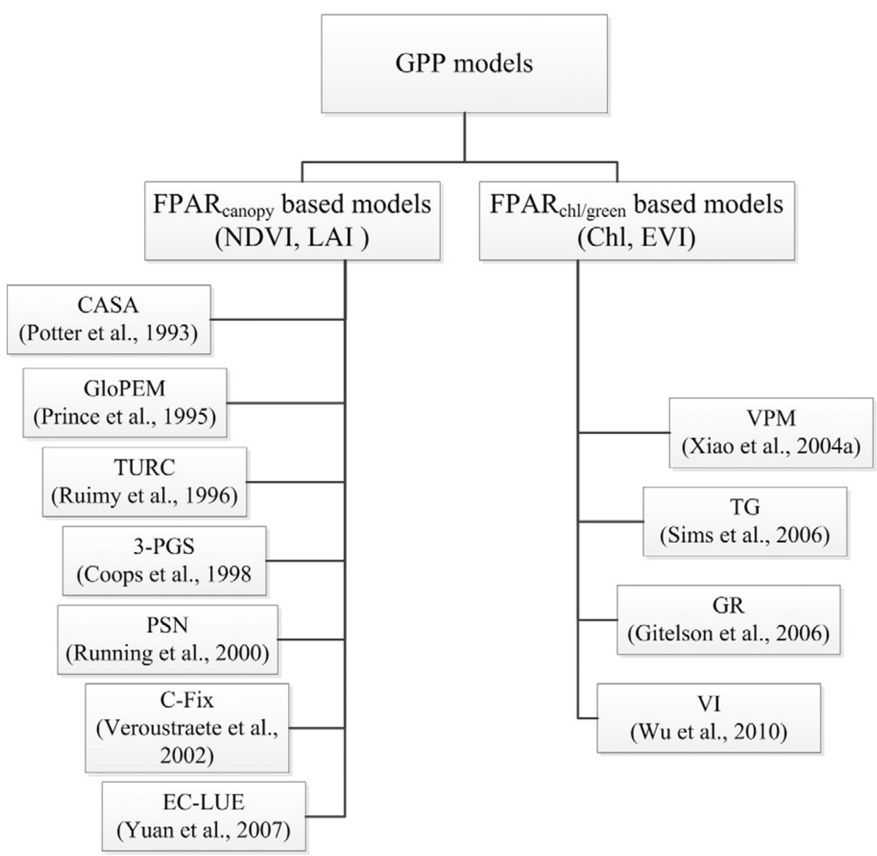

Fig. 1. Evolution of Gross Primary Production (GPP) models distinguished by the fraction of absorbed photosynthetically active radiation (FPAR).