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Vegetation-specific model parameters are not required for estimating gross primary production

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ABSTRACT

Models of gross primary production (GPP) based on remote sensing measurements are currently parameterized with vegetation-specific parameter sets and therefore require accurate information on the distribution of vegetation to drive them. Can this parameterization scheme be replaced with a vegetation-invariant set of parameters that can maintain or increase model applicability by reducing errors introduced from the uncertainty of land cover classification? Based on the measurements of ecosystem carbon fluxes from 168 globally distributed sites in a range of vegetation types, we examined the predictive capacity of seven light use efficiency (LUE) models. Two model experiments were conducted: (i) a constant set of parameters for various vegetation types and (ii) vegetation-specific parameters. The results showed no significant differences in model performance in simulating GPP while using both set of parameters. These results indicate that a universal of set of parameters, which is independent of vegetation cover type and characteristics can be adopted in prevalent LUE models. Availability of this well tested and universal set of parameters would help to improve the accuracy and applicability of LUE models in various biomes and geographic regions.

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1. Introduction

In the past decades, a long series of terrestrial ecosystem models has been developed to simulate and predict the vegetation primary productivity. These play an important role in the global carbon cycle at various spatiotemporal scales (Cramer et al., 2001). However, modeling the carbon cycle using ecosystem models at continental to global scale is subject to large errors, primarily due to uncertainties of model parameterizations (Knorr and Heimann, 2001). Conventional parameterization schemes assume constant parameter sets for each vegetation types. Consequently, land cover products based on remote sensing technology are routinely used to characterize vegetation characteristics for model applications. However, classifying remote sensing images to obtain reliable and accurate land cover type and associated vegetation characteristics over large areas remains a major challenge because of the complexity of landscapes, availability and suitability of remote sensing data, uncertainty of image processing and classification methods, etc. (Hansen et al., 2003).

Satellite-based light use efficiency (LUE) models have been widely used because they rely on simple algorithms to estimate gross primary production (GPP). Most LUE models are based on look-up tables to set the parameter values for given vegetation types (Running et al., 2004). Yet a few LUE models (CASA and EC-LUE) use a set of constant parameters regardless of vegetation type by arguing that photosynthesis is independent of species and vegetation but driven by biophysical conditions such as light, temperature and available water (Potter et al., 1993a; Yuan et al., 2007, 2010). Moreover, Aber and Federer (1992) argued that the amount of carbon fixed through photosynthesis per light quantum intercepted is invariant of species. The use of invariant parameter values across vegetation types would clearly simplify the parameterization of LUE models at broad spatial scales and the prediction of GPP over large areas. However, the advantages of this approach have not yet been verified against surface observations. In this study, we tested a series of popular LUE models by using both vegetation invariant and vegetation dependent parameters across a range of geographic regions and ecosystem types. Model predictions of GPP are finally validated using in situ observations from flux towers belonging to the global Fluxnet network (Baldocchi et al., 2001).

2. Data and methods

The LUE models are in general built on two fundamental assumptions (Goetz and Prince, 1999; Running et al., 2004): (1) ecosystem GPP is linearly related to absorbed photosynthetically active radiation (APAR) through LUE, where LUE is defined as the amount of carbon fixed per unit of APAR, and (2) potential LUE may be reduced below its theoretical potential value by environmental stresses such as low temperature or water shortage (Landsberg and Sands, 2010). In this study, seven LUE models were selected to conduct a global comparison of model performance against GPP estimates from flux tower measurements: CASA (Potter et al., 1993b), CFix (Veroustraete et al., 2002), CFlux (Turner et al., 2006; King et al., 2011), EC-LUE (Yuan et al., 2007, 2010), MODIS-GPP (Running et al., 2004), VPM (Xiao et al., 2004) and VPRM (Mahadevan et al., 2008). Detailed information about these models is reported in Table 1 and Appendix A.

The LaThuile FLUXNET dataset was used in this study (http://www.fluxdata.org). Data from a total of 168 eddy covariance (EC) towers from seven major terrestrial biomes were analyzed: deciduous broadleaf forest (DBF, 25 sites), evergreen broadleaf forest (EBF, 14 sites), evergreen needleleaf forest (ENF, 62 sites), grassland (GRA, 40 sites), mixed forest (MF, 9 sites), shrubland (SHR, 9 sites) and wetland (WET, 9 sites) (Table S1; Fig. S1). Detailed information on data processing and site information (i.e. vegetation, climate and soils) is available at the LaThuile FLUXNET web portal (http://www.fluxdata.org). The methodology applied to derive GPP from the net ecosystem exchange is reported in Reichstein et al. (2005). Eddy covariance systems directly measure net ecosystem exchange (NEE) rather than GPP. In order to estimate GPP, it is necessary to estimate daytime respiration (R_d):

Table 1
The overview of light use efficiency models in this study.

Model	Environmental scalars	Parameters
CASA	T_s, W_{SSM}	ε_{max}
CFix	T_s, W_{SEF}, S_{CO_2}	ε_{max}, ε_{min}
CFlux	T_s, W_{SEF}, W_{SVPD}, S_{CI}	ε_{max}, ε, T_{min}, T_{max}, VPD_{min}, VPD_{max}
EC-LUE	T_s, W_{SEF}	ε_{max}
MODIS	T_s, W_{SVPD}	ε_{max}, T_{min}, T_{max}, VPD_{min}, VPD_{max}
VPM	T_s, W_{SLSWI}, P_s	ε_{max}
VPRM	T_s, W_{SLSWI}, P_s	ε_{max}, PAR_0

$$GPP = R_d - NEE_d \quad (1)$$

where NEE_d is daytime NEE. Daytime ecosystem respiration R_d is usually estimated by using daytime temperature and an equation describing the temperature dependence of respiration, which is subsequently developed from nighttime NEE measurements. Nighttime NEE represents nighttime respiration because plants do not photosynthesize at night. The following model (Lloyd and Taylor, 1994) was used to describe the effects of temperature on night-time NEE:

$$NEE_{night} = R_{ref} \times e^{E_0 \times (1/(T_{ref}-T_0)-1/(T-T_0))} \quad (2)$$

where NEE_{night} is night-time ecosystem respiration, T is average air temperature at night time. The regression parameter T_0 is kept constant at −46.02 °C as in Lloyd and Taylor (1994), and the reference temperature (T_{ref}) is set to 10 °C as in the original model. The parameters E_0 (activation energy) and R_{ref} (reference ecosystem respiration) were determined using nonlinear optimization. Eq. (2) and daytime temperature were subsequently used to estimate daytime respiration (R_d).

Two model experiments were conducted to evaluate the vegetation-invariant parameters in LUE models. First, we calibrated the seven LUE models to find a set of invariant model parameters that did not change across all vegetation types. Half of the sites were randomly selected to calibrate model parameters, and the remaining half were used for model validation. This parameterization process was repeated until all possible combinations of 50% sites were achieved. Second, model parameters were calibrated for each model and vegetation type, applying the same site selection criterion and calibration process in each case. This study selected the parameters which are the default parameters within the original models. The nonlinear regression procedure (Proc NLIN) in the Statistical Analysis System (SAS, SAS Institute Inc., Cary, NC, USA) was used to optimize the model parameters by minimizing the residual sum of squares. Only the results from the validation sites were used to analyze model performance. Two metrics, the coefficient of determination (R^2) and the root mean square error (RMSE), were used to evaluate the performance of the LUE models at the 8-day time scales.

The 8-day MODIS-surface reflectance (MOD09), NDVI/EVI data (MOD13), MODIS-fPAR/LAI (MOD15), ET (MOD16) and at 1-km spatial resolution were the basis for model verification at the EC sites. MODIS reflectance product was used to calculate Land Surface Water Index (LSWI) which was used in the VPM and VPRM models. Quality control (QC) flags, which signal cloud contamination in each pixel, were examined to screen and reject data of insufficient quality. We temporally filled the missing or unreliable values at each 1-km MODIS pixel based on their corresponding quality assessment data fields as proposed by Zhao et al. (2005).

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