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Development of a two-leaf light use efficiency model for improving the calculation of terrestrial gross primary productivity

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ABSTRACT

Gross primary productivity (GPP) is a key component of land–atmospheric carbon exchange. Reliable calculation of regional/global GPP is crucial for understanding the response of terrestrial ecosystems to climate change and human activity. In recent years, many light use efficiency (LUE) models driven by remote sensing data have been developed for calculating GPP at various spatial and temporal scales. However, some studies show that GPP calculated by LUE models was biased by different degrees depending on sky clearness conditions.

In this study, a two-leaf light use efficiency (TL-LUE) model is developed based on the MOD17 algorithm to improve the calculation of GPP. This TL-LUE model separates the canopy into sunlit and shaded leaf groups and calculates GPP separately for them with different maximum light use efficiencies. Different algorithms are developed to calculate the absorbed photosynthetically active radiation for these two groups. GPP measured at 6 typical ecosystems in China was used to calibrate and validate the model. The results show that with the calibration using tower measurements of GPP, the MOD17 algorithm was able to capture the variations of measured GPP in different seasons and sites. But it tends to understate and overestimate GPP under the conditions of low and high sky clearness, respectively. The new TL-LUE model outperforms the MOD17 algorithm in reproducing measured GPP at daily and 8-day scales, especially at forest sites. The calibrated LUE of shaded leaves is 2.5–3.8 times larger than that of sunlit leaves. The newly developed TL-LUE model shows lower sensitivity to sky conditions than the MOD17 algorithm. This study demonstrates the potential of the TL-LUE model in improving GPP calculation due to proper description of differences in the LUE of sunlit and shaded leaves and in the transfer of direct and diffuse light beams within the canopy.

1. Introduction

The carbon cycle of terrestrial ecosystems is interactively linked with the global climate system at various temporal and spatial scales and has been a focus of global change studies in recent decades. Gross primary productivity (GPP), the integral of photosynthesis by all leaves (Lieth, 1973), is a key component of the terrestrial carbon cycle (Field et al., 1998; Yang et al., 2007; Gao and Liu, 2008). Quantitative estimates of GPP at global/regional scales are necessary for understanding the response of terrestrial ecosystems to the increases in atmospheric CO_2 and temperature and to various natural and human-induced disturbances (Metz et al., 2006).

In recent decades, a variety of models have been developed for calculating regional/global GPP, embracing process-based ecological models and remote sensing driven light use efficiency (LUE) models. Widely used LUE models, such as CASA (Potter et al., 1993), MOD17 algorithm (Running et al., 2000), VPM (Xiao et al., 2004a,b), EC-LUE (Yuan et al., 2007), commonly calculate GPP or NPP (net primary productivity) as the product of absorbed photosynthetically active radiation (APAR) and LUE, which is downscaled from

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the maximum by the scalars of temperature, soil water content, and atmospheric water vapor pressure deficit. The differences in various LUE models mainly exist in the ways of calculating APAR and these scalars and in the determination of maximum LUE. The MOD17 algorithm, which is currently used to produce the global GPP product (MOD17A2) in near real time, calculates APAR on the basis of Beer's law (Jarvis and Leverenz, 1983) and remotely sensed leaf area index (LAI) and integrates the effects of minimum temperature and water vapor deficit on GPP.

Recent validations using tower-based GPP show that there are some uncertainties in MODIS GPP related to inaccuracy of input meteorological data (Baldocchi et al., 2001; Turner et al., 2003; Zhao et al., 2005, 2006; Heinsch et al., 2006; Nightingale et al., 2007), remotely sensed LAI (Wang et al., 2004; Hill et al., 2006; Zhang et al., 2008), and the underestimation of the maximum light use efficiency ($\varepsilon_{\max}$) (Running et al., 2004; Zhang et al., 2008). In addition, the assumption that GPP linearly increases with APAR in LUE models, such as the MOD17 algorithm, has been recently proved to be sometimes questionable (Zhang et al., 2011; Propastin et al., 2012). Many studies indicated that GPP and LUE are affected by both the quantity and composition of the incoming solar radiation. With a given value of total incoming radiation, LUE of entire canopy will increase with the increasing fraction of diffuse radiation that results in an increase in the canopy fraction that is receiving illumination without photo-saturation (Roderick et al., 2001; Mercado et al., 2009; Oliphant et al., 2011; Zhang et al., 2011). A recent study conducted by Propastin et al. (2012) found that for a tropical rainforest in Sulawesi, Indonesia, GPP of the MOD17A2 product was underestimated during phases of low photosynthesis production due to the underestimation of MODIS *f*PAR (fraction of photosynthetically active radiation) and was overestimated during phases with clear sky conditions due to the fact that the MOD17A2 algorithm ignores the saturation effect of canopy photosynthesis under the conditions of high incoming solar radiation.

Sunlit leaves within the canopy can simultaneously absorb direct and diffuse radiation. Under clear sky conditions, these leaves are often light saturated, resulting in low LUE. In contrast, shaded leaves suffer from a lower exposure to incoming radiation. Their photosynthesis is limited by low APAR. Under cloudy or aerosol-laden skies, incoming radiation is more diffuse and more uniformly distributed in the canopy with a smaller faction of the canopy that is light saturated. As a result, canopy photosynthesis tends to be significantly more light-use efficient under diffuse sunlight than under direct sunlight conditions (Roderick et al., 2001; Gu et al., 2002, 2003; Niyogi et al., 2004; Misson et al., 2005; Urban et al., 2007; Mercado et al., 2009; Sun and Zhou, 2010; Oliphant et al., 2011;).

In order to quantify the effect of changes in the quality of incoming radiation on GPP, models need to stratify the canopy into sunlit and shaded leaves and consider the differences in the transfer of direct and diffuse beams within the canopy (Mercado et al., 2009). Many ecological models and land surface process models recently separate canopy into shaded and sunlit leaves for which APAR and GPP are individually calculated (Norman, 1993; De Pury and Farquhar, 1997; Wang and Lenuing, 1998; Chen et al., 1999). However, all LUE models, including the MOD17 algorithm, currently treat the whole canopy as a big extended leaf and ignore the difference in APAR and LUE of leaves at different locations within the canopy. These simplifications would induce systematic errors in calculated GPP (De Pury and Farquhar, 1997; Wang and Lenuing, 1998; Chen et al., 1999).

The aims of this study are: (1) to develop a light use efficiency model (TL-LUE) with sunlit and shaded leaf separation based on the MOD17 algorithm, (2) to prove that the TL-LUE model outperforms the MOD17 algorithm in calculating GPP, and (3) to test the hypothesis that LUE of sunlit and shaded leaves differs significantly. GPP measured at 6 typical sites (including three forest sites, two grassland sites, and one cropland site) using the eddy covariance technique was used as benchmarks for calibrating maximum LUE and valuating the performance of the TL-LUE model. China is in the east monsoon area of Eurasia, and has diverse climates and ecosystems. Terrestrial ecosystems play an important role in the global carbon cycle (Piao et al., 2005; Wang et al., 2007) and outcomes of this study can offer valuable references for calculating GPP in other regions.

2. Data and method

2.1. Data

2.1.1. Flux data

GPP measured at 6 typical sites across China was used for model calibration and validation in this study (Fig. 1), including the Changbai Mountain pine and broadleaf mixed forest site (CBS) (Zhang et al., 2006a; Yu et al., 2006), Qianyanzhou planted coniferous forest site (QYZ) (Zhang et al., 2006a; Yu et al., 2006), Dinghushan South Subtropical evergreen broadleaved forest site (DHS) (Zhang et al., 2006a; Yu et al., 2006), Yucheng warmer temperate dry farming cropland (YC) (Zhang et al., 2008; Li et al., 2006), Haibei alpine meadow (HB) (Zhang et al., 2008; Li, 2006), and Xinlinhot grassland in Inner Mongolia (XLHT) (Liu et al., 2011). The main information on vegetation and climate of these sites is summarized in Table 1.

Daily and 8-day GPP data are derived from the net ecosystem productivity (NEP) measured every 30-min using the eddy covariance technique. GPP was calculated from the measured NEP, which was processed using the same method as Zhang et al. (2011). A model based on the Lloyd–Taylor equation (Lloyd and Taylor, 1994) for calculating ecosystem respiration (Re) was firstly fitted using the nighttime NEP data under turbulent conditions (Fu et al., 2006a,b; Yu et al., 2008), i.e.

$$\mathrm{NEP} = \mathrm{Re} = R_{\mathrm{ref}} e^{E_0(1/(T_{\mathrm{ref}}-T_0)-1/(T-T_0))} \tag{1}$$

where R_{ref} represents the ecosystem respiration rate at a reference temperature (T_{ref}, 10 °C); E_0 is the parameter that determines the temperature sensitivity of ecosystem respiration, and T_0 is a constant and set as −46.02 °C; and T is the air temperature or soil temperature (°C).

Eq. (1) was employed in conjunction with measured NEP to calculate GPP, i.e.

$$\mathrm{GPP} = \mathrm{Re} + \mathrm{NEP} \tag{2}$$

In order to reduce the influences of the uncertainties in meteorological data on GPP calculation, the in situ measured meteorological data, including PAR, air temperature (T_a), and vapor pressure deficit (VPD), are used to drive the model. The daily meteorological data are obtained by averaging or minimizing the original 30-min data.

Data measured at CBS, QYZ, DHS, YC, and HB in 2003 and at XLHT in 2004 were used to calibrate model parameters. Data measured at CBS, QYZ, DHS, YC, and HB in 2004 and at XLHT in 2007 were used for model validation.

2.1.2. MODIS data

The MOD15A2 and MOD17A2 products were used here. MOD17A2 is the GPP product and MOD15A2 is the LAI and *f*PAR products. They are all the 8-day composites and were downloaded from the website of Land Processes-Distributed Active Archive Center (LPDAAC) (http://lpdacc.usgs.gov/get_data). MOD17A2 GPP and MOD15A2 LAI in a 2-year period from January 1, 2003 to December 31, 2004 were used for the CBS, QYZ, DHS, YC, and HB sites, and those in a 2-year period from January 1, 2004 to December 31, 2004 and from January 1, 2007 to December 31, 2007 were