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Effects of canopy photosynthesis saturation on the estimation of gross primary productivity from MODIS data in a tropical forest

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ABSTRACT

The Moderate Resolution Imaging Spectroradiometer (MODIS) gross primary production (GPP) product ($GPP_{MOD17A2}$) was evaluated against GPP from the eddy covariance flux measurements (GPP_m) at a CO_2 flux tower test site in a tropical rainforest in Sulawesi, Indonesia. The dynamics of 8-day $GPP_{MOD17A2}$ averages generally showed similarities with observed values for the period 2004–2005 (r-value is 0.66, RMSE = 1.31 g C m^{-2} d^{-1}). However, the results revealed some underestimation of GPP by the MOD17A2 product during phases of low photosynthetic production while it overestimated GPP during phases with clear sky conditions. Obviously, these seasonal differences are caused by too large seasonal amplitudes in $GPP_{MOD17A2}$. The observed inconsistencies of the $GPP_{MOD17A2}$with GPP_m were traced to the inputs of the MODIS GPP algorithm, including fraction of absorbed photosynthetically active radiation (fAPAR) and light use efficiency (ε_g). This showed that underestimation of low values is caused by several uncertainties in the MODIS fAPAR input, whereas overestimation at high irradiance is caused by the MODIS light use efficiency approach which does not account for saturation of canopy photosynthesis under clear sky conditions. The performance of the MODIS GPP algorithm has been improved through the use of a site-validated fAPAR data set and a novel approach for ε_g adjustment which allows for saturation of gross photosynthesis at high irradiance. Our study revealed a weakness of a commonly used light use efficiency approach to estimate global GPP at the example of a moist tropical rain forest in Indonesia and demonstrated a potential need for MOD17 enhancement.

1. Introduction

Gross Primary Production (GPP) refers to an incoming carbon flux at the ecosystem level, which drives such ecosystem functions as respiration and growth. With respect to the contemporary global warming debate, the importance of GPP is recognized as one of the major processes controlling land-atmosphere carbon dioxide exchange, which can provide the capacity to compensate for anthropogenic emissions of carbon dioxide (Beer et al., 2010). In addition, terrestrial GPP is a very significant contributor to human welfare because it builds the basis for food, fiber, and wood production.

Field estimates of carbon fluxes are based on CO_2 flux measurements between ecosystems and the atmosphere commonly use the eddy covariance technique (Aubinet et al., 2000; Falge et al., 2002). In terms of spatial scale, the eddy covariance method provides representative GPP measurements over areas that range from a few thousand square meters to several hectares, depending upon tower height, physical characteristics of canopy and atmospheric stratification. Scaling up data from flux tower measurements is an important challenge in understanding the terrestrial GPP across different spatial and temporal scales (Chiesi et al., 2005; Ruimy et al., 1999). One of the up-scaling approaches for regional analysis is integration of flux measurements with remotely sensed data (Running et al., 1999a, 2000; Hunt et al., 2004; Xiao et al., 2004a,b, 2005).

Satellite-based models use the light use efficiency (LUE, ε) approach first described by Montheith (1977) to calculate GPP by linking the incoming radiation to GPP through an empirical biophysical conversion factor. In such models, a number of satellite-derived input parameters including leaf area index (LAI), fraction of absorbed photosynthetically active radiation (fAPAR), and information on land cover distribution are combined with meteorological data and derivates from the eddy covariance measurements. Since 2000, satellite-based GPP products have been produced continuously using data from the Moderate Resolution Imaging Spectroradiometer (MODIS) at a spatial resolution of 1 km. The MODIS GPP products provide global coverage at an 8-day temporal resolution and are intended for monitoring photosynthetic activity of vegetation (Heinsch et al., 2003; Running et al., 1999a,1999b). Global estimates of GPP from MODIS

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are available for download at a NASA DAAC (Distributed Active Archive Center).

Validation of MODIS GPP products is a fundamental step in the assessment of their effectiveness. The extensive validation of MODIS GPP products is in progress using ground truth data from different regions. However, validation is a challenging task because of scale differences between the spatial resolution of the MODIS products and plot-scale measurements on the ground (Turner et al., 2004; Running et al., 1999b; Heinsch et al., 2006). The assessment of MODIS GPP is generally based on the use of time series of GPP estimated from eddy covariance flux tower data (Turner et al., 2004; Turner et al., 2006a,b; Wu et al., 2009; Xiao et al., 2004a,b; Xiao et al., 2005). The reported results reveal a wide range of variability between the ground-based and MODIS-based GPP estimates. Since the MODIS algorithm incorporates a number of global biome-specific default parameters, which neglects the inter-regional and within-region variability of their values (Heinsch et al., 2006), specific causes of under- or over-prediction of GPP by the MODIS product can be traced to the MODIS algorithm inputs, including the climate input data, fAPAR, LAI and LUE. In case studies from various regions, the performance of the MODIS GPP algorithm could be improved by using modified input for meteorological data (Fensholt et al., 2006; Zhao et al., 2005, 2006), fAPAR (Xiao et al., 2004a,b; Xiao et al., 2005; Fensholt et al., 2006), or LUE (Turner et al., 2006a,b).

With respect to the validity of MODIS GPP, MODIS fAPAR input to the algorithm has two main sources of uncertainty. The first source is the inconsistency of modeled fAPAR with the ground measurements. Rigorous validation of MODIS fAPAR is difficult and has been made in only a few cases, primarily in ecosystems with low fAPAR (Fensholt et al., 2006; Myneni et al., 2002; Weiss et al., 2007). In these validation studies, the most critical points were a poor correlation with the ground-based data and a problem with MODIS fAPAR outside the growing season. The second source of uncertainty is the contamination of MODIS fAPAR pixels by atmospheric noise leading to unreliable values. Although the temporal filling of unreliable fAPAR values greatly improves the accuracy of inputs to MODIS GPP algorithm, as discussed by Zhao et al. (2005) and Heinsch et al. (2003), the filled values are artificial and introduce uncertainties. Various issues associated with the effect of fAPAR on MODIS GPP have been addressed for test sites in hardwood forest (Xiao et al., 2004a,b; Turner et al., 2005), beech forest (Wang et al., 2005), grassland (Fensholt et al., 2006) and tundra (Stow et al., 2004). These studies found biome- and site-validated effects of MODIS fAPAR which resulted in under- or overestimation of the ground-based GPP by the MODIS algorithm.

In the satellite-based LUE models, a potential value of LUE, ε_g, can be obtained from eddy covariance measurements (Hunt et al., 2004; Turner et al., 2003) and is usually considered as a biome-specific constant (Hill et al., 2004; Olofsson et al., 2007; Seaquest et al., 2003). Values of potential ε_g are summarized in several publications (Gower et al., 1999; Ruimy et al., 1999). The optimal value of ε_g is modified taking into account the constraints imposed by climatic limitations such as temperature, soil moisture or vapor pressure deficit. The MODIS GPP algorithm suggests simple linear ramp functions of climatic variables to calculate the scalars that attenuate the potential ε_g to produce the final ε_g used to predict GPP (Heinsch et al., 2003; Turner et al., 2006a,b; Xiao et al., 2004a,b). However, a number of studies have concluded that the light use efficiency rate is also dependent on incoming solar radiation and saturates on days with clear sky conditions and high amount of PAR (Turner et al., 2003; Lagergren et al., 2005; Ibrom et al., 2008).

Tropical rainforests account for 34% of the global terrestrial GPP and have the highest GPP per unit area (Beer et al., 2010). Therefore, the ability to monitor GPP in tropical rainforests is of great interest in relation to understanding the current status of the global carbon cycle and climate forcing and to evaluate climate change mitigation measures. With respect to validation and the improvement of MODIS GPP product, tropical rainforests represent regions where these tasks are particularly challenging because of small seasonal variability, high cloudiness throughout the year, and saturation effects of radiation at high LAI values. Nonetheless, most of the studies on MODIS GPP validation have been carried out in non-tropical biomes. For this reason, each new related study from a tropical rainforest is of great interest and findings from such studies can be valuable for improvement of the MODIS algorithm (Zhao et al., 2005).

The study presented here follows a previous study, where the phenomenon of canopy photosynthesis saturation in the observed tropical rain forest was shown and an improved light-use efficiency approach was suggested (Ibrom et al., 2008). Here we modify the LUE approach by means of incorporating canopy photosynthesis saturation into model's ε_g inputs. We combine the modified LUE model with satellite-derived fAPAR data (Propastin & Erasmi, 2010) to estimate GPP in a tropical rain forest in Sulawesi (Indonesia). The results from the modified LUE approach are compared with the currently used approach for the calculation of MODIS GPP products. Systematic comparison with GPP derived from measured CO_2 flux data showed in which way that the quality of the MODIS GPP product could be improved by using more realistic input data, namely light use efficiency and fAPAR.

2. Material and methods

2.1. Site-validated carbon dioxide flux data

The test measurements for this study were carried out at a flux tower site located in the southern part of the Lore-Lindu National Park (01°39′ southern latitude and 120°10′ eastern longitude, 1412 m above sea level) (Ibrom et al., 2007; Ibrom et al., 2008) (Fig. 1). The Lore-Lindu National Park, covering an area of 221,505.300 ha, represents one of the largest remaining areas of natural tropical rainforest in Sulawesi. The terrain around the flux tower site is generally horizontal with a very small slope (<3°). Average daytime temperature is about 19.5 °C, while average annual precipitation is about 1700 mm. Natural forests in the study region are generally classified into major tree types based on altitudinal distribution with lowland forest (<1000 m), pre-montane forest (1000–1400 m), and montane forest (>1400 m). According to this classification, the flux tower site is located approximately at the border between

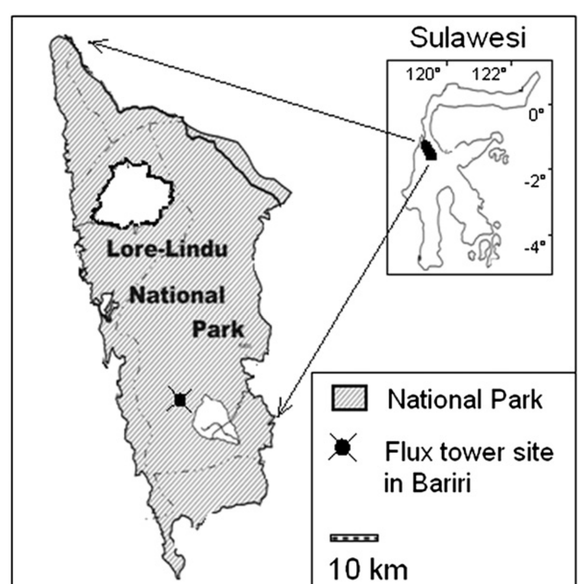

Fig. 1. The area of the Lore-Lindu National Park on the map of Sulawesi with the location of the eddy covariance flux tower.