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Estimation of gross primary production over the terrestrial ecosystems in China

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ABSTRACT

Gross primary production (GPP) is of significant importance for the terrestrial carbon budget and climate change, but large uncertainties in the regional estimation of GPP still remain over the terrestrial ecosystems in China. Eddy covariance (EC) flux towers measure continuous ecosystem-level exchange of carbon dioxide (CO_2) and provide a promising way to estimate GPP. We used the measurements from 32 EC sites to examine the performance of a light use efficiency model (i.e., EC-LUE) at various ecosystem types, including 23 sites in China and 9 sites in adjacent areas with the similar climate environments. No significant systematic error was found in the EC-LUE model predictions, which explained 79% and 62% of the GPP variation at the validation sites with C_3 and C_4 vegetation, respectively. Regional patterns of GPP at a spatial resolution of 10 km × 10 km from 2000 to 2009 were determined using the MERRA (Modern Era Retrospective-analysis for Research and Applications) reanalysis dataset and MODIS (MODerate resolution Imaging Spectroradiometer). China's terrestrial GPP decreased from southeast toward the northwest, with the highest values occurring over tropical forests areas, and the lowest values in dry regions. The annual GPP of land in China varied between 5.63 Pg C and 6.39 Pg C, with a mean value of 6.04 Pg C, which accounted for 4.90–6.29% of the world's total terrestrial GPP. The GPP densities of most vegetation types in China such as evergreen needleleaf forests, deciduous needleleaf forests, mixed forests, woody savannas, and permanent wetlands were much higher than the respective global GPP

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densities. However, a high proportion of sparsely vegetated area in China resulted in the overall low GPP. The inter-annual variability in GPP was significantly influenced by air temperature (R^2 = 0.66, P < 0.05), precipitation (R^2 = 0.71, P < 0.05), and normalized difference vegetation index (NDVI) (R^2 = 0.83, P < 0.05), respectively.

1. Introduction

Terrestrial ecosystems, driving most seasonal and inter-annual variations in atmospheric CO_2 concentration, have taken up about 20–30% of the annual total anthropogenic CO_2 emission as organic compounds over the last two and half decades (Canadell et al., 2007). Gross primary productivity (GPP), defined as the sum of photosynthetic carbon uptake by vegetation in terrestrial ecosystems, is a start of the carbon biogeochemical cycle and the principle indicator of biosphere carbon flux. Moreover, GPP contributes to human welfare because it is the basis for food, fiber and wood production, and retains human development (Beer et al., 2010). Predicting the GPP of terrestrial ecosystems has received increasing attention in global change studies (Canadell et al., 2000).

Numerous ecosystem models have been used to quantify the spatio-temporal variations in terrestrial vegetation production at large scales in China (Xiao et al., 1998; Liu et al., 1999; Chen et al., 2001; Liu, 2001; Piao et al., 2001; Gong et al., 2002; Tao et al., 2003). However, different ecosystem models are inconclusive regarding the magnitude and spatial distribution of GPP at the regional scales. Chen et al. (2001) quantified annual GPP in China as 12.26 Pg C, which is 3.14 times the estimate of Piao et al. (2001), who estimated China's annual primary production to be 3.90 Pg C (Table 1). Model outputs were indicated by low confidence at regional scales due to the following major limitations: (1) the spatial and temporal heterogeneity of ecosystem processes used by models, (2) the nonlinearity of the functional responses of ecosystem processes to environmental variables, (3) the requirements of both physiological and site-specific parameters, and (4) inadequate validation against observation (Baldocchi et al., 1996; Friend et al., 2007; Yuan et al., 2010).

Of all the predictive methods, the light use efficiency (LUE) model may have the most potential to adequately address the spatial and temporal dynamics of GPP because it is practical and has a theoretical basis (Running et al., 2000, 2004). The light use efficiency model is based on process-based algorithms that emphasize the uniqueness, similarity, and consistency of ecosystem processes in both time and space and it, therefore, avoids the problem of responsive nonlinearity of ecosystem processes to environmental variables (Yuan et al., 2010). Moreover, the light use efficiency model integrates remote sensing observations to provide consistent model inputs in time and space.

EC-LUE (Eddy Covariance Light Use Efficiency) was developed to simulate daily GPP, driven by four variables including the normalized difference vegetation index (NDVI), photosynthetically active radiation (PAR), air temperature and the evaporative fraction (the ratio of latent heat to the sum of latent and sensible heat) (Yuan et al., 2007, 2010). The EC-LUE model is an alternative approach that enables mapping of daily GPP over large areas because the potential LUE is invariant across various land cover types, and all driving forces of the model can be derived from remote sensing data or existing climate observation networks. The EC-LUE model was calibrated and validated using estimated GPP from eddy covariance towers in the AmeriFlux and EuroFlux networks covering a variety of forests, grasslands, and savannas (Yuan et al., 2007, 2010). However, EC-LUE has not been validated over the China ecosystem due to limited EC measurements. This study had the following objectives: (1) to examine the performance of the EC-LUE model over the terrestrial ecosystems in China, (2) to quantify the spatial and temporal patterns of GPP over the land in China, and (3) to investigate the inter-annual variability of GPP and environmental regulations during the period 2000–2009.

Table 1
Estimation of GPP in different terrestrial models.

Model	GPP (Pg C yr^{-1})	Study period	References
TEM	7.31	1993–1996	Xiao et al. (1998)
CASA	3.90	1997	Piao et al. (2001)
RSM	12.26	1990	Chen et al. (2001)
CEVSA	6.18	1981–1998	Tao et al. (2003)
BEPS	4.42	2001	Feng et al. (2007)
TEPC	9.44	2001	Liu (2001)
Revised CASA	6.24	1989–1993	Zhu et al. (2007)
EC-LUE	6.04	2000–2009	In this study

Abbreviations: TEM: terrestrial ecosystem model, CASA: Carnegie–Ames–Stanford-approach, CEVSA: carbon exchange between vegetation, soil, and the atmosphere, BEPS: boreal ecosystem productivity simulator, TEPC: terrestrial ecosystem production process model in China, EC-LUE: Eddy covariance and light use efficiency, and RSM: remote sensing model.
When GPP values are not available in some references, GPP was calculated by NPP multiplying a factor of 2.

2. Materials and methods

2.1. The EC-LUE model

In this study, we used the EC-LUE (Eddy Covariance – Light Use Efficiency) model to estimate GPP over the terrestrial ecosystem in China. The EC-LUE model was developed, parameterized, and validated using estimated GPP based on eddy covariance measurements covering various ecosystem types. Previous EC-LUE models were hampered by poor simulation of the evaporative fraction at large spatial scales, which was used to present the moisture constraint on light use efficiency. Net radiation (R_n) is substituted for both the latent heat (LE) flux and sensible heat (H) flux (Yuan et al., 2010), thus omitting the soil heat flux. R_n can be derived from existing climate observation networks. The revised RS-PM (Remote Sensing-Penman Monteith) model was used to estimate evapotranspiration (ET), which is equivalent to LE (Yuan et al., 2010). The calibrated values for optimal temperature and potential light use efficiency of the EC-LUE model were 21 °C and 2.25 g C M J^{-1}, respectively (Yuan et al., 2010).

In the latest study, the EC-LUE and the revised RS-PM models were calibrated and validated using estimated GPP based on EC measurements at twenty-two and thirty-three sites from the AmeriFLUX and EuroFLUX networks, respectively (Yuan et al., 2010). The revised RS-PM model explained 82% and 68% of the observed variations of ET for all the calibration and validation sites, respectively. Using estimated ET as the input, the EC-LUE model explained 75% and 61% of the observed GPP variation for calibration and validation sites, respectively. Global patterns of GPP at a spatial resolution of 10 km × 10 km from 2000 to 2003 were determined using the EC-LUE model based on the global MERRA and MODIS datasets. The global GPP estimates of 110 ± 21 Pg C yr^{-1} agreed well with other global models from the literature (Beer et al., 2010). Because the potential LUE of the EC-LUE model is invariant across