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Deriving a light use efficiency model from eddy covariance flux data for predicting daily gross primary production across biomes

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Abstract

The quantitative simulation of gross primary production (GPP) at various spatial and temporal scales has been a major challenge in quantifying the global carbon cycle. We developed a light use efficiency (LUE) daily GPP model from eddy covariance (EC) measurements. The model, called EC-LUE, is driven by only four variables: normalized difference vegetation index (NDVI), photosynthetically active radiation (PAR), air temperature, and the Bowen ratio of sensible to latent heat flux (used to calculate

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moisture stress). The EC-LUE model relies on two assumptions: First, that the fraction of absorbed PAR (fPAR) is a linear function of NDVI; Second, that the realized light use efficiency, calculated from a biome-independent invariant potential LUE, is controlled by air temperature or soil moisture, whichever is most limiting. The EC-LUE model was calibrated and validated using 24,349 daily GPP estimates derived from 28 eddy covariance flux towers from the AmeriFlux and EuroFlux networks, covering a variety of forests, grasslands and savannas. The model explained 85% and 77% of the observed variations of daily GPP for all the calibration and validation sites, respectively. A comparison with GPP calculated from the Moderate Resolution Imaging Spectroradiometer (MODIS) indicated that the EC-LUE model predicted GPP that better matched tower data across these sites. The realized LUE was predominantly controlled by moisture conditions throughout the growing season, and controlled by temperature only at the beginning and end of the growing season. The EC-LUE model is an alternative approach that makes it possible to map daily GPP over large areas because (1) the potential LUE is invariant across various land cover types and (2) all driving forces of the model can be derived from remote sensing data or existing climate observation networks.
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1. Introduction

Predicting the gross primary productivity (GPP) of terrestrial ecosystems has been a major challenge in quantifying the global carbon cycle (Canadell et al., 2000). Among 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 of its theoretical basis and practicality (Running et al., 2000). The LUE model is built upon two fundamental assumptions (Running et al., 2004): (1) that ecosystem GPP is directly related to absorbed photosynthetically active radiation (APAR) through LUE, where LUE is defined as the amount of carbon produced per unit of APAR and (2) that realized LUE may be reduced below its theoretical potential value by environmental stresses such as low temperatures or water shortages (Landsberg, 1986). The general form of the LUE model is:

$$\mathrm{GPP} = \mathrm{fPAR} \times \mathrm{PAR} \times \varepsilon_{\max} \times f \qquad (1)$$

where PAR is the incident photosynthetically active radiation (MJ m^{-2}) per time period (e.g., day or month), fPAR is the fraction of PAR absorbed by the vegetation canopy, $\varepsilon_{\max}$ is the potential LUE (g C m^{-2} MJ^{-1} APAR) without environment stress, and f is a scalar varying from 0 to 1 and represents the reduction of potential LUE under limiting environmental conditions, the multiplication of $\varepsilon_{\max}$ and f is realized LUE.

Independently and as a part of integrated ecosystem models, the LUE approach has been used to estimate GPP and net primary production (NPP) at various spatial and temporal scales (Potter et al., 1993; Prince and Goward, 1995; Landsberg and Waring, 1997; Coops et al., 2005; Running et al., 2000; Xiao et al., 2004; Law and Waring, 1994a).

The CASA model (Potter et al., 1993) combines AVHRR satellite data, monthly temperature, precipitation, soil attributes, and a biome-independent potential LUE of 0.389 g C m^{-2} MJ^{-1} APAR to estimate global terrestrial NPP.

The Global Production Efficiency Model (GLO-PEM) (Prince and Goward, 1995) simulates both global GPP and global NPP by retrieving APAR directly from satellite data, along with environmental variables that affect the utilization of APAR.

The 3-PG model (Physiological Principles in Predicting Growth) (Landsberg and Waring, 1997) calculates forest GPP from APAR and LUE, and takes into consideration the effects of freezing temperatures, soil drought, atmospheric vapor pressure deficits, soil fertility, carbon allocation, and stand age. A model output is NPP, where the NPP/GPP ratio is assumed to be fairly constrained (Waring et al., 1998). A spatial version of 3-PG, is based on spatially derived climatology, soil surveys, and remote sensing estimates of fPAR.

MODIS-GPP algorithms (Running et al., 1999, 2000) also rely heavily on the LUE approach, with inputs from MODIS LAI/fPAR (MOD15A2), land cover, and biome-specific climatologic data from NASA's Data Assimilation Office. Light use efficiency (ε) is calculated from two factors: the biome-specific maximum conversion efficiency $\varepsilon_{\max}$, a multiplier that reduces the conversion efficiency when cold temperatures limit plant function, and a second multiplier that reduces the maximum conversion efficiency when vapor pressure deficit (VPD) is high enough to inhibit photosynthesis. It is assumed that soil water deficit co-varies with VPD and that VPD will account for drought stress. The GPP algorithm was tested with flux datasets from a range of biomes (Heinsch et al., 2006).

In the Vegetation Production Model (VPM) (Xiao et al., 2004), the potential LUE is affected by

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