Remote Sensing of Environment 163 (2015) 206–216

Contents lists available at ScienceDirect

Remote Sensing of Environment

journal homepage: www.elsevier.com/locate/rse

Global vegetation gross primary production estimation using satellite-derived light-use efficiency and canopy conductance

Marta Yebra [a,c,d,*], Albert I.J.M. Van Dijk [a,c,d], Ray Leuning [b], Juan Pablo Guerschman [d]

[a] Fenner School of Environment and Society, The Australian National University, ACT, Canberra, Australia
[b] CSIRO Oceans and Atmosphere Flagship, ACT, Canberra, Australia
[c] Bushfire & Natural Hazards Cooperative Research Centre, Melbourne, Australia
[d] CSIRO Land and Water Flagship, ACT, Australia

ARTICLE INFO

Article history:
Received 12 December 2014
Received in revised form 19 March 2015
Accepted 20 March 2015
Available online 15 April 2015

Keywords:
Photosynthesis
Canopy conductance
Light use efficiency
FLUXNET
MODIS
Gross primary production
GPP
Vegetation

ABSTRACT

Climate and physiological controls of vegetation gross primary production (GPP) vary in space and time. In many ecosystems, GPP is primary limited by absorbed photosynthetically-active radiation; in others by canopy conductance. These controls further vary in importance over daily to seasonal time scales. We propose a simple but effective conceptual model that estimates GPP as the lesser of a conductance-limited (F_c) and radiation-limited (Fr) assimilation rate. F_c is estimated from canopy conductance while Fr is estimated using a light use efficiency model. Both can be related to vegetation properties observed by optical remote sensing. The model has only two fitting parameters: maximum light use efficiency, and the minimum achieved ratio of internal to external CO_2 concentration. The two parameters were estimated using data from 16 eddy covariance flux towers for six major biomes including both energy- and water-limited ecosystems. Evaluation of model estimates with flux tower-derived GPP compared favourably to that of more complex models, for fluxes averaged; per day ($r^2 = 0.72$, root mean square error, RMSE = 2.48 μmol C m^2 s^{-1}, relative percentage error, RPE = −11%), over 8-day periods ($r^2 = 0.78$ RMSE = 2.09 μmol C m^2 s^{-1}, RPE = −10%), over months ($r^2 = 0.79$, RMSE = 1.93 μmol C m^2 s^{-1}, RPE = −9%) and over years ($r^2 = 0.54$, RMSE = 1.62 μmol C m^2 s^{-1}, RPE = −9%). Using the model we estimated global GPP of 107 Pg C y^{-1} for 2000–2011. This value is within the range reported by other GPP models and the spatial and inter-annual patterns compared favourably. The main advantages of the proposed model are its simplicity, avoiding the use of uncertain biome- or land-cover class mapping, and inclusion of explicit coupling between GPP and plant transpiration.

1. Introduction

The transport of CO_2 from the atmosphere into plant leaves, where it is used in photosynthesis, is inextricably linked to the simultaneous transport of water vapour in the opposite direction (transpiration). Plant physiological control of these opposing fluxes is exerted by stomata and the degree of control is quantified in terms of leaf stomatal conductance. At the ecosystem level, canopy conductances for water vapour (G_{cw}) and CO_2 (G_{cc}) provide links between transpiration and photosynthesis, respectively. Estimates of canopy conductance can be obtained by up-scaling stomatal conductances for all leaves in the canopy (Kelliher, Leuning, Raupach, & Schulze, 1995), or be inferred from ecosystem level measurements of exchanges of water vapour and CO_2 (Baldocchi, 2008). Both approaches have been shown to be suitable for application at canopy or local scales (<1–2 km) but to derive regional or global estimates of canopy conductance, satellite remote sensing based methods are needed.

In a previous study, Yebra, Van Dijk, Leuning, Huete, and Guerschman (2013) used eddy covariance measurements of water vapour fluxes at 16 sites distributed globally to establish relationships between G_{cw} and Moderate Resolution Imaging Spectroradiometer (MODIS) reflectance observations. When the derived estimates of G_{cw} were combined with net radiation, wind speed and humidity deficit data, the resulting estimates of evapotranspiration (ET) were compared favourably with those from alternative approaches. Moreover, the method allowed a single parameterisation for all land cover types, which avoids artefacts resulting from errors in vegetation classification. In principle, the same satellite-derived G_{cw} values can be used within a process-based model for Gross Primary Production (GPP) while providing a direct link to the coupled energy and water balance of plant canopies.

In many ecosystems, GPP is limited by the amount of absorbed photosynthetically-active radiation (APAR), rather than by canopy conductance. The simplest approach to estimating GPP for these conditions is to multiply APAR by a light-use efficiency term (LUE or ε, mol C mol^{-1} APAR) representing the plant's capacity to convert light into fixed carbon (Running, Nemani, Glassy, & Thornton, 1999; Sims et al., 2008; Sjöström et al., 2011). This approach requires maximum LUE to be

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* Corresponding author.
E-mail address: marta.yebra@anu.edu.au (M. Yebra).

http://dx.doi.org/10.1016/j.rse.2015.03.016

modified where or when environmental conditions limit the rate of photosynthesis. In particular, a lack of soil water leads to stomatal closure, which reduces both ET and GPP. Over longer periods, sustained reduction in water availability will reduce vegetation cover, APAR and hence GPP (Andela, Liu, van Dijk, de Jeu, & McVicar, 2013).

In this paper the study of Yebra et al. (2013) is extended to allow the prediction of GPP globally. Our aim was to test a simple model that links GPP and ET through canopy conductance, while retaining the smallest number of 'free' fitting parameters necessary to construct a well-performing model that can be used at a global scale, without the need for ancillary information on land cover class. To account for the radiation limitation of GPP, we calibrate a simple LUE model that uses MODIS remote sensing data to estimate APAR, LUE and GPP. The lesser of the two estimates of GPP based on LUE or G_{cw} were assigned to each MODIS pixel encompassing a flux tower and globally. The results were then compared to the official MODIS GPP product (Zhao, Heinsch, Nemani, & Running, 2005) and to estimates from a regression tree approach (Jung, Reichstein, & Bondeau, 2009).

2. Theory

We use a 'big-leaf' description of the plant canopy and estimate the mean GPP (symbolised by F μmol C m^{-2} s^{-1}) as the lesser of conductance-limited and radiation-limited assimilation rates, denoted by F_c and F_r, respectively:

$$F = \min(F_c, F_r). \tag{1}$$

If it is assumed that transport of CO$_2$ from the bulk air to the intercellular leaf space is limited by molecular diffusion through the stomata, then F_c can be calculated from G_{cw} as:

$$F_c = c_g G_{cw}(1 - R_0)C_a \tag{2}$$

where G_{cw} (in m s^{-1}) is canopy conductance to water vapour and $R_0 = C_i/C_a$ the achieved *minimum* ratio of internal (C_i) to external (C_a) CO$_2$ concentration (mol mol^{-1}), and the conversion coefficient c_g (26 mol C m^{-3}) relates G_{cw} (m s^{-1}) to the conductance for CO$_2$ in molar units (G_{cc}, μmol C m^{-2} s^{-1}) (it can be calculated as 41.6 mol C m^{-3} following the ideal gas law for standard air pressure and 25 °C temperature, divided by 1.6 to account for the lesser diffusivity of CO$_2$ compared to H$_2$O). If it can be assumed that R_0 is constant for a given vegetation community or at least relatively narrowly constrained, then Eq. (2) can be used to estimate the maximum rate of CO$_2$ uptake for a given value of G_{cw}. Support for assuming a narrow range for R_0 is given by Figure 3c in Schulze, Kelliher, Korner, Lloyd, and Leuning (1994). They extracted data from the literature for maximum surface conductance (G_{Sw}) and maximum assimilation rates (F_c) for various vegetation types across the globe. A plot of F_c versus G_{Sw} (their Fig. 3C) yields a slope of 1.048 with an r^2 of 0.66. Using this value into Eq. (2) and C_a = 360 ppm results in $(1 - R_0) = 0.11$. The corresponding value of $R_0 = 0.89$ is for optimal conditions and is expected to be lower when various environmental factors limit photosynthesis (Tuzet, Perrier, & Leuning, 2003). Here we adopt a global value of $R_0 = 0.76$ which was obtained by fitting Eq. (2) to flux station data from 16 sites distributed globally across six biomes (see Section 4 below).

Radiation-limited GPP (F_r) was estimated using Eq. (3), where f_{PAR} is the fraction of absorbed PAR, Q is incident PAR (mol photons m^{-2} s^{-1}) and ε is a light use efficiency (mol C mol^{-1} photons).

$$F_r = \varepsilon f_{PAR} Q \tag{3}$$

Most enzyme-mediated reactions have an optimum temperature range, and several other algorithms adjust GPP estimates for T (e.g. Yuan et al. (2007)). Consequently, temperature was tested for inclusion as part of algorithm development, but rejected because model performance was only very marginally improved (see Supplementary material).

3. Data

3.1. MODIS-derived reflectances and canopy conductance to water vapour

The 16-day Terra-Aqua MODIS nadir reflectance product (MCD43A4, 500 m; Strahler, Muller, & Modis Sciences Team Members, 1999) provides surface reflectance corrected for the bidirectional reflectance distribution function (BRDF) and atmospheric effects, creating an apparent reflectance that is not affected by the location of the sensor relative to the pixel at the time of acquisition (Schaaf et al., 2002). Subsets of MCD43A4 data for each 500 m pixel containing a flux station were retrieved for the period 2000–2012 from the MODIS Web service (http://daac.ornl.gov/MODIS/MODIS-menu/modis_webservice.html) in order to calibrate and validate our approach. For global GPP estimates we used the 0.05° (ca. 5600 m) resolution MCD43C4 global reflectance product (collection 5) for the same period. The imagery was downloaded from the Land Processes Distributed Active Archive Center (LP DAAC, https://lpdaac.usgs.gov/data_access/data_pool) and the quality control and state flags were used to remove pixels with partial or complete cloud cover or low pixel quality in the study areas. Global estimates of canopy conductance based on remote sensing (G_{cRS}) were calculated as described by Yebra et al. (2013) for 8-day periods and at 0.05° spatial resolution. The calculations utilized three vegetation indices derived from the MCD43C4 reflectance product: the Enhanced Vegetation Index (EVI) (Huete et al., 2002), the Normalized Difference Vegetation Index (NDVI) (Rouse, Haas, Schell, Deering, & Harlan, 1974) and a crop coefficient (K_c) estimated following Guerschman et al. (2009). The data are available via http://www.wenfo.org/wald/.

3.2. Flux tower observations

The GPP estimates and meteorological data used in developing the model were derived from the 'free fair-use' Fluxnet LaThuile dataset (Agarwal et al., 2010). Following Yebra et al. (2013) we analysed 16 sites that have at least five years of data from 2000 onwards, to coincide with the period of MODIS data availability. The flux stations were surrounded by homogeneous land cover within 1 km from the measurement tower (Table 1) to ensure that the results are not compromised if some of the MODIS pixels are not fully centred on the tower (Goerner, Reichstein, & Rambal, 2009). Homogeneity was assessed visually, as judged by colour and texture, using high spatial resolution aerial and satellite images from various sources (Google Earth™ http://earth.google.com). The selected sites are located across several continents and included six major biomes, following the International Geosphere–Biosphere Programme classification scheme (Hansen, 2000): woody savannas (WSA), grasslands (GRA), croplands (CRO), evergreen needleleaf (ENF), evergreen broadleaf (EBF) and deciduous broadleaf forest (DBF). In ecohydrological terms, both energy-limited (i.e., potential evaporation (PET) < precipitation (P)) and water-limited (PET > P) ecosystems are represented. Table 1 presents the values of a wetness index (WI), computed as the ratio between the long-term (1950–2000) annual average P and annual average PET. Sites with WI > 1 are described as energy-limited while areas with WI < 1 are termed water-limited. Here we define as

$$PET = \alpha_{PT}\, sR_n/(s + \gamma) \tag{4}$$

where s (Pa K^{-1}) is the slope of the saturation water vapour pressure versus temperature curve, γ is the psychrometric constant (Pa K^{-1}), R_n is absorbed net radiation (W m^{-2}) and $\alpha_{PT} = 1.26$ (Priestley & Taylor, 1972).

Half-hourly GPP and meteorological data were quality-checked using the flags included in the Fluxnet La Thuile dataset. Half-hourly