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Development of a coupled carbon and water model for estimating global gross primary productivity and evapotranspiration based on eddy flux and remote sensing data

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ABSTRACT

Terrestrial gross primary productivity (GPP) and evapotranspiration (ET) are two key ecosystem fluxes in the global carbon and water cycles. As carbon and water fluxes are inherently linked, knowing one provides information for the other. However, tightly coupled and easy to use ecosystem models are rare and there are still large uncertainties in global carbon and water flux estimates. In this study, we developed a new monthly coupled carbon and water (CCW) model. GPP was estimated based on the light-use efficiency (LUE) theory that considered the effect of diffuse radiation, while ET was modeled based on GPP and water-use efficiency (WUE). We evaluated the non-linear effect of single (GPP_{OR}) or combined (GPP_{AND}) limitations of temperature and vapor pressure deficit on GPP. We further compared the effects of three types of WUE (i.e., WUE, inherent WUE, and underlying WUE) on ET (i.e., ET_{WUE}, ET_{IWUE} and ET_{UWUE}). CCW was calibrated and validated using global eddy covariance measurement from FLUXNET and remote sensing data from Moderate Resolution Imaging Spectroradiometer (MODIS) from 2000 to 2007. Modeled GPP_{AND} and GPP_{OR} explained 67.3% and 66.8% of variations of tower-derived GPP, respectively, while ET_{UWUE}, ET_{IWUE} and ET_{WUE} explained 65.7%, 59.9% and 58.1% of tower-measured ET, respectively. Consequently, we chose GPP_{AND} and ET_{UWUE} as the best modeling framework for CCW, and estimated global GPP as 134.2 Pg C yr^{-1} and ET as 57.0×10^3 km^3 for vegetated areas in 2001. Global ET estimated by CCW compared favorably with MODIS ET (60.5×10^3 km^3) and ET derived from global precipitation (56.5×10^3 km^3). However, global GPP estimated by CCW was about 19% higher than MODIS GPP (109.0 Pg C yr^{-1}). The mean global WUE value estimated by CCW (2.35 g C kg^{-1} H_2O) was close to the mean tower-based WUE (2.60 g C kg^{-1} H_2O), but was much higher than the WUE derived from MODIS products (1.80 g C kg^{-1} H_2O). We concluded that the new simple CCW model provided improved estimates of GPP and ET. The biome-specific parameters derived in this study allow CCW to be further linked with land use change models to project human impacts on terrestrial ecosystem functions.

1. Introduction

Carbon and water cycles are two fundamental biogeophysical processes in the biosphere (Law et al., 2002). As the initial carbon fixed by vegetation through photosynthesis, terrestrial gross primary productivity (GPP) is a primary driver of the global carbon cycle (Running et al., 2004; Anav et al., 2015). GPP also regulates basic ecosystem functions, such as respiration and growth, and provides the total carbohydrate matter to sustain the food web, which directly contributes to human welfare (Beer et al., 2010; Running, 2012). As a vital component of the water cycle, evapotranspiration (ET) is the sum of plant transpiration, soil evaporation and canopy interception (Mu et al., 2007; Sun et al., 2011a; Fang et al., 2015). ET

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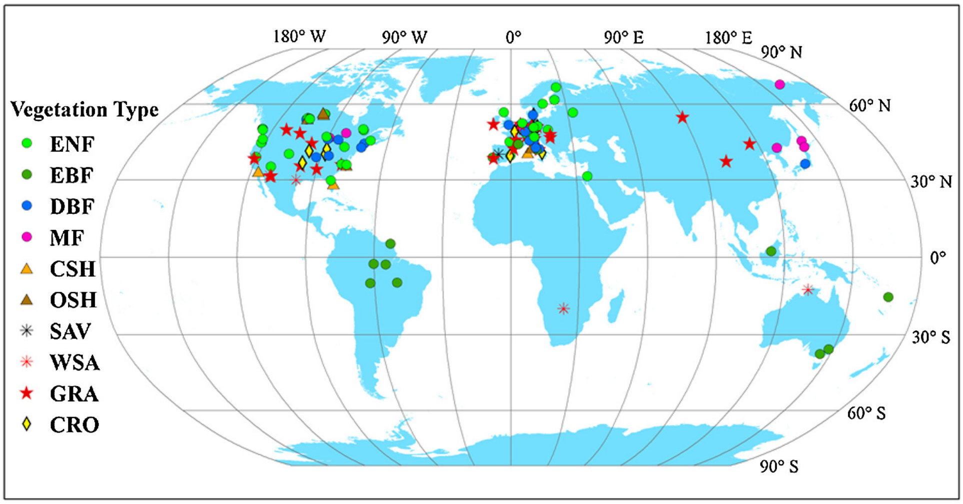

Fig. 1. FLUXNET tower sites used in this study. Biomes include evergreen needle-leaf forest (ENF), evergreen broad-leaf forest (EBF), deciduous broad-leaf forest (DBF), mixed forest (MF), closed shrub (CSH), open shrub (OSH), savannas (SAV), woody savannas (WSA), grassland (GRA), and cropland (CRO). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

not only controls soil moisture and catchment water yield (Bosch and Hewlett, 1982; Sun et al., 2011a,b), but also affects regional precipitation patterns due to its feedback to the climate system (Koster et al., 2004; Seneviratne et al., 2006). Accurately estimating spatial and temporal distributions of GPP and ET are critical to understand ecosystem functions and their responses to global environmental changes, such as human-induced climate warming and land use change (McGuire et al., 2001; Tian et al., 2010).

Carbon and water fluxes are inherently coupled on multiple scales (Law et al., 2002; Waring and Running 2010; Sun et al., 2011b). From leaf to stand and ecosystem levels, carbon gains through photosynthesis and water losses through transpiration are mainly regulated by plant stomatal behavior in response to a set of environmental conditions (Jarvis, 1976). The ratio of GPP over ET, defined as the water use efficiency (WUE), is an essential quantity that characterizes complex trade-offs between carbon gain and water loss (Ponton et al., 2006; Waring and Running, 2010). Thus, between GPP and ET, knowing one provides information to estimate the other given WUE, providing an efficient way to integrate GPP and ET into simplified eco-hydrological models (Sun et al., 2011a,b). Methodologically, those models that independently estimate ET and then use ET or ET-inferred water stress to estimate GPP can be regarded as water-centric models. For example, Beer et al. (2010) used the water-centric approach to estimate global GPP based on basin-scaled ET and WUE. Sun et al. (2011b) developed the WaSSI model in which they first estimated ET with an empirical model, and then estimated GPP based on WUE. Other models, such as CASA (Potter et al., 1993), 3 PG (Landsberg and Waring, 1997; Nole et al., 2009), TECO (Weng and Luo, 2008), and EC-LUE (Yuan et al., 2010), used a soil moisture sub-model or a Penman-Monteith equation to independently estimate ET, and then use ET-related water stress to estimate GPP. However, ET is still the least quantifiable component of water cycle at all scales due to the challenge in characterizing large sets of controlling factors, including climate, plant biophysics, soil properties, and topography (Mu et al., 2007; Sun et al., 2011a,b; Wang and Dickinson, 2012; Wilson et al., 2001). Thus, water-centric models that use ET to estimate GPP can have large predictive errors.

Compared to ET, GPP has been more readily estimated with remotely sensed-based models, such as light-use efficiency (LUE) models (Potter et al., 1993; Running et al., 2004; Song et al., 2013; Yuan et al., 2007; Zhao and Running, 2010). LUE is a key biophysical parameter, quantifying the capacity of plants to convert absorbed light to carbohydrate through photosynthesis (Monteith, 1972). GPP models based on LUE using remotely sensed data from space-borne satellites are considered to have high potential to adequately capture the spatial-temporal dynamics of GPP on the global scale due to its simplicity and the solid biophysical basis (Running et al., 2004; Song et al., 2013). Although numerous LUE-based GPP models have been developed, they have rarely been coupled with the estimation of ET (Hu et al., 2013). Recent studies showed that the coupling of GPP and ET in terms of WUE may be further regulated by the linear or non-linear effects of vapor pressure deficit (VPD), corresponding to the inherent WUE (IWUE) (Beer et al., 2009) or underlying WUE (UWUE) (Zhou et al., 2014), respectively. With appropriate WUE, LUE-based GPP model potentially provides a new and effective pathway to estimate ET, which can be referred to as a carbon-centric model.

The objective of this study is to develop a monthly coupled carbon and water (CCW) model that first estimates GPP based on LUE theory and then estimates ET based on WUE theory. We intend to develop CCW as a tool that is computationally simple, yet provides GPP and ET estimates with comparable accuracy to more complex models that are currently in use. Such a carbon-centric model can be used to evaluate the impacts of land-use/land-cover change and climate change on GPP and ET at a wide range of scales. In CCW, we accounted for the effect of diffuse radiation on LUE. Diffuse radiation had been shown to be more efficiently used in photosynthesis by both theoretical and observational studies (Gu et al., 2002; King et al., 2011; Medlyn, 1998; Mercado et al., 2009; Turner et al., 2006b). However, most LUE models do not account for this effect (Yuan et al., 2014), potentially leading to underestimation of GPP. We evaluated two forms of GPP models: one considers Liebig's law, taking the more limiting factor between temperature and VPD (Yuan et al., 2007), and the other takes co-limiting effects of temperature and VPD on LUE simultaneously (Landsberg and Waring, 1997; Raich et al., 1991). We evaluated three water use efficiencies in estimating ET, including WUE, IWUE, and UWUE. We calibrated the CCW model parameters with global eddy covariance (EC) flux data from FLUXNET and remote sensing data from MODerate resolution Imaging Spectroradiometer (MODIS) from 2000 to 2007. The model performance was evaluated with reserved flux tower data that were not used in the model development. Finally, we used CCW to estimate global GPP and ET in 2001 and evaluated the model results with MODIS GPP and ET products as well as regional basin-scale ET derived from precipitation and stream flow data.