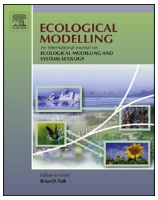
Ecological Modelling 368 (2018) 205–232

Contents lists available at ScienceDirect

Ecological Modelling

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



Evaluation and improvement of the daily boreal ecosystem productivity simulator in simulating gross primary productivity at 41 flux sites across Europe

Sha Zhang[a,b], Jiahua Zhang[a,*], Yun Bai[a,b], Upama Ashish Koju[a,b], Tertsea Igbawua[a,b,c], Qing Chang[a,b], Da Zhang[a,b], Fengmei Yao[b,*]

[a] Key Laboratory of Digital Earth Science, Institute of Remote Sensing and Digital Earth, Chinese Academy of Sciences, Beijing, China
[b] University of Chinese Academy of Sciences, Beijing, China
[c] University of Agriculture, Makurdi, Benue State, Nigeria

ARTICLE INFO

Article history:
Received 18 August 2017
Received in revised form
11 November 2017
Accepted 28 November 2017

Keywords:
Gross primary productivity (GPP)
Daily boreal ecosystem productivity simulator (BEPSd)
Water stress factor
Chlorophyll constraint
NDVI
Europe

ABSTRACT

Vegetation gross primary productivity (GPP) is an important component in the global carbon cycle and its accurate estimation is essential in ecosystem monitoring and simulation. Previous studies show that ecosystem models usually overestimate GPP under drought and during spring, late fall and winter. In this study, these issues are addressed in the daily boreal ecosystem productivity simulator (BEPSd) by introducing a new water stress factor (f_w) to replace the old one and a designed fraction in term of the normalised difference vegetation index (NDVI) (f_{ndvi}) to indicate the effect of chlorophyll on photosynthesis. GPP simulations are conducted at 41 flux sites across Europe to test BEPSd with the new f_w and f_{ndvi}. The new f_w captures drought conditions well and f_{ndvi} expresses the chlorophyll constraint on photosynthesis. Although BEPSd with the old f_w performs well for some plant function types (PFTs), it is unsatisfactory for others. BEPSd incorporating both the new f_w and f_{ndvi} gives better simulations than the old version, particularly for evergreen broadleaf forest, deciduous broadleaf forest and closed shrub with R (RMSE) value increasing (decreasing) from 0.69 (3.20 $gCm^{-2}\,d^{-1}$) to 0.74 (1.65 $gCm^{-2}\,d^{-1}$), 0.72 (4.01 $gCm^{-2}\,d^{-1}$) to 0.82 (2.91 $gCm^{-2}\,d^{-1}$), 0.54 (1.82 $gCm^{-2}\,d^{-1}$) to 0.75 (1.59 $gCm^{-2}\,d^{-1}$), respectively. Furthermore, the new f_w effectively mitigates GPP overestimates under drought, and f_{ndvi} counteracts GPP overestimates during spring, late fall and winter. Overall, the improved BEPSd shows a satisfactory performance at flux sites over Europe.

1. Introduction

Gross primary productivity (GPP) is defined as the gross carbon fixed by terrestrial ecosystems through photosynthesis per unit time and area (Beer et al., 2010; Wu et al., 2010b; Wu et al., 2014). GPP is an important component in the terrestrial carbon cycle (Beer et al., 2010; Wang et al., 2010; Yuan et al., 2014; Li et al., 2016), through which carbon dioxide from the atmosphere is fixed into vegetation. It is also one of the major fluxes controlling the land-atmosphere carbon exchanges (Raupach et al., 2008; Li et al., 2016). An accurate estimate of GPP is particularly essential for quantifying other parameters in the carbon cycle such as net primary productivity (NPP) and net ecosystem production (NEE) (Wu et al., 2014).

As reported, numerous ecosystem models are developed to simulate terrestrial GPP, such as light use efficiency (LUE) models and process-based models (Li et al., 2016). In LUE models, GPP is estimated through the Monteith (1972) equation GPP = LUE × f_{APAR} × PAR, where LUE is the light use efficiency during a period and f_{APAR} represents the fraction of absorbed photosynthetically active radiation (PAR). In this type of model, LUE is the key parameter. Wu et al. (2010d) modified LUE × f_{APAR} in the Monteith equation to VI × VI and used the modified LUE model to obtain an improved estimate of the GPP of wheat at the National Experimental Station for Precision Agriculture (40°10.6′ N, 116°26.3′ E), 20 kilometres northeast of Beijing, China. The modified LUE model was also succussful for maize (Wu et al., 2010b). GPP estimation in the vegetation photosynthesis model (VPM) is also based on LUE,

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* Corresponding authors at: Institute of Remote Sensing and Digital Earth, Chinese Academy of Sciences, No. 9 Dengzhuang South Road, Haidian District, Beijing 100094, China and University of Chinese Academy of Sciences, No.19A, Yuquan Road, Shijingshan District, Beijing, 100049, China.
E-mail addresses: jhzhang@ceode.ac.cn (J. Zhang), yaofm@ucas.ac.cn (F. Yao).

https://doi.org/10.1016/j.ecolmodel.2017.11.023
0304-3800/

and LUE in VPM is estimated as a function of temperature, soil moisture and/or vapor pressure deficit (VPD) (Xiao et al., 2004). LUE-based models have been embraced for estimating spatial and temporal GPP dynamics on a large spatial scale (Wu et al., 2010a) as they are simple and easy to use, although they lack strong theoretical basis and sufficient understanding of ecosystem function (Feng et al., 2007). Alternatively, process-based models are based on plant ecological mechanisms (Liu et al., 1997). Process-based models try to simulate the sophisticated interaction processes between vegetation and atmosphere during plant growth such as photosynthesis, respiration and evapotranspiration (Feng et al., 2007). Process-based models include the boreal ecosystem productivity simulator (BEPS) (Liu et al., 1997) and dynamic land ecosystem model (DLEM) (Tian et al., 2010). Both BEPS and DLEM can simulate the carbon cycle and the water cycle, and their photosynthetic assimilations are based on the Farquhar model (Liu et al., 1999; Tian et al., 2010). As a big model, DLEM can also simulate the nitrogen cycle, and it includes an agriculture module and a city module (Tian et al., 2010). In contrast, BEPS is simple and hence easier to use. Considering the advantages of process-based models and that we only focused on GPP simulation in this study, we selected daily BEPS (BEPSd). This model was developed from the FOREST biogeochemical cycles (FOREST-BGC) model (Liu et al., 1997) and has been widely used in GPP, NPP and evapotranspiration (ET) simulations (Liu et al., 1999, 2002; Liu et al., 2003; Zhang et al., 2012a). There are also researches focusing on parameter optimisation in BEPS (Chen et al., 2012; He et al., 2014). Chen et al. (2012) studied the effect of the clumping index (Ω) on GPP simulation. He et al. (2014) used the ensemble Kalman filter method to optimise two key parameters (the water stress factor (f_w) and the maximum photosynthetic carboxylation rate at 25 °C($V_{m,25}$)) in BEPS and demonstrated their seasonal variations.

f_w and $V_{m,25}$ are two of the most important parameters in ecosystem models related to carbon uptake by vegetation (He et al., 2014). The soil water stress factor is included in most ecosystem models, e.g. W_ε in Carnegie-Ames-Stanford Approach (CASA) model (Potter et al., 1993), $f(LWP)$ in BEPSd (Liu et al., 1997), f_w in half-hourly or hourly BEPS (BEPSh) (Ju et al., 2006; Chen et al., 2012) and W_{scalar} in VPM (Xiao et al., 2004). These factors are calculated in different ways. In LUE-based models, e.g. CASA and VPM, the water stress factor is used to scale the maximum LUE (ε_{max}) (Potter et al., 1993; Xiao et al., 2004). It is computed using evapotranspiration information in CASA (Potter et al., 1993) and other factors in VPM (Xiao et al., 2004). In process-based models such as BEPSd and BEPSh, the water stress factor, parameterised using the soil water content (SWC) (Liu et al., 1997; Ju et al., 2006), is included in the Jarvis stomatal conductance (g_s) model (Jarvis 1976; Liu et al., 1997; Liu et al., 1999) and in the Ball-Woodrow-Berry (BWB) type equations (Ju et al., 2006). SWC used to calculate f_w is computed using soil water balance modules with a single soil layer (Liu et al., 1997) or multiple layers (Ju et al., 2006). It is demonstrated that f_w derived from a multi-layer model is more effective than that from a single layer model. Results averaged from five models, including BEPSd, showed that the GPP of evergreen Mediterranean oak woodlands was overestimated under drought (Vargas et al., 2013), probably because the stomatal conductance was overestimated under drought (Xu and Baldocchi, 2003; Vargas et al., 2013). The accurate estimation of f_w is critical in ecosystem models and is essential for studying carbon and water cycles.

V_m, calculated from $V_{m,25}$, has a significant impact on both vegetation photosynthesis and evapotranspiration in process-based ecosystem models (He et al., 2014). Houborg et al. (2015) employed a semi-mechanistic relationship between chlorophyll and $V_{m,25}$ based on previous works (Sage et al., 1987; Evans 1989; Friend 1995; Houborg et al., 2013) to study the constraint of leaf chlorophyll on GPP simulation in agricultural systems. Using chlorophyll as a constraint factor in an ecosystem model can improve the accuracy of GPP simulations. Croft et al. (2017) showed that the leaf chlorophyll content (LCC) and $V_{m,25}$ are highly correlated, with an R^2 value of 0.78 for deciduous forest samples, including trembling aspen, bigtooth aspen, red maple and ash. The intercomparison from 26 models suggested that GPP is overestimated during winter, spring and fall (Schaefer et al., 2012) when the LCC is low. However, few of the widely used ecosystem models include a chlorophyll constraint factor. It is likely that the overestimation of GPP during these periods when chlorophyll stays at a low level (early spring, late fall and winter) may result from the lack or insufficient consideration of chlorophyll constraint on modelling photosynthesis. However, a temporally and spatially continuous chlorophyll content record cannot be obtained easily. Previous studies demonstrated a strong relationship between chlorophyll and the vegetation index (VI). Wu et al. (2010c) showed a close correlation between vegetation indices (VIs) and canopy chlorophyll content (CCC). Dian (2011) also showed a strong relationship between VIs and both LCC and CCC. Thus, using a VI, e.g. the normalised difference vegetation index (NDVI), as the chlorophyll indicator is a good solution to the problem of attaining continuous chlorophyll. However, few of the widely used ecosystem models include a chlorophyll constraint factor. Thus, in the present study, we experiment by introducing a chlorophyll constraint factor into the BEPSd ecosystem model.

The objectives of this paper are (1) to evaluate the performance of the original BEPSd over Europe, (2) to improve the accuracy of GPP simulation using BEPSd by incorporating a new f_w in the g_s calculation formula, (3) to use NDVI as an indicator of chlorophyll to quantify the effect of chlorophyll on V_m by introducing a designed chlorophyll constraint factor (f_{ndvi}) into BEPSd and (4) to validate and compare the improved versions of BEPSd across Europe.

2. Method and data

2.1. Overview of BEPS

BEPS was initially developed at the Canada Centre for Remote Sensing to assist in natural resources management (Liu et al., 1997) especially for the boreal forest. Later, most of its applications were in North America (Liu et al., 1999, 2002; Liu et al., 2003; Liu et al., 2005; Ju et al., 2006; Mo et al., 2008; Govind et al., 2011; Zhang et al., 2012a; Gonsamo et al., 2013; He et al., 2014; Sprintsin et al., 2015) and also expanded for global applications (Zheng et al., 2015). It has been developed at the daily (Liu et al., 1997; Liu et al., 1999), the half-hourly (Ju et al., 2006), and the hourly step (Chen et al., 2012). In BEPS, GPP is simulated by scaling Farquhar's leaf level biochemical model up to the canopy level using a 'two-leaf' approach (He et al., 2014). In BEPSd, g_s is calculated using the Jarvis model, and V_m is parameterised by temperature and nitrogen content.

Some key equations pertaining to the carbon cycle in BEPSd are described as follows.

Daily gross primary productivity. Daily gross primary productivity is calculated in BEPSd as

$$A_{canopy} = A_{sun} LAI_{sun} + A_{shade} LAI_{shade} \tag{1}$$

$$GPP = A_{canopy} \times daylength \times Factor_{GPP} \tag{2}$$

where A_{canopy} is the assimilation rate of canopy in $\mu mol\,m^{-2}\,s^{-1}$, A_{sun} and A_{shade} are the assimilation rates of sunlit and shaded leaves, respectively. LAI_{sun} and LAI_{shade} are the leaf area index (LAI) values of the sunlit and shaded leaves, respectively. GPP is the gross primary productivity in $g\,C\,m^{-2}\,d^{-1}$, $daylength$ is the day of length in second, $Factor_{GPP}$ converts GPP unit into $g\,C\,m^{-2}\,day^{-1}$.