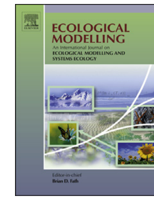
Ecological Modelling 292 (2014) 26–36

Contents lists available at ScienceDirect

Ecological Modelling

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



Variance-based sensitivity analysis of BIOME-BGC for gross and net primary production

R. Raj*, N.A.S. Hamm, C. van der Tol, A. Stein

Faculty of Geo-Information Science and Earth Observation (ITC), University of Twente, PO Box 217, 7500 AE Enschede, The Netherlands

ARTICLE INFO

Article history:
Received 27 March 2014
Received in revised form 12 August 2014
Accepted 14 August 2014
Available online 21 September 2014

Keywords:
Process-based simulator
BIOME-BGC
Gross and net primary production
Sensitivity analysis

ABSTRACT

Parameterization and calibration of a process-based simulator (PBS) is a major challenge when simulating gross and net primary production (GPP and NPP). The large number of parameters makes the calibration computationally expensive and is complicated by the dependence of several parameters on other parameters. Calibration can be simplified by first identifying those parameters for which GPP and NPP are most sensitive. For an appropriate application of a PBS, a sensitivity analysis is an essential step. Sensitivity analysis based on local derivatives (i.e., one-at-a-time analysis) does not examine the PBS behaviour over the whole parameter space. This study therefore implements a variance-based sensitivity analysis (VBSA) addressing the full range of PBS input. A VBSA is also independent of non-linearity in a PBS. This paper performs a VBSA of the process-based simulator BIOME-BGC for GPP and NPP output in a Douglas-fir stand at the Speulderbos forest site, The Netherlands. The results show that GPP and NPP are highly sensitive to the following parameters: fraction of leaf nitrogen in Rubisco, the ratio of fine root carbon to leaf carbon, the ratio of carbon to nitrogen in leaf and fine root, the leaf and fine root turnover, the water interception coefficient and soil depth. GPP and NPP are particularly sensitive to the ratio of fine root carbon to leaf carbon that is responsible for leaf area index development. The study concludes that a VBSA analysis provides a reliable and useful approach for a sensitivity analysis of process-based simulators with a complicated structure in the parameters.

1. Introduction

Forest gross and net primary production (GPP and NPP) are crucial measures of vegetation dynamics, as they determine carbon storage and biomass. Knowledge of these carbon fluxes is indispensable for understanding the ecology of forests. GPP refers to the total photosynthesis of a stand (Farquhar et al., 1980), expressed either as moles or as mass of gross CO_2 uptake per unit of soil surface and per unit of time. A part of the energy stored through photosynthesis is lost by plant respiration, leading to the emission of CO_2. The difference between GPP and plant respiration is referred to as NPP. Their behaviour over time thus reflects key processes in soil, plants and atmosphere interactions (Jung et al., 2008). Forest play an important role in global carbon cycle by controlling atmospheric CO_2 level via the process of photosynthesis. The global database of forest carbon budget developed by Luyssaert et al. (2007) summarized the GPP and NPP across forest biomes, which shows GPP ranges from 900 to 4000 $g\,C\,m^{-2}\,year^{-1}$ and NPP from 270 to 900 $g\,C\,m^{-2}\,year^{-1}$ with the highest value and uncertainty by tropical humid evergreen forest. Verma et al. (2013) showed the variation of GPP from 1023 to 2240 $g\,C\,m^{-2}\,year^{-1}$ across biomes with the highest uncertainty of 913 and 592 $g\,C\,m^{-2}\,year^{-1}$ by evergreen broadleaf and needleleaf forest respectively. Accurate quantification of GPP and NPP is always necessary for studying the carbon cycle.

Different models are available to estimate the GPP and NPP of forest ecosystems. First, regression models are based on empirically derived statistical relationships between the biometric parameters such as height and volume of trees and production (Tatarinov and Cienciala, 2006). Second, light use efficiency (LUE) models estimate GPP as the product of the radiation flux absorbed by the plant canopy as the main driver of photosynthesis and a term accounting for the conversion efficiency of absorbed radiation into organic matter (Ruimy et al., 1994; Running et al., 2004) that is usually calibrated against flux tower measurements. Because of this calibration against actual conditions, regression and LUE models do not incorporate changes due to forest growth, mortality, fires or other critical ecological processes. The third type of models, process-based simulators (PBS), simulate these processes, keeping account of carbon, nutrient and water stocks, and simulate state variables such as

* Corresponding author. Tel.: +31 685143519.
E-mail address: r.raj@utwente.nl (R. Raj).

http://dx.doi.org/10.1016/j.ecolmodel.2014.08.012

LAI that would otherwise be parameters. With a PBS, one could anticipate ecosystem activity including GPP and NPP by simulating different physiological plant responses to climatic conditions, atmospheric properties and plant structures, provided that they are well parameterized.

PBS's require input parameters that describe vegetation physiological and morphological characteristics. Implementation of PBS for specific sites is difficult due to the large number of parameters for plants and soil. This difficulty arises due to the incomplete knowledge of site specific input parameters for the occurring species. Therefore, values for those parameters are often taken from the literature. Uncertainty in these inputs leads to uncertainty in the simulated production, making calibration to measured GPP and NPP necessary. Calibration of a PBS is often computationally demanding, because it includes the optimization of several input parameters. It may not be necessary to calibrate all parameters, as some output variables may be independent of some specific parameters. Calibration can thus be simplified by first identifying the most influential parameters by means of a sensitivity analysis.

BIOME-BGC is a widely employed PBS to simulate carbon, water and nitrogen fluxes (Thornton, 1998; Thornton et al., 2002). BIOME-BGC requires 39 ecophysiological parameters, each having a different degree of influence on the simulated production. White et al. (2000) conducted a one-at-a-time (OAT) sensitivity analysis on BIOME-BGC for major natural temperate biomes in the USA. They tested sensitivity of simulated annual NPP to variation in parameter level of ±20% from the mean value. Variation in leaf and fine root C:N ratio and fraction of leaf nitrogen in Rubisco affected strongly the simulated NPP. Tatarinov and Cienciala (2006) reassessed the sensitivity as an OAT analysis of BIOME-BGC ecophysiological parameters (with ±10% variation from mean) to simulated NPP of major tree species in central Europe. They found that the effect of leaf C:N ratio was different for different species, whereas White et al. (2000) found that NPP decreased with increasing leaf C:N ratio for all woody biomes. The effect of the new stem carbon to new leaf carbon allocation ratio on NPP was also reported by Tatarinov and Cienciala (2006), but it was not observed by White et al. (2000). These studies suggest that results of a sensitivity analysis may vary according to specific species and region. This may also affect the choice of influencing parameters to be optimized in the calibration procedure of BIOME-BGC for specific species in different environmental and site conditions. OAT has two key limitations. First, it is a local sensitivity analysis (LSA) and it is thus only informative at the base point where it is computed and does not provide information over the rest of the input parameter space. This is contrast to a global sensitivity analysis (GSA) that quantifies the sensitivity over the whole input space and allows evaluation of interactions among the inputs (Saltelli et al., 2000). Second, it is not valid if the PBS output is non-linear or non-monotonic (Saltelli et al., 2008). BIOME-BGC, for example, shows a non-linear dependence between simulated fluxes (such as GPP) and the input parameters (Wang et al., 2001). Variance-based sensitivity analysis (VBSA) is a form of GSA that quantifies the sensitivity of a model output for a given set of probability distributions over the model inputs (Saltelli et al., 2000, 2008). Such an analysis allows identification of the most influential input parameters and provides insight into the model function (Hamm et al., 2006; Saltelli et al., 2008; Odongo et al., 2013).

In this study, we applied VBSA to the simulation of GPP and NPP using BIOME-BGC for Douglas fir (*Pseudotsuga menziesii*) at the Speulderbos forest site, The Netherlands. Our objectives were to identify the sensitivity of BIOME-BGC to the input parameters and to use this knowledge to gain insight into the simulator function. This information is of value for subsequent studies concerned with the calibration of BIOME-BGC and for making decisions about which parameters to target in a field campaign.

2. Study area

The Speulderbos forest is located at 52°15′08″ N, 05°41′25″ E within a large forested area in the Netherlands. A flux tower is placed within a dense 2.5 ha Douglas fir stand planted in 1962. The tree density at Speulderbos varies between 765 trees ha^{-1} in the eastern part of the stand to 812 in the west, with a mean tree height of 18 m in 1989, 22 m in 1993 and approximately 30–32 m in 2006 (Steingrover and Jans, 1994; Su et al., 2009). The single-sided leaf area index (LAI) varies between 8 and 11 throughout the year. These LAI values were estimated from allometric relationships, established for different crown levels from destructive sampling in the period 1989–1994 (Steingrover and Jans, 1994). The values agreed with optical (LAI2000) estimates in 1992 after accounting for a needle-shoot ratio of 1.7 (Steingrover and Jans, 1994). The topography is slightly undulating with height variations of 10–20 m within distances of 1000 m. Dominant species in the neighbourhood of the Douglas fir stand are Japanese Lark (*Larix kaempferi*), Beech (*Fagus sylvatica*), Scots Pine (*Pinus sylvestris*) and Hemlock (*Tsuga spp*). At a distance of 1500 m east from the tower the forest is bordered by a large heather area. In all other directions the vegetation consists of forest for distances of several kilometres. The soil at Speulderbos is a Haplic Podzol which is well drained with textures ranging from fine sand to sandy loam consisting of ice-pushed fluviatile deposits (van Wijk et al., 2001).

3. Methodology

Fig. 1 represents the adopted methodology for the sensitivity analysis of BIOME-BGC for GPP and NPP. Details are given in the subsequent sections.

3.1. BIOME-BGC

BIOME-BGC simulates carbon, water and nitrogen fluxes within the vegetation, litter and soil compartment of terrestrial ecosystem with a daily time steps (Running and Hunt, 1993; Thornton et al., 2002). It was developed originally for biomes. Species are not defined explicitly, although species-specific physiological characterization are reported extensively (White et al., 2000; Hessl et al., 2004). BIOME-BGC has been used to simulate fluxes of particular species: e.g. boreal black spruce (Bond-Lamberty et al., 2005), Norway spruce, Scots pine, common beech and oak (Tatarinov and Cienciala, 2006). BIOME-BGC generates output per square metre of a horizontally projected area and can be extended to the regional scale. Maximum physical boundaries of the simulation are defined by this horizontally projected area as well as the vertical extent of the canopy and its rooting system (Trusilova et al., 2009). The carbon budget simulated by BIOME-BGC includes all forest production output variables such as gross primary production (GPP), net primary production(NPP), net ecosystem production (NEP), and net ecosystem exchange (NEE). NEP is the difference between NPP and the carbon loss by heterotrophic respiration, which is estimated as a proportion of prescribed soil and litter carbon pool. NEE is the difference between NEP and the carbon loss by fire. BIOME-BGC uses the Farquhar biochemical model to estimate GPP (Farquhar et al., 1980; Thornton et al., 2002). This is estimated independently for the sunlit and shaded canopy fractions. Final GPP is the sum of these two fractions. GPP is a function of temperature, vapour pressure deficit, soil water content, solar radiation, atmospheric CO_2 concentration, LAI and leaf nitrogen concentration (Churkina and Running, 1998). Maintenance respiration is calculated as a function of leaf and root nitrogen concentration and tissue temperature. Growth respiration is the proportion of total new carbon allocated to growth. NPP is the difference between GPP and the sum of growth