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Research article

Development of the BIOME-BGC model for the simulation of managed Moso bamboo forest ecosystems

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ABSTRACT

Numerical models are the most appropriate instrument for the analysis of the carbon balance of terrestrial ecosystems and their interactions with changing environmental conditions. The process-based model BIOME-BGC is widely used in simulation of carbon balance within vegetation, litter and soil of unmanaged ecosystems. For Moso bamboo forests, however, simulations with BIOME-BGC are inaccurate in terms of the growing season and the carbon allocation, due to the oversimplified representation of phenology. Our aim was to improve the applicability of BIOME-BGC for managed Moso bamboo forest ecosystem by implementing several new modules, including phenology, carbon allocation, and management. Instead of the simple phenology and carbon allocation representations in the original version, a periodic Moso bamboo phenology and carbon allocation module was implemented, which can handle the processes of Moso bamboo shooting and high growth during "on-year" and "off-year". Four management modules (digging bamboo shoots, selective cutting, obtruncation, fertilization) were integrated in order to quantify the functioning of managed ecosystems. The improved model was calibrated and validated using eddy covariance measurement data collected at a managed Moso bamboo forest site (Anji) during 2011–2013 years. As a result of these developments and calibrations, the performance of the model was substantially improved. Regarding the measured and modeled fluxes (gross primary production, total ecosystem respiration, net ecosystem exchange), relative errors were decreased by 42.23%, 103.02% and 18.67%, respectively.

1. Introduction

Combustions of fossil fuels and changes in land use and land cover, such as those resulting from deforestation, are considered as the primary causes for the increasing concentration of atmospheric CO_2 (IPCC, 2007). At present, combating with climate change have shifted from focusing only on reducing CO_2 emission to an integrated approach of reducing anthropogenic CO_2 emission and conserving natural ecosystems with high carbon sequestration rate (Canadell and Raupach, 2008). Our ability to adequately prioritize conservation and restoration efforts relies on accurate estimates of the carbon stock and retention potential of various ecosystems (Keith et al., 2009). Carbon dynamics in forest ecosystems have received substantial attention from ecologists (IPCC, 1999; Sabine et al., 2004), and recent research has revealed the significant and great contribution of bamboo forests to carbon cycling (Chen et al., 2009; Isagi et al., 1997; Wang and Wang, 2003; Yen and Lee, 2011; Zhou et al., 2011).

Bamboos belong to the subfamily *Bambusoideae* in the family *Gramineae*, and have about 1500 species in the worldwide (Li and Kobayashi, 2004). Bamboo is an important forest type in subtropical and tropical regions (Song et al., 2011), with a total area of covering 31.5 million hectares globally, thus accounting for about 0.8 percent of the world's total forest area in 2010 (FAO, 2010). Although the total forest area has substantially reduced in many countries, bamboo forest area has gradually increased, due to the

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specific characteristics in regenerating asexually and high economic value (Guo et al., 2005). China has the most abundant species of bamboo in the world (>500 kinds by 39 species), and it has long been known as the "Kingdom of Bamboo". During the past 30 years, the bamboo industry of China has been rapidly developed, under the China's economic reforms. Bamboo forest area has increased steadily, as it currently reached about 6 million hectares (the Eighth National Forest Resource Inventory Report), 73.8% of which is covered by Moso bamboo (*Phyllostachys pubescens*) forests.

Moso bamboo reaches its full height in two to three months, thus representing one of the fastest-growing plants in the worldwide (Fu, 2001). It grows so rapidly in part due to the developed rhizome system, which enables the transport of carbonates and nutrients from full-grown to young culms by connecting them in the soil (Komatsu et al., 2012; Li et al., 1998). According to previous research, 1/4 of the biomass in tropical regions and 1/5 in subtropical regions is represented by bamboo (Zhou et al., 2005). This was because most of the Moso bamboo ecosystems are growing within the latitudes circumscribed by the Tropics of Cancer and Capricorn, thus its contribution to the global carbon sequestration could be substantial (Li et al., 2015).

Several researchers have explored carbon cycling in Moso bamboo forests and have synthesized information concerning primary production, biomass, litter production, carbon emissions, and other variables (Li et al., 2015; Yen and Lee, 2011; Zhou et al., 2011). These studies have confirmed that Moso bamboo forests are important carbon sinks and have a high carbon sequestration potential (Du et al., 2012; Li et al., 2003; Zhou et al., 2009, 2011). However, the characteristics of Moso bamboo forest carbon dynamic and their response to changing environmental conditions are still poorly understood (Xu et al., 2013). Numerical models are the handiest tool to accomplish this issue, because they use mathematics to describe the biogeochemical processes properly (Cramer et al., 2001; Oreskes et al., 1994; Vetter et al., 2008).

There are several types of numerical models that may be used in ecosystem analysis. Regression models are based on empirically derived statistical relationships between biometric parameters and production in the biome of interest (Reichstein et al., 2007; Yuan et al., 2007). Process-based models are essential scientific tools, which are based on a theoretical understanding of ecophysiological processes (Mäkelä et al., 2000). This kind of models describe the ecosystem functioning mechanistically (Cramer et al., 2001; Vetter et al., 2008) and provide a useful framework to incorporate specific responses to altered environmental conditions (Cuddington et al., 2013). Process-based models usually require various site and ecophysiological parameters to represent the interaction and development of biomass and soil components. Hence, parameterization is the most important step in applying process-based models (Van Oijen et al., 2005; Wang et al., 2009).

Generally, process-based models were designed to analyze biogeochemical cycles of undisturbed ecosystems (Vetter et al., 2008). Research in this field has focused on disturbed ecosystems, as the leading role of human activities in the formation of the land use and land cover in recent years (Vitousek et al., 1997). Moso bamboo forest ecosystem is frequently managed, and it has particular rhizome system, which connects the bamboo culms in the soil. Therefore, simulation of Moso bamboo forest should account the issues related to these specific managements and adequate representation of the rhizome system and carbon allocation (Isagi et al., 1997; Tang et al., 2012).

However, current process-based models are incapable to adequately quantify the CO_2 exchange processes of a managed Moso bamboo forest ecosystem. Thus, developing existing process-based models for simulating the CO_2 exchange processes of the disturbed Moso bamboo forest ecosystem has become necessary (Ciais et al., 2010). BIOME-BGC (Thornton and Rosenbloom, 2005) is a widely used biogeochemical model, developed to represent coniferous forests (evergreen and deciduous), broadleaf forests (evergreen and deciduous), grasses and shrubs.

Our main purpose was to further improve the functioning of the BIOME-BGC model for advancing its applicability in disturbed Moso bamboo forests. Our aim was to make significant improvements in the carbon allocation module with "on/off year" (see Section 2.3.1) and rhizome system characteristics (Qiu, 1984; Isagi et al., 1997). Phenology module was developed for providing the accurate litter fall rates and time period of the growing season. Furthermore, management modules were implemented for providing more realistic fluxes for managed Moso bamboo forests – including digging bamboo shoots, selective cutting, obtruncation and fertilization.

2. Materials and methods

2.1. Study site and eddy covariance measurements

The study site, Anji (30°28′N, 119°40′E), is placed in the northeast of Zhejiang Province, China. The site's elevation is about 380 m above sea level. The site is flat in southern and southeastern region, whereas moderately steep in the northern and northwestern. The average slope is 15°. Anji's climate is 'subtropical monsoon', with an average annual precipitation of 1100–1900 mm and an average annual temperature of 12.20–15.60 °C. The area (1000 m × 1000 m) around the flux tower comprises Moso bamboo forest. The average diameter at breast height of the bamboo was 9.3 cm (range: 6.90–11.30 cm). The bamboo density was about 3235 culms per hectare. The growth characteristics of bamboo forest are in an alternating 'on-year' and 'off-year' pattern (see Section 2.3.1). The odd-numbered years (e.g., 2009, 2011, etc.) were the on-years and the even-numbered years (e.g., 2010, 2012, etc.) were the off-years (Xu et al., 2013).

We compared the model output and measured data to accomplish the validation of the model simulation. CO_2 over the bamboo vegetation has been previously measured at the Anji site, by the eddy covariance technique (Xu et al., 2013). The eddy covariance technique is a key measurement technique to measure and calculate vertical turbulent fluxes within the atmospheric boundary layers, and has widely used in CO_2 fluxes evaluation (Baldocchi et al., 2001). The NEE (net ecosystem exchange) is the difference of TER (total ecosystem respiration; positive value) and GPP (gross primary production; positive value). So, the NEE is negative when the biosphere is a carbon sink. By the extrapolation of nighttime NEE to daytime, we partitioned the measured NEE into TER and GPP. For details of this method, see Reichstein et al. (2005).

2.2. Original BIOME-BGC model

2.2.1. Model description

BIOME-BGC is a typical ecological process model simulating physiological and ecological processes of ecosystems with high degree of integration, good extension, and therefore has been widely applied in many studies (e.g., Dixon et al., 1994; Running and Coughlan, 1988; Running and Gower, 1991; Running and Hunt, 1993; Thornton et al., 2000; Trusilova et al., 2009; White et al., 2000). The most important modules in BIOME-BGC are the carbon cycle module, phenology module, and soil flux module. In the carbon cycle module, the GPP of the ecosystem is calculated using De Pury and Farquhar's (1997) two leaf photosynthesis model. Autotrophic respiration is divided into maintenance respiration and growth respiration. Maintenance respiration is calculated using the function of the Q_{10} relationship model and the organization of the