Journal of Environmental Management 191 (2017) 126–135

Contents lists available at ScienceDirect

Journal of Environmental Management

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

Research article

Optimizing selective cutting strategies for maximum carbon stocks and yield of Moso bamboo forest using BIOME-BGC model

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ARTICLE INFO

Article history:
Received 7 March 2016
Received in revised form
6 January 2017
Accepted 8 January 2017

Keywords:
Ecosystem model
BIOME-BGC
Moso bamboo forest
Selective cutting
Optimization
Forest management

ABSTRACT

The selective cutting method currently used in Moso bamboo forests has resulted in a reduction of stand productivity and carbon sequestration capacity. Given the time and labor expense involved in addressing this problem manually, simulation using an ecosystem model is the most suitable approach. The BIOME-BGC model was improved to suit managed Moso bamboo forests, which was adapted to include age structure, specific ecological processes and management measures of Moso bamboo forest. A field selective cutting experiment was done in nine plots with three cutting intensities (high-intensity, moderate-intensity and low-intensity) during 2010–2013, and biomass of these plots was measured for model validation. Then four selective cutting scenarios were simulated by the improved BIOME-BGC model to optimize the selective cutting timings, intervals, retained ages and intensities. The improved model matched the observed aboveground carbon density and yield of different plots, with a range of relative error from 9.83% to 15.74%. The results of different selective cutting scenarios suggested that the optimal selective cutting measure should be cutting 30% culms of age 6, 80% culms of age 7, and all culms thereafter (above age 8) in winter every other year. The vegetation carbon density and harvested carbon density of this selective cutting method can increase by 74.63% and 21.5%, respectively, compared with the current selective cutting measure. The optimized selective cutting measure developed in this study can significantly promote carbon density, yield, and carbon sink capacity in Moso bamboo forests.

1. Introduction

Forests play an important role in the global carbon cycle, not only as carbon sources as a result of deforestation, but also as contributors to the sink that helps to balance the current disturbed budget (Lindner and Karjalainen, 2007; Pan et al., 2011; Rose and Sohngen, 2011). The forest ecosystem stored 861 ± 66 Pg C, comprises 70–80% of total terrestrial carbon (Pan et al., 2011; Baccini et al., 2012). Globally, total CO_2 emissions as a result of land-use change from 1850 to 1998 was 136 ± 55 Gt, of which about 87% derived from deforestation (IPCC, 2000). The atmospheric CO_2 concentration can reduce by either increasing forest cover or the abundance of plants with high carbon sequestration capability (FAO, 2015). Furthermore, certain key issues related to forestry, such as those known as Land Use, Land Use Change and Forestry and Reducing Emissions from Deforestation and Degradation, have been the focal points in a number of crucial environmental negotiations (Wu et al., 2009). Thus, strengthening research on forest management practices and their effects on ecosystems and the carbon cycle is becoming increasingly important (Moss et al., 2010; Susaeta et al., 2014).

Abbreviations: AGB, aboveground biomass; AGC, aboveground carbon; DBH, diameter of breast high; D_{LC}, days of leaf changing period; D_{new}, days of new bamboo leaves start growth to start litterfall; GPP, gross primary production; LR_N, average leaf litterfall rate during the whole year; L_{LCE}, leaf litterfall of Moso bamboo at *off year* during leaf changing period; L_{NE}, leaf litterfall of Moso bamboo at *off year* during normal days; L_{new}, leaf litterfall of new bamboo; L_{odd}, leaf litterfall of Moso bamboo at *on year*; LS_{LC}, leaf litterfall scalar; NEE, net ecosystem exchange; NPP, net primary production; R^2, coefficient of determination; S.E., standard error; δ, relative error.

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http://dx.doi.org/10.1016/j.jenvman.2017.01.016
0301-4797/

Bamboos belong to the subfamily *Bambusoideae* in the family *Gramineae*, which is divided into about 1450 species (Gratani et al., 2008). Bamboo is known as "the world's second largest forest" and is widely distributed in tropical, subtropical and warm temperate regions, from 46°N to 47°S, with its total area having reached 31.5 million hectares in 2010 (FAO, 2010). Bamboo has great economic value, playing an important role in replacing wood and maintaining the biosphere's CO_2 balance (Liu et al., 2013a; Xiao, 2001; Zhou et al., 2009, 2011). Although the total forest area has substantially reduced in many countries, bamboo forest area has gradually increased, largely due to its special characteristics of asexual reproduction and high economic value (Guo et al., 2005).

China is located in the center of the world's distribution of bamboo, and is the largest bamboo producer (Zhou et al., 2011). The country has more than 500 bamboo species of 39 genera (Chen et al., 2009), and is well known as the "bamboo civilized country" (Jung and Lowdermilk, 1996). The area of bamboo forest accounts for 2.97% of the total forest area (SFAPRC, 2015). Among the numerous bamboo resources, Moso bamboo (*Phyllostachys heterocycla cv. Pubescens*) —widely distributed in southern China—has the longest history of cultivation and utilization, the highest economic value (Jung and Lowdermilk, 1996), and great carbon sequestration capability (Li et al., 2015; Zhou, 2006; Zhou et al., 2009, 2011). The area of Moso bamboo has expanded rapidly since the 1950s (Zhang and Miao, 2000), reaching 6.16 million hectares, 73.8% of the total area of bamboo forest (SFAPRC, 2015). Thus, Moso bamboo plays a significant role in the development of China's bamboo industry.

Selective cutting is an essential method for maintaining the productivity (Lou et al., 1997; Yen and Lee, 2011). Because of the specific growth characteristics of Moso bamboo, the culms are cut according to age rather than DBH (Huang et al., 1996; Zhang and Miao, 2000). For this reason, research results from the selective cutting of other forest types cannot be applied to Moso bamboo forests (Chen et al., 1998; Xiong et al., 2007). To achieve maximum economic return, farmers usually harvest the old culms (aged 5 years and over) via selective cutting every two years during late autumn (Zhou et al., 2009). This selective cutting strategy was widely applied in Moso bamboo forests, improving bamboo timber production to a certain extent, but also resulting in a reduction in long-term site productivity (Liu et al., 2013a; Liu, 2009; Lou et al., 1997) and soil carbon storage (Li et al., 2013; Zhou et al., 2006). Furthermore, the timing and intervals adopted for selective cutting are generally estimated subjectively, and the effects of cutting intensity on the carbon cycle of Moso bamboo forests was still not clear (Li et al., 2015). Therefore, the current approach should be analyzed in detail, and improved methods should seek to reduce or eliminate the adverse impacts on long-term productivity and carbon storage (Du et al., 2010; Li et al., 2015).

One option to address this issue is to use ground measurements of carbon balance and productivity of managed Moso bamboo forests. However, such an approach is time- and labor-intensive, and thus measurements of this kind are spatially and temporally limited (Liao, 1986; Sun, 2010; Zhang and Chen, 2008). As a better alternative, numerical models, which use mathematical principles to describe the biogeochemical processes involved, can be used to accomplish this task (Cramer et al., 2001; Oreskes et al., 1994; Vetter et al., 2008). There are several types of numerical models that can be used in ecosystem analysis. Traditional models, like regression models, are based on statistical relationships, derived empirically, between production and biometric parameters (Yuan et al., 2007). Naturally, such models remain descriptive and are not so useful for incorporating changes in growth conditions (Reichstein et al., 2007). Hence, such models lack explanatory power in ecosystem analysis. Instead, so-called process-based models must be deployed, which simulate ecosystem development as a result of eco-physiological processes described mechanistically (Cramer et al., 2001).

In contrast to regression models, process models usually incorporate the effect of environmental change (e.g., land-use scenarios, nitrogen deposition, elevated CO_2, and changes in climate) on ecosystem functioning, including both soil and biomass components and their interactions (Vetter et al., 2008). BIOME-BGC (Running and Hunt, 1993; Thornton et al., 2002; Thornton and Rosenbloom, 2005; White et al., 2000) is a widely used biogeochemical model, developed to represent needleleaf forest (evergreen and deciduous), broadleaf forest (evergreen and deciduous), grasses and shrubs. BIOME-BGC was originally designed to represent the processes of natural biomes (Running and Hunt, 1993). However, recently, the model has also been applied to managed forest ecosystems (Petritsch et al., 2007; Tatarinov and Cienciala, 2006; Vetter et al., 2005).

Nevertheless, the simulation of Moso bamboo forest faces problems both in terms of the specific management measures involved and with adequately representing the rhizome system and carbon allocation (Isagi et al., 1997; Tang et al., 2012). Accordingly, we have improved the applicability of BIOME-BGC for managed Moso bamboo forest ecosystems by implementing several new modules, including phenology, carbon allocation, and management (digging bamboo shoots, selective cutting, obtruncation, and fertilization) (Mao et al., 2016). The present paper extends that work by analyzing the effects of the timing, interval, and intensity of selective cutting on the carbon cycle and long-term productivity of Moso bamboo forest. As part of this work, further improvements were made to BIOME-BGC so as to advance its applicability in the structure of vegetation carbon pools and selective cutting in Moso bamboo forest ecosystem.

2. Materials and methods

2.1. Field selective cutting experiment

2.1.1. Study area

The study site was located in the northwest of Zhejiang Province, China (30°10′N, 119°45′E), at an altitude of 90–100 m. The area has a monsoonal subtropical climate with four distinct seasons. In the study area, the annual average temperature, rainfall, sunlight, and frost-free period is 15.9 °C, 1442 mm, 1774 h, and 236 days, respectively. The main forest type is Moso bamboo forest. The density of bamboo is 2400–4300 culms per hectare, and the diameter of breast high (DBH) lies mostly between 8 and 10 cm.

2.1.2. Experiment design

The Moso bamboo forest was selectively logged twice during the study period. Culms aged 5 and over are cut during the selective cutting period; therefore, only culms aged 1–5 years remain distributed throughout the entire forest. In our study, the following three cutting intensities were defined for sampling: high-intensity cutting (cutting all culms aged 4 and 5); moderate-intensity cutting (cutting 50% of culms aged 4 and 5); and low-intensity cutting (no cutting). As shown in Fig. 1, a total of nine sample plots (30 m × 30 m) were surveyed for data collection, and each cutting intensity experiment was repeated three times. Each plot was surrounded by a 5 m buffer zone, and the data was collected from the central region (20 m × 20 m), to reduce the interference caused by rhizome spreading from adjacent plots.

2.1.3. Biomass measurement

Twice field surveys, during July of 2010 and July of 2013, were conducted for the collection of Moso bamboo biophysical