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The response of the net primary production of Moso bamboo forest to the On and Off-year management: A case study in Anji County, Zhejiang, China

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ABSTRACT

The On and Off-year management affects the carbon sequestration capacity and carbon allocation of Moso bamboo forest. However, to date, the impact of the On and Off-year management on stand-scale NPP has not been estimated. This paper used the Triplex-Flux model to estimate the 30-min averaged net primary production (NPP) and carbon use efficiency (CUE) of the Moso bamboo stand in Anji during the period 2011–2014. Comparison of the simulated NEP and NPP with the observed NEP from the eddy covariance measurements and the NPP from the previous studies in Moso bamboo forest showed that the Triplex-Flux model was suitable for NPP and CUE estimation in the Moso bamboo stand in Anji County. The annual averaged NPP and CUE were 835.58 $g\,C\,m^{-2}\,year^{-1}$ and 0.53 $year^{-1}$, which were higher than those of the other forest types in subtropical China. In Anji County, the On and Off-year management affects the NPP and CUE of Moso bamboo forest. Overall, the NPP and CUE in the On-year were higher than those in the Off-year. The selective bamboo cutting and culm sheaths hooking that lasts from September of the On-year to February of the Off-year reduced the NPP and CUE of Moso bamboo forest by 25.81% and 14.93%. The fresh bamboo shoots harvest in the Off-year significantly reduced the NPP and CUE of Moso bamboo forest by 40.17% and 16.36%.

1. Introduction

The IPCC Fifth Assessment Report showed that over the past decade, the Northern Hemisphere has been successively warmer than any preceding decade since 1850 (IPCC, 2013). The largest contribution to climate warming is caused by the increase in carbon dioxide concentrations since the 1950s. Moso bamboo (*Phyllostachys edulis*) forest has a strong carbon fixation ability, and plays an important role in the global carbon cycle (Chen et al., 2017). By fixing CO_2 and releasing O_2, Moso bamboo forest maintains the dynamic equilibrium of CO_2 and O_2 in the atmosphere, thereby slowing the rise of atmospheric carbon dioxide concentrations (Malhi et al., 1999; Poulter et al., 2014).

Moso bamboo forest is the main species of bamboo and widely distributed in tropical and subtropical regions of China. Moso bamboo forest covers an area of 3.87 million ha, accounting for 73.8% of the Chinese bamboo forest area (Wang et al., 2013; Song et al., 2016a). Being greatly different from other forest types, Moso bamboo forest is well known for its high growth rate. A bamboo shoot can reach a height of 10–20 m within two months (Xu et al., 2013; Song et al., 2016b). In recent years, Moso bamboo serves as a good substitute for wood, and is used to produce pulp, paper, board and charcoal products. So, it plays an important role in China's rural economy (Zhou et al., 2011; Zhang et al., 2017). Over the last three decades, the area of Moso bamboo forest grows rapidly with the averaged annual growth rate of about 3% (Song et al., 2013; Mao et al., 2016). Therefore, the study of net primary production (NPP) and carbon use efficiency (CUE) of Moso bamboo on stand-scale allows us to better understand the CO_2 fixation process in Moso bamboo forest, provide theoretical guidance for Moso bamboo forest management.

The On and Off-year management was widely applied in Moso bamboo forest in subtropical regions of China, and affected the carbon sequestration capacity and carbon allocation of Moso bamboo forest (Mao et al., 2016). How to monitor and evaluate the NPP of Moso bamboo forest, and analyze the impact of the On and Off-year management on NPP is a problem faced by ecologists.

So far, several studies focused on the NPP estimation in Moso bamboo forest, and the methods differed widely in complexity, but could be divided into two main categories: sample survey method (Wen et al., 2011; Zhou et al., 2011; Q.N. Song et al., 2017), and biogeochemical model (Mao et al., 2016, 2017; Chen et al., 2017). However,

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the researchers only analyzed the interannual variation of regional scale NPP in Moso bamboo forest (Mao et al., 2016; Xu et al., 2016b; Chen et al., 2017). To date the impact of the On and Off-year management on stand-scale NPP has not been estimated.

Triplex-Flux model is a biogeochemical model that uses the difference between gross primary production (GPP) and autotrophic respiration (R_a) to calculate NPP (Sun et al., 2008; Zhou et al., 2008). The model runs at each 30 min time step, and outputs the 30-min averaged GPP, NPP, and net ecosystem production (NEP). Therefore, it can be used to monitor and evaluate the NPP of Moso bamboo forest on the daily and monthly time scales, and analyze the impact of the On and Off-year management on NPP. So far, the Triplex-Flux model has been widely used to estimate the GPP, NPP and NEP of different vegetation types in North America, and the results were consistent with the observed NEP from the eddy covariance measurements ($R^2 \geq 0.62$) (Sun et al., 2008; Zhou et al., 2008; Li et al., 2015). However, the model has not been used in China.

Based on the site-level CO_2 flux data and meteorological data observed in Moso bamboo forest in Anji during the period 2011–2014, this paper used the Triplex-Flux model to simulate the 30-min averaged NPP. The objectives of this study were to (1) test the Triplex-Flux model in Moso bamboo forest in subtropical China, and (2) analyze the impact of the On and Off-year management on stand-scale NPP on the daily and monthly time scales.

2. Study area

In Anji, Moso bamboo forest is the main forest type, and covers about 43.7% of the total area of Anji. The On and Off-year management is widely applied in Moso bamboo forest, the odd-numbered years are the On-year, while the even-numbered years are the Off-year. In different seasons, the management of Moso bamboo in the On-year is different from that in the Off-year. In the winter (December, January, and February), farmers always cut the old bamboo (aged 5 years or over), the selective bamboo cutting and culm sheaths hooking lasts from December of the On-year to February of the Off-year. In the spring (March, April and May) of the On-year, farmers are forbidden to dig bamboo shoots, the bamboo shoots can reach the height of 10–20 m and breast diameter of 8–16 cm within two months (Song et al., 2016a), while in the spring of the Off-year, farmers usually dig bamboo shoots, and the two-year-old leaves and one-year-old leaves are all shed. In the summer (June, July, and August) of the On-year, the new bamboo fully expands the leaves in June, while in the summer of the Off-year, few new bamboo retained because of the bamboo shoots harvest in spring, and the old bamboo (aged 1–5 years) replaces and expands their leaves in the June of the Off-year. In the autumn (September, October, and November), the selective bamboo cutting and culm sheaths hooking is usually carried out from September to November in the On-year.

The Moso bamboo carbon flux tower site is located in southeast of Anji, China, with the longitude of 119°40′25.7″E, and lantitude of 30°28′34.5″N. The altitude of the site is 380 m, and the slope range is roughly from 2.5 to 14.0°. The main forest type of the 1 km × 1 km square around the site is Moso bamboo forest, combines with small proportion of shrubs, herbs, agricultural land and buildings. The height of the Moso bamboo ranges between 13 and 20 m, with the breast diameter of 12–18 cm.

The equipments at the site typically consist of a Campbell CSAT3 3D sonic anemometer (CSAT3, Campbell Inc., USA) and an open-path CO_2/H_2O gas analysers (Li-7500, LiCor Inc., USA) at 38 m above ground. The meteorological data observation equipments are also equipped at the site, and these are air temperature and relative humidity sensors (HMP45C, Vaisala, Finland) and wind speed sensors (010C, Met One, USA) with inlets at 1, 7, 11, 17, 23, 30, and 38 m above ground. The CNR4 net radiometer (CNR4, Campbell Inc., USA) which measures the energy balance between incoming and outgoing radiation is equipped at 15 m above ground. The soil temperature sensors (109, Campbell Inc. USA) and soil water probes (CS616, Campbell Inc., USA) are equipped at 5, 50, and 100 cm below ground.

3. Method and data

3.1. Triplex-Flux model

The Triplex-Flux model consists of three submodels: (1) the leaf photosynthesis submodel, based on the Farquhar's biochemical model (Farquhar et al., 1980) and Collatz's semi-analytical model (Collatz et al., 1991), estimates the instantaneous leaf gross photosynthetic rate (A) using the Rubisco-limited gross photosynthetic rate (V_c), light-limited gross photosynthesis rate (V_j), and leaf dark respiration (R_d) (Leuning, 1990; Chen et al., 1999; Cai and Dang, 2002). The equation of A is:

$$\mathrm{A} = \min(V_c, V_j) - R_d \tag{1}$$

(2) The canopy photosynthesis submodel, based on the De Pury and Farquhar's two-leaf model (De Pury and Farquhar, 1997), estimates the GPP as the sum of the canopy net assimilation rate of sunlit and shaded leaves (Chen et al., 1999; Zhou et al., 2008). The equation of GPP is:

$$\mathrm{GPP} = \mathrm{A_{sun}LAI_{sun}} + \mathrm{A_{shade}LAI_{shade}} \tag{2}$$

where $\mathrm{A_{sun}}$ and $\mathrm{A_{shade}}$ are the net CO_2 assimilation rate for sunlit and shaded leaves, $\mathrm{LAI_{sun}}$ and $\mathrm{LAI_{shade}}$ are the leaf area index for sunlit and shaded leaves.

(3) The ecosystem production submodel, based on the Lloyd and Taylor's empirical model (Lloyd and Taylor, 1994), estimates the NEP as the difference between the GPP and ecosystem respiration (R_e), and simulates the NPP by subtracting autotrophic respiration (R_a) from the GPP. The equations of NEP and NPP are as follows:

$$\mathrm{NEP} = \mathrm{GPP} - R_e \tag{3}$$

$$\mathrm{NPP} = \mathrm{GPP} - R_a \tag{4}$$

3.2. CUE estimation

Carbon use efficiency (CUE), defined as the ratio of NPP to GPP, describes the carbon fixation ability of forest (DeLucia et al., 2007). The CUE was calculated as:

$$\mathrm{CUE} = \mathrm{NPP/GPP} \tag{5}$$

ΔNPP, defined as the difference of the NPP in the On-years and Off-years, was calculated as:

$$\Delta\mathrm{NPP} = \mathrm{NPP_{on}} - \mathrm{NPP_{off}} \tag{6}$$

where $\mathrm{NPP_{on}}$ was the NPP in the On-year, and was the NPP in the Off-year.

3.3. Input data

The input data of the Triplex-Flux model can be divided into three types: (1) meteorological data, including the air temperature (T_a, °C), air relative humidity (rh, %), vapor pressure deficit (VPD, kPa), photosynthetic photon flux density (PPFD, $\mu\mathrm{mol\,m^{-2}\,s^{-1}}$), and soil temperature at 5 cm depth (T_s, °C). (2) the flux data, which is the CO_2 concentration in the atmosphere (C_a, $\mu\mathrm{mol\,mol^{-1}}$). (3) The vegetation index, which is the leaf area index (LAI).

The VPD is the difference between saturated water pressure (e_s, kPa) and actual water pressure (e_a, kPa). For the detailed algorithm of e_s and e_a, see Zhang et al. (2014). We used the photosynthetic quantum conversion factor (μ) for the conversion of the photosynthetically active radiation (PAR) to PPFD. For details see Zhou et al. (1996).

The abnormal data appeared in the eddy covariance CO_2 flux measurements due to the instrument failure, weather conditions and