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Quantifying driving factors of vegetation carbon stocks of Moso bamboo forests using machine learning algorithm combined with structural equation model

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A R T I C L E I N F O

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A B S T R A C T

Moso bamboo (*Phyllostachys pubescens*) is widely distributed in subtropical China and plays an important role in carbon cycling in terrestrial ecosystems. Knowledge of the main driving factors that affect aboveground carbon stocks in Moso bamboo forests is needed to increase carbon sequestration potential. We used a large-scale database from national forest continuous inventory from 2004 to 2014 in Zhejiang, China, and combined Random Forest analysis (RF) with structural equation modeling (SEM) to quantify the contribution of main driving factors on vegetation carbon stocks in Moso bamboo forests, and to evaluate the direct and indirect total effects of the main driving factors on aboveground carbon stocks, as well as to investigate changes in the standardized total effects from 2004 to 2014. The RF model explained 84.9% of the variation in 2004, 78.8% in 2009, and 82.2% in 2014. The SEM that included the average age, average diameter at breast height (DBH), culms density, mean annual temperature (MAT), and mean annual precipitation (MAP) explained 92.5% of the variation in 2004, 88.2% in 2009, and 88.6% in 2014. The results showed that average age, average DBH, culms density, MAT, and MAP were the most crucial driving factors of vegetation carbon stocks in Moso bamboo forests. The values of standardized total effects of the main driving factors showed that the average age, average DBH, and culms density had positive effects on vegetation carbons stocks, whereas MAT and MAP had negative effects. Furthermore, the positive effects of average age on the increase of vegetation carbon stocks increased significantly, the negative effects of MAT increased with the increasing MAT, but the negative effects of MAP decreased with the increasing MAP. Overall, our study provided new insights into the sensitivity and potential response of carbon sequestration in Moso bamboo forests to structural development and climate change in Zhejiang Province.

1. Introduction

Increasing atmospheric carbon dioxide (CO_2) concentration caused by human activities, for example by combustion of fossil fuels and deforestation, is considered one of the main drivers of global climate change (IPCC, 2014). Forests play an important role in the global terrestrial ecosystems carbon cycle, and the potential to sequester C is considered an important mitigation strategy to reduce the concentration of CO_2 (Luyssaert et al., 2007; Pan et al., 2011; Xu et al., 2016a). Therefore, an accurate investigation of the driving factors of vegetation carbon stocks in forests and quantitating the effects of main driving factors at regional and even at a global scale is important for understanding carbon dynamics and the potential of forest ecosystems to mitigate climate change.

The approximately 1500 bamboo species belong to the subfamily *Bambusoideae* in the family *Gramineae* (Gratani et al., 2008; Li and Kobayashi, 2004). Bamboo forests are widely distributed in the subtropical regions of Asia, Africa, and Latin America, with a total area of

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31.5 Mha, accounting for about 0.8% of the world's total forest area (FAO, 2010). Over 500 bamboo species in 39 genera grow in China. Moso bamboo (*Phyllostachys pubescens*) is widely distributed in the tropical and subtropical regions of eastern and southeastern Asia. Out of the 6 Mha bamboo forest area in China, Moso bamboo covers 74% (SFAPRC, 2015; Song et al., 2011). Moso bamboo forests have a unique growth pattern. The shoots usually begin to emerge from the ground at the end of March, and culms reach full height and full diameter at breast height (DBH) within months (Li et al., 1998; Song et al., 2016b; Zhou et al., 2010), suggesting that Moso bamboo biomass accumulates mainly in the initial growth stage for individual culms (Yen, 2016). Moso bamboo forests have a strong regeneration capacity, and the productivity of Moso bamboo forests increases gradually with the increase in bamboo culms (Nie, 1994). Under intensive management, the age structure of bamboo culms is homogeneous (Yen, 2015). Furthermore, Moso bamboo forests growth is characterized by alternating off and on years as a result of long-term harvesting activities (Chen, 1996; Zhou et al., 2010). During the on years, shoots are produced while the belowground rhizome grows slowly. During the off years, the belowground rhizome grows quickly while only a few shoots are produced.

Carbon stocks in Moso bamboo forests have been estimated based on remote sensing data (Du et al., 2009; Han et al., 2013; Li et al., 2017; Shang et al., 2013; Xu et al., 2011; Xu et al., 2016c), or carbon flux observations with the Eddy covariance technique (Song et al., 2017; Xu et al., 2016b; Xu et al., 2013). Moso bamboo forests are large carbon sinks with high carbon sequestration potential (Li et al., 2015; Li et al., 2013; Song et al., 2016b; Yen and Lee, 2011; Zhou et al., 2011a; Zhou et al., 2011b). Compared with Chinese fir forests, aboveground carbon sequestration in Moso bamboo forests was significantly higher (Yen and Lee, 2011). Furthermore, the carbon stocks of Moso bamboo forests in China could substantially increase in the next five decades (Chen et al., 2009).

The environmental and structural factors can significantly affect the carbon sequestration capacity of Moso bamboo forests; the carbon stocks were significantly affected by slope aspect and slope position (Fan et al., 2012), and the carbon stocks increased over the long-term with increasing culms density, average DBH, and culms age at a large scale (Xu et al., 2018b). However, the contributions of main driving factors and their change over the long-term at a regional scale remain poorly understood, which limits our understanding of the important role of Moso bamboo forests in the regional carbon budget and their contribution to mitigating climate change.

In this study, we collected data from 159 permanent Moso bamboo forest plots from 2004 to 2014 in Zhejiang, China. We used Random Forest analysis to identify the main driving factors of aboveground carbon stocks, and structural equation modeling (SEM) to evaluate the direct and indirect total effects of the main driving factors on vegetation carbon stocks. In addition, we estimated changes in the standardized total effects of the main driving factors. The approaches provide complementary insights on the patterns that drive vegetation carbon stocks over the long-term at a regional scale. The main objectives of our study were (1) to quantify the contributions of the structural and environmental driving factors and select the main driving factors, (2) to evaluate the direct and indirect total effects and changes in the standardized total effects of the main driving factors on vegetation carbon stocks, (3) and to reveal the response of vegetation carbon sequestration to structural development and climate change.

2. Materials and methods

2.1. Study area

The study area is in Zhejiang (118°01′–123°10′E, 27°06′–31°11′N), on the southeastern coast of China (Fig. 1). Zhejiang is in the central subtropical zone, and which has characterized by a typical subtropical monsoon climate with four distinct seasons. The average annual precipitation at the study site is 1100–2000 mm and the average temperature is 15–18 °C, as well as the average annual sunshine hours are 1100–2200 h. The terrain varies from mountains (with an average altitude of 800 m) in the southwest to hills in the central area and alluvial plains in the northeast (Mao et al., 2017). The primary vegetation types are coniferous evergreen forests, mixed coniferous forests, deciduous broad-leaf forests, and bamboo forests; the primary soil types are yellow and red soils. The conditions of altitude, temperature and humidity are more suitable for Moso bamboo culms growth than inland monsoon at the same latitude. At the end of 2014, forests area covered 6.05 Mha with the Moso bamboo forests accounted for 0.78 Mha and the average density of Moso bamboo was 3026 culms ha^{-1} in Zhejiang Province (DFZP, 2015).

2.2. Sample plots design and data collection

The vegetation dataset was collected from the 159 permanent Moso bamboo forests sample plots which were designed and sampled following the national forest continuous inventory protocols. The east-west interval distance between adjacent plots was 6 km, the south-north interval was 4 km, and each plot covered an area of 800 m^2 (Xu et al., 2018b). In each permanent sample plots, the environmental factors (slope, slope aspect, slope position, altitude, soil thickness, mean annual temperature (MAT), mean annual precipitation (MAP)), and structural factors (diameter at breast height (DBH), average age, total culms number, shrub coverage, herb coverage, shrub height, herb height, vegetation coverage, humus layer thickness, litter thickness) were recorded in 2004, 2009 and 2014. Slope, aspect, position, and altitude were measured with a hand-held GPS, an electronic total station, and a compass. The culm age was decided by the color of the bamboo pole in Moso bamboo forests (green bamboo pole represent 1–2 years old, yellow bamboo pole represent 5–6 years old, between green and yellow represent 3–4 years old). Soil thickness was measured using a soil excavation method (excavate the soil profile and excavate to the parent rock (bedrock) in sample plots), and structural factors were measured using sample plot survey methods (DFZP, 2014). The shrub and herb characteristics (average height, average ground diameter, and coverage) were measured from three randomly selected 2 m × 2 m quadrats in the sample plots (Xu et al., 2018b). The MAT and MAP data were obtained from the meteorological stations using kriging methods and the local statistical yearbook. The kriging interpolation analyses were performed using ArcMap 10.0 (Environmental Systems Research Institute, Inc., Redlands, USA).

The vegetation biomass of Moso bamboo forests in each permanent sample plots were estimated using forests biomass model designed by Yuan et al. (2009), which was based on long-term practical measurements of forest vegetation in Zhejiang, including hardwood broadleaf, softwood broadleaf, pine (*Pinus*), Chinese fir (*Cunninghamia lanceolata*), bamboo, shrub, and herb biomass models (Dai et al., 2018; Xu et al., 2018a) (Table 1). The total vegetation biomass of Moso bamboo forests was a sum of the biomass of bamboo culms, shrub and herb. Furthermore, the total vegetation carbon stocks were calculated by multiplying the total vegetation biomass per unit area (Mg ha^{-1}) with the carbon conversion coefficient (Tan et al., 2007; Tao et al., 2014; Zhang et al., 2007) (Table 1). It was worth to note that belowground parts (e.g. rhizome, root) of the Moso bamboo forests were not investigated in this study.

2.3. Data analysis

We used the average vegetation carbon stocks of the sample plots multiplied by the area of Moso bamboo forests to determine the total vegetation carbon stocks. Then we performed Random Forest algorithm to identify the importance of environmental and structural factors (Liaw and Wiener, 2002). RF algorithm is an ensemble method proposed by Breiman (2011) in 2001, which extends standard classification