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Spatial pattern of carbon stocks in forest ecosystems of a typical subtropical region of southeastern China

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ABSTRACT

Spatial pattern information of carbon (C) density and storage in forest ecosystems plays an important role in the evaluation of C sequestration potential and forest management practices. However, such information related to subtropical forests still remain poorly understood. In this study, we collected forest samples from 838 plots in a typical subtropical forest of Zhejiang Province, southeastern China. The Moran's I, geostatistics and geographical information system (GIS) techniques were applied to reveal the spatial pattern of C stocks in forest ecosystems. The results showed that the mean C density of forest ecosystems in Zhejiang Province was 145.22 Mg ha^{-1}, and the forest vegetation, soil, litter, and dead wood layer C densities were 27.34, 108.89, 1.79, and 1.38 Mg ha^{-1}, respectively. The spatial distribution of forest ecosystems C density showed a decreasing trend from the southwest to northeast area, roughly in line with Zhejiang Province's topographic feature, as well as differences in land use, forest management, economic and social development. In addition, the C storage of forest ecosystems in Zhejiang Province was approx. 877.19 Tg (1 Tg = 10^{12} g), with 203.88 Tg in the vegetation layer, 656.20 Tg in the soil layer, 10.84 Tg in the litter layer, and 6.27 Tg in the dead wood layer, accounting for 23.24%, 74.81%, 1.24%, and 0.71% of the total C storage, respectively. These results indicated that the soil layer is the most important contributor to C storage in subtropical forest ecosystems. The young and middle-aged forests with low C densities dominated in the study area. Therefore, in order to enhance the C sequestration potentials, forest management should focus on the selection of tree species, management of stand-age structures and implementation of sustainable afforestation and reforestation practices in the future.

1. Introduction

The increasing concentration of atmospheric CO_2 and its contribution to global warming has become a well-known phenomenon and long-term large-scale research topic (IPCC, 2007; Jones et al., 2009; Alam et al., 2012). Mitigation methods mainly include reducing anthropogenic CO_2 emission and enhancing the potentials of C sequestration by terrestrial ecosystems (Litton et al., 2007; Luyssaert et al., 2010). Forest ecosystems are receiving special attention and could play a leading role in the regional and global C cycles as they store approx. 80% of all above-ground carbon and 40% of all below-ground terrestrial carbon (Dixon et al., 1994; Pan et al., 2011). Therefore, C sequestration in forest ecosystems is identified as an effective and economic approach for mitigating the CO_2 concentration in the atmosphere and global warming (Bonan, 2008; He et al., 2016), as well as for improving productivity, ecological functioning, and sustainability of the Earth System (Liao et al., 2009).

However, the greenhouse effect and global warming may directly and indirectly have impacts on accelerating forest ecosystems to become net sources of C to the atmosphere (Stinson et al., 2011; Alam et al., 2012), and may cause huge changes in forest structure, composition, and functional processes (Alexander et al., 2012; Zhang and Liang, 2014). It is therefore significant important to estimate C storage in forest ecosystems and evaluate C sequestration potentials that affect the net C balance in order to explore the direction and magnitude of feedback from forest ecosystems to global warming. This knowledge could assist forest management practices to improve mitigation efforts dealing with global climate change.

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In recent decades, substantial advancements concerning the C storage and their sequestration potentials are mainly related to tropical (Körner, 1998; Cernusak et al., 2013; Cavaleri et al., 2015), temperate (Magnani et al., 2007; Thurner et al., 2014), and boreal forest ecosystems (French et al., 2000; Johnstone et al., 2010; Alam et al., 2012). However, the subtropical forest ecosystems received relatively less attention to their role in the C cycle of terrestrial ecosystems (McEwan et al., 2011; He et al., 2013; Li et al., 2013; Conti et al., 2014). Rosenfield and Souza (2013) found that subtropical forests had been indicated to have high biodiversity and great potential for C accumulation. Yu et al. (2014) also reported that the subtropical forest ecosystems played a critically important role in global climate change and CO_2 sequestration. The total net ecosystem productivity (NEP) of East Asian monsoon subtropical forest ecosystems was estimated to be 0.72 ± 0.08 Pg C yr^{-1}, which contributes approx. 8% to the global NEP of forest ecosystems. Therefore, these findings suggested that the role of subtropical forest ecosystems in the global C cycle and dynamics should not be ignored.

Zhejiang Province is located in a typical subtropical region of southeastern China, as well as has abundant forest resources and high forest productivity (Liu et al., 2002). Extensive research on forest resources and C storage in Zhejiang Province have been conducted in the recent decade. For example, Zhang et al. (2007) studied that C density, C storage, and their dynamics in ecological service forests (ESFs) by using 149 sample plots data in mountainous areas of Zhejiang Province. Jiang et al. (2011) conducted an experiment to calculate C fixation ability of three forest stands at Linlong Mountain in Lin'an County of Zhejiang Province. Fu et al. (2014b, 2015) reported that spatial variation of C density in forest vegetation and forest litter layer, but failed to estimate the corresponding C storage, its sequestration potential and total C storage of forest ecosystems in Zhejiang Province. Furthermore, forest ecosystems C storage is characterized by high spatial and temporal variability owing to natural factors (e.g., topography, forest type and age) (McEwan et al., 2011; Posse et al., 2016; Lin et al., 2017) and human disturbances (e.g., land-use change) (Ren et al., 2013; Conti et al., 2014). Appropriate forest management practices require a deep understanding of the spatial variation of forest ecosystems C storage by producing high-efficiency spatial distribution maps in order to support further C sequestration research. Currently, the C storage of forest ecosystems in Jilin (Wang et al., 2011) and Heilongjiang (Wang et al., 2012) in northeast part of China, had reported the total forest ecosystems C sequestration, but there is no accurate and complete report for subtropical region of China's Zhejiang Province, including vegetation, soil, litter, and dead wood layer.

The main objectives of this study were (1) to characterize the spatial variation of C density in forest ecosystems, and (2) to accurately estimate the C storage in forest ecosystems in Zhejiang Province of southeastern China. It is expected that the findings of this study can guide sustainable forest management practices in subtropical forest regions.

2. Materials and methods

2.1. The study area and sampling site description

The study area was carried out in Zhejiang Province of southeastern China (118°01′-123°10′ E and 27°06′-31°11′ N) (Fig. 1). The total land area is 101,800 km^2, accounting for 1.1% of China's total land area. It has complex topography including plains, basins, mountains, and hills with altitudes gradually decreasing from southwest to northeast (Zhi, 2014). Zhejiang Province has a subtropical marine monsoon climate with an average annual rainfall of 1490 mm and mean annual temperature of 16.5 °C. According to the Soil Taxonomy of China, the soils are mainly red soils, red-yellow soils, and yellow soils (Liu et al., 2002). The total area of forest is approximate 60,406 km^2 accounting for 59.34% of the total land area in Zhejiang Province (Tao et al., 2014). The primary forest types include evergreen broad-leaved forest, coniferous forest, mixed coniferous broad-leaved forest, bamboo forest and others (such as economic forest) (Fu et al., 2015).

In 2012, a total of 838 forest plots (28.28-m × 28.28-m per plot) were established in the whole forest regions, based on a grid system of 4-km (E-W) × 6-km (S-N). Relevant information related to forest plots such as forest type and age, canopy density, litter thickness, soil type and physical-chemical properties, slope aspect and position, human activities (e.g., forest harvesting and fertilizer use), was collected and recorded. The portable global positioning system (GPS) was used to record the longitudes, latitudes and altitudes of forest plots. In each forest plot, we also sampled forest vegetation, soil, and litter for use in further laboratory analysis.

Lu et al. (2012) reported that the C storage in dead wood is the fourth largest C pool in forest ecosystems. Therefore, to explore explicitly spatial patterns of C stocks in Zhejiang's forest ecosystems, based on the information provided by Forest Resources Monitoring Center in Zhejiang Province, the corresponding mean dead wood layer C density (1.38 Mg ha^{-1}) and the C storage (6.27 Tg) in this study were calculated (Tao et al., 2014).

2.2. Data collection and analysis

2.2.1. Forest vegetation survey and relevant C estimation

Three duplicate quadrats with a size of 10-m × 10-m were created at each forest plot, we measured the tree height, crown length, and diameter at breast height (DBH ≥ 5.0 cm). In addition, both the shrub and herb samples were measured at least three 2-m × 2-m sub-quadrats randomly distributed in each quadrat, and then we documented the basic information of the shrub and herb, such as average height, average ground diameter, and coverage. The corresponding vegetation biomass (above-ground and roots biomass) was estimated using forest biomass model designed by Yuan et al. (2009), which was based on long-term practical measurements in forest vegetation of Zhejiang Province, mainly including hard broad, soft broad, pine (*Pinus*), Chinese fir (*Cunninghamia lanceolata*), bamboo, shrub, and herb biomass models (Table 1). For each forest plot, the total biomass was a sum of biomass of each vegetation types in the plot.

The C density of the forest vegetation biomass was calculated by multiplying the forest vegetation biomass per unit area (in Mg ha^{-1}) with the corresponding C conversion coefficient (Tan et al., 2007). The value of 0.50 (Karjalainen, 1996) was determined as the conversion coefficient, which is confirmed by the previous studies (Zhang et al., 2007; Ren et al., 2011). Based on the data of forest vegetation biomass C density, we performed spatial interpolation using kriging method to develop a forest vegetation biomass C density (FBCD) map of the forest area in Zhejiang Province. This map could provide FBCD value (in Mg ha^{-1}) and the corresponding area (in m^2). Then, the total C storage of forest vegetation biomass in Zhejiang Province was calculated. The formula was as follows:

$$\mathrm{FBCS} = \sum_{i=1}^{n} \mathrm{FBCD}_i \times \mathrm{Area}_{\mathrm{grid}} \times 10^{-12} \quad (1)$$

where FBCS is the total C storage of forest vegetation biomass (in Tg) in the study area, n is the total number of grids, i is the ith grid square, FBCD_i is the forest vegetation biomass C density (in Mg ha^{-1}) for the ith grid square, and $\mathrm{Area}_{\mathrm{grid}}$ is the area (in m^2) of each grid square. All of these calculations were performed using the ArcMap 10.2 software package.

2.2.2. Soil sampling collection and estimation of soil C storage

Soil profile samples, which were divided into four layers (0–10, 10–30, 30–60 and 60–100 cm) (Thickness less than 100 cm of soil profiles measured at actual depths), were collected from the forest plots, giving a total of 2799 soil samples. The corresponding soil bulk