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Spatiotemporal patterns of carbon storage in forest ecosystems in Hunan Province, China

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ABSTRACT

Forest ecosystems act as a carbon sink and contribute to climate change mitigation. Research on the spatiotemporal patterns of C storage and density in forest ecosystems is essential to understand the role of forest ecosystems in the C sink and is helpful to select the efficient forest management practice to maximize the C sequestration potential. We quantified the C storage in forest ecosystems in Hunan Province in southern China over two decades by combining forest inventory data with field survey. The C storage in forest ecosystems in Hunan Province increased from 820.2 Tg to 1277.8 Tg over the two decades, with 457.6 Tg (134.4 Tg in vegetation and 323.2 Tg in soil) of C sequestration in the forest ecosystems. Forest C storage increased sharply from 1996 to 2007, but slowly from 2007 to 2015. The mean annual C sequestration was 25.8 Tg yr^{-1}, with 19.0 Tg yr^{-1} in soil and 6.8 Tg yr^{-1} in vegetation. The C density in forest ecosystems increased from 110.3 Mg ha^{-1} in 1996 to 130.8 Mg ha^{-1} in 2013. C densities varied in forest types, with the highest value in evergreen broadleaved forest ecosystems. The uneven spatial distributions of forest C storage, density, and sequestration in Hunan Province exhibited similar pattern with the highest in the western Hunan and the lowest in the central Hunan. The forest ecosystems in Hunan Province present a significant C sequestration potential (1321.5 Tg, including 1029.2 Tg in biomass C and 292.3 Tg in soil C), given the proportion of the area of young and middle-aged forests (71.3%). To maximize the C sequestration potential of forest ecosystems in Hunan Province, future forest management should focus on the conversion of forest type, the selection of tree species in reforestation, and the prevention of adverse human disturbances in young and middle-aged forests.

1. Introduction

Forest ecosystems play an important role in carbon (C) sequestration to mitigate global climate change and significantly contribute to the global C balance (Dixon et al., 1994). Forest ecosystems store more than 80% of aboveground C in terrestrial ecosystems, more than 70% of global soil organic C (Six et al., 2002), and more than double the amount of C in the atmosphere (FAO, 2006; Pan et al., 2011). Annual C sequestration in forest ecosystems accounts for two thirds of that in terrestrial ecosystems (Liu et al., 2000). The accurate quantitative evaluation of C stocks in forest ecosystems and their temporal and spatial patterns is critical for understanding the mechanisms that control the global terrestrial C cycle and is fundamental to formulating climate change policies on sequestering anthropogenic CO_2 emissions (Keith et al., 2009; Ren et al., 2013). As a result, the estimation of C storage in forest ecosystems on large spatial scales has received increasing attention (Pan et al., 2011; Ren et al., 2013; Köhl et al., 2015; Gray et al., 2016; Hoover and Smith, 2017; Vargas-Larreta et al., 2017; Tang et al., 2018).

Numerous studies on the spatial and temporal patterns of C storage in forest ecosystems have been conducted on national, regional, and global scales, which have provided evidence of the importance of forest ecosystems in global C cycle (Kauppi et al., 1992; Dixon et al., 1994; Houghton and Hackler, 2000; Fang et al., 2001; Pan et al., 2011). However, uncertainties remain in forest C storage estimates. For example, the C storage estimates for forests in China differ substantially, ranging from 3.3 Pg to 11.5 Pg of biomass C (Liu et al., 2000; Fang et al., 2001; Li et al., 2004; Xu et al., 2010; Guo et al., 2013; Zhao et al., 2014). Zhou et al. (2000) investigated the spatial heterogeneity of C density in forest ecosystems in China and found that the C density in

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vegetation decreased and the C density in soil increased with the increase in latitude. The spatial heterogeneity of C density in forest ecosystems may be one of the main causes of the variations in forest C storage estimates. Moreover, the incomplete knowledge of the temporal dynamics of forest C storage limits the accuracy of estimates of forest C sequestration and sink (Cui et al., 2015). The estimates of C sequestration rate in European forests differ by more than 10-fold, ranging from 0.068 Pg yr^{-1} to 0.7 Pg yr^{-1} (Nabuurs et al., 2003). The C sequestration rate in China forests ranges from 0.021 Pg yr^{-1} to 0.14 Pg yr^{-1} (Liu et al., 2000; Fang et al., 2001; Li et al., 2004; Xu et al., 2010; Guo et al., 2013). For American forests, the rate of C sequestration vary from 0.067 Pg yr^{-1} to 1.7 Pg yr^{-1} (Fan et al., 1998; Houghton and Hackler, 2000). Aside from different geographic regions (spatial heterogeneity), time range may be a reason for the large discrepancies in the rate of forest C sequestration. Houghton and Hackler (2000) found that the rate of C sequestration in American forest ecosystems increased from 10 Tg yr^{-1} in 1700 to 400 Tg yr^{-1} in 1880 and then decreased to approximately zero by 1950. Thus, the knowledge of the spatio-temporal patterns of C storage in forest ecosystems is essential to understand the role of forest ecosystems in C budget and global climate change mitigation.

Data source is another cause of the variations in forest C storage estimates. Among a few studies on forest C storage estimation in China, Fang et al. (2001), Guo et al. (2013), and Liu et al. (2000) used China's forest inventory data. Forest inventory data that come from continuous monitoring on a national or regional scale are the most reliable data used to estimate forest C storage and assess the functions of forests as C sinks (Fang et al., 2001; Goodale et al., 2002; Nabuurs et al., 2010; Wang et al., 2011b). Although many studies on forest C storage and sink that have used forest inventory data on a large scale have obtained reliable results, several drawbacks remain in forest C storage estimates. First, a high spatial heterogeneity of forest C density exists on a small scale, which causes the differences in forest C storage reported by many papers and the imprecise results of forest C storage on a large scale (Ren et al., 2013). Second, C storages in understories, litters, and soils are disregarded (Cui et al., 2015), which leads to the underestimation of forest C storage and sink. Third, a C concentration coefficient of 0.5 is usually adopted to estimate forest C storage (Liu et al., 2000; Fang et al., 2001). In fact, the C concentration coefficients of many tree species, especially broadleaved species in mixed forests in the subtropical region of China, are less than 0.5 (Chen et al., 2005; Gong et al., 2011; Zeng et al., 2013). Consequently, an overestimation of forest C storage is yielded when the coefficient of 0.5 is used. These deficiencies increase the uncertainties in forest C storage estimates and ultimately result in inaccurate and incomplete estimates of forest C storage and sinks. Thus, it is necessary to thoroughly estimate forest C storage in a small scale, to reevaluate the C sequestration capability of forest ecosystems as C sinks.

Several papers have reported the estimates of comprehensive C storage in forest ecosystems in a few provinces in China, such as Anhui, Hainan, Gansu, Guangdong, Jilin, and Shaanxi (Wang et al., 2011a; Ren et al., 2013, 2014; Cui et al., 2015; Guan et al., 2016; Ji et al., 2016), and these data help to increase the accuracy of the estimates of forest C storage on a national scale. However, integrated research for Hunan Province is lacking, although several estimations of forest tree C storage with large variations have been conducted on the basis of forest inventory data (Hu et al., 2005; Jiao et al., 2005; Wu and Zhou, 2015; Xia et al., 2016). These reports on forest C storage did not include understory, litter, and soil, hence resulting in the underestimation of C storage in forest ecosystems in Hunan Province. Moreover, no report is available on the spatial distribution and temporal change of forest ecosystem C storage in Hunan Province. These gaps result in an inaccurate estimation of forest ecosystem C storage and leads to an obstacle to an exact understanding of the roles of forest ecosystems in the C budget in Hunan Province.

Here, we examined the spatial and temporal patterns of C storage in forest ecosystems in Hunan over two decades from 1996 to 2015 to accurately estimate forest ecosystem C storage and understand the C budget of forest ecosystems on a provincial scale. The specific objectives were to determine (1) the spatial and temporal patterns of C storage and density in forest ecosystems in Hunan Province over the two decades and (2) the changes in the C sequestration rates of forest ecosystems in Hunan.

2. Material and methods

2.1. Description of Hunan Province

Hunan Province, situated in the mid-subtropical zone of China, covers an area of 21.18×10^4 km^2, ranging from 108°47′E to 114°15′E and from 24°38′N to 30°08′N, at an elevation of 21–2122 m above sea level. Hunan is located at the transition zone from the Yunnan–Guizhou Plateau to the lower mountains and hills on the southern side of the Yangtze River. This area represents 2.2% of China's land and consists of mountains (51.2%), hilly lands (29.3%), plains (13.1%), and rivers and lakes (6.4%). Mountains surround on the three sides of east, south, and west, with a gradual tilt to the central and northeast of Hunan Province. The climate of this region is continental humid mid-subtropical monsoon. The mean annual air temperature is 16–18 °C with the maximum in July and the minimum in January. The mean annual precipitation is 1200–1700 mm, of which approximately 68–84% falls between April and October (Chen et al., 2016b).

The soil type of forests is red-yellow soil (mainly in the east of the Wuling and Xuefeng Mountains below an altitude of 700 m), yellow soil (in the west of the Wuling and Xuefeng Mountains between an altitude of 500 and 1200 m), yellow brown soil (above an altitude of 1000 m), purple soil (in the Hengyang Basin), fluvoaquic soil (in the plain), and calcareous soil (in Sangzhi County in Zhangjiajie) according to Chinese Soil Taxonomic Classification. The native vegetation is natural evergreen broadleaved forest in subtropics, with *Castanopsis* spp., *Cyclobalanopsis* spp., and *Quercus* spp. as the dominant species. Existing forests mainly include evergreen broadleaved forest, Chinese fir (*Cunninghamia lanceolata*) plantation, Masson pine (*Pinus massoniana*) plantation, slash pine (*Pinus elliottii*) plantation, cypress (*Cupressus funebris*) plantation, poplar (*Populus* spp.) plantation, eucalyptus (*Eucalyptus* spp.) plantation, bamboo forest, *Cryptomeria*, *Taxodium*, and *Metasequoia* forests, and open forest of above types. The forest coverage in Hunan Province increased from 51.1% in 1996 to 59.5% in 2015, with 0.42% of the annual increase (Fig. 1). In 2015, the highest forest coverage (above 70%) was in the west of Hunan Province, including Huaihua, Zhangjiajie, and Xiangxi, followed by the south (including Chenzhou, Yongzhou, and Shaoyang) and the east (including Zhuzhou

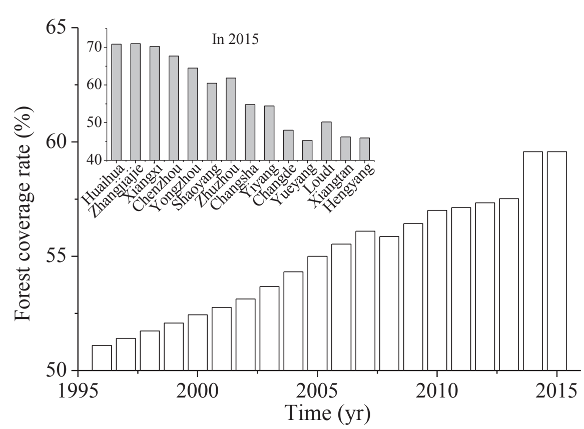

Fig. 1. Changes in the forest coverage rate in Hunan Province from 1996 to 2015. The gray bar in a smaller figure inserted the larger figure showed forest coverage rates of 14 prefecture-level cities in Hunan in 2015.