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Carbon stocks and potential carbon storage in the mangrove forests of China

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ABSTRACT

Mangrove forests provide important ecosystem services, and play important roles in terrestrial and oceanic carbon (C) cycling. Although the C stocks or storage in terrestrial ecosystems in China have been frequently assessed, the C stocks in mangrove forests have often been overlooked. In this study, we estimated the C stocks and the potential C stocks in China's mangrove forests by combining our own field data with data from the National Mangrove Resource Inventory Report and from other published literature. The results indicate that mangrove forests in China store about 6.91 ± 0.57 Tg C, of which 81.74% is in the top 1 m soil, 18.12% in the biomass of mangrove trees, and 0.08% in the ground layer (i.e. mangrove litter and seedlings). The potential C stocks are as high as 28.81 ± 4.16 Tg C. On average, mangrove forests in China contain 355.25 ± 82.19 Mg C ha^{-1}, which is consistent with the global average of mangrove C density at similar latitudes, but higher than the average C density in terrestrial forests in China. Our results suggest that C storage in mangroves can be increased by selecting high C-density species for afforestation and stand improvement, and even more by increasing the mangrove area. The information gained in this study will facilitate policy decisions concerning the restoration of mangrove forests in China.

1. Introduction

Combustion of fossil fuel and changes in land use, such as those resulting from deforestation, are considered the primary causes for the increasing concentration of atmospheric CO_2 (IPCC et al., 2007). Current strategies to combat climate change have shifted from focusing only on reducing CO_2 emission to an integrated approach of reducing anthropogenic CO_2 emission and reinforcing CO_2 sequestration and storage via conservation of natural ecosystems with high carbon (C) sequestration rates (Canadell and Raupach, 2008). For example, the United Nations Collaborative Programme REDD+ (Reduced Emissions from Deforestation and Forest Degradation in Developing Countries) proposed financial incentives for forest management that controls C emission (Miles and Kapos, 2008). Our ability to adequately prioritize conservation and restoration efforts relies on accurate estimates of the C stock and C retention potential of various ecosystems (Keith et al., 2009). Although C dynamics in terrestrial forests and oceanic ecosystems have received the most attention from ecologists (IPCC, 1999; Sabine et al., 2004), recent research has underscored the importance and disproportionate contribution of mangrove forests in C cycling (Alongi, 2012; Donato et al., 2012; Ren et al., 2010).

Mangrove forests are ecotone ecosystems that occur along most tropical and subtropical coastlines and provide a broad array of ecosystem services. In addition to purifying water (Duke et al., 2007) and dissipating waves, they provide important habitats for wildlife and nutrient supplies to adjacent ecosystems (Wang and Wang, 2007). Mangrove forests also rank among the most C-rich forests (Alongi, 2012), with a large portion of C allocated belowground (Kristensen et al., 2008; Mcleod et al., 2011). While occupying only a small percentage (<0.1%) of Earth's continents' surface, mangroves are responsible for 10–11% of the total export of terrestrial C to the ocean and for 8–15% of the C deposited in coastal sediments (Dittmar et al., 2006; Joshua et al., 2012; Jennerjahn and Ittekkot, 2002).

Several reviews have explored C cycling in mangrove forests and synthesized primary production, biomass, litter production, decomposition, C emission, and other variables of mangrove forests

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(Bouillon et al., 2008; Breithaupt et al., 2012; Suratman, 2008; Twilley et al., 1992). These reviews have confirmed that mangrove forests are important C sinks and have high capabilities to sequester C. These reviews, however, mostly focused on the quantities of C imported, produced, and exported per year, and largely ignored the quantity of C that is trapped by mangrove forests. The quantity of C trapped becomes especially important as it relates to the quantity of C that will be released if mangrove forests are cleared or degraded. A recent study quantified the global mangrove C stocks (or C storage, an indicator of the quantity of carbon stored in mangrove forests) based on published literature but did not include mangrove forests in China (Siikamäki et al., 2012). A few studies have attempted to quantify mangrove ecosystem C for specific stands in China (Mao et al., 2011, 2012; Ren et al., 2010), but no study has addressed C stocks and C retention potential in mangrove forests at the national level. Such information is needed for designing management policy and approaches for mangrove forests in China.

A volume-derived method based on forest inventory data is often used to estimate the C stocks in terrestrial forests in China (Fang et al., 2001; Ren et al., 2013; Zhou et al., 2008). Unfortunately, this method cannot be applied to mangrove forests because, due to their exclusion from the national inventory, mangrove forest volume data are not available. Instead, analysis of previously published data combined with extensive field sampling is considered an effective method for estimating the C stocks or C dynamics in mangrove forests at the global or regional scale (Alongi, 2012; Bouillon et al., 2008; Donato et al., 2012; Siikamäki et al., 2012; Twilley et al., 1992). We used this integrated method here.

The objectives of this study were to 1) quantify the current C stocks in mangrove forests in China, and 2) quantify the potential for C storage in the future. We also discussed the implications of these data for mangrove forest management.

2. Methods

2.1. Data sources

We obtained data from three sources: the National Mangrove Resource Inventory Report in 2002 (Ministry of Forestry, 2002), published biomass and soil C data in the literature, and collections and measurements by ourselves for this study. The National Mangrove Resource Inventory Report in 2002 was the most comprehensive inventory available and provided the area and forest type classification data. The survey was conducted in 2001 and the State Forestry Bureau issued *National mangrove survey technical regulations* and organized training programs. This report included inventory data covering 95,680.9 ha and 5909 compartments and contains data on area, distribution, community types, land ownership, forest ownership, origin, mangrove plantation age, canopy density, tree height class, and mangrove management situation. We used this report to determine the main community types and community areas.

The second source was published data of ecosystem C storage. Ecosystem C storage includes vegetation C (aboveground and root C), ground layer C (i.e. C in mangrove litter and seedlings), and soil C. We searched data of mangrove forest in China using "China Knowledge Resource Integrated Database" and "Google Scholar Database" up to the end of 2012. The third source was field data we collected in this study.

2.2. Field sampling and laboratory analysis

Similar to the C assessment of terrestrial forests, our overall sampling design considered both geographical and species factors. At least three duplicative plots were sampled at each sampling site. In each plot, aboveground and belowground biomass and soil C were measured. Regional C stocks were derived combining plot level soil C with area data. We quantified the ecosystem C density of 13 mangrove forest types that account for 80.6% of the total mangroves area. The C storage of the remaining 19.4% of mangroves was estimated using the mean C density of the 13 forest types except that the biomass of *Sonneratia apetala, Bruguiera sexangula, Bruguiera gymnorrhiza* came from published literature. Of the 13 mangrove forests, five are monospecific mangrove forests (i.e. they contain only one species of mangrove: *Avicennia marina, Aegiceras corniculatum, Kandelia candel, Rhizophora stylosa,* and *Sonneratia caseolares*), and the rest are mixed forests of five species (*A. marina, A. corniculatum, K. candel, R. stylosa,* and *B. gymnorrhiza*).

The final data base included 113 sites for biomass measurement (76 sites were sampled in this study, and 37 sites were assessed in previous studies), 39 sites for ground layer C measurement (all 39 sites were sampled in this study), and 49 sites for soil C measurement (30 sites were sampled in this study, and 19 sites were assessed in previous studies) (Table 1, Fig. 1). Field sampling at each site in this study was conducted as following:

Among 76 sites that we conducted field sampling for biomass measurement, three 10 m × 10 m plots were established at each site. For biomass measurement of monospecific forests, in each plot, we recorded tree diameter at breast height (DBH), basal diameter (D_0), and tree height. At one *B. gymnorrhiza* site in Guangdong province we measured diameter at 0.6 m ($D_{0.6}$) since there are many branches under breast height. We adopted region-specific allometric equations for each type mangrove forest from previous studies to calculate tree biomass (Wen, 1999; Supplementary Table S3). In regions where allometric equations were not available, we used the "mosaic stratified cutting method" to derive allometric equations with three to seven standard trees. The standard trees were trees with the average DBH in the plot. We

Table 1
Mangrove forest type, area, and number of sites used for determination of biomass carbon (C), ground layer C, and soil C.

Forest type	Area/total mangrove area (%)	Number of sites from which biomass C, ground layer C, and soil C data were obtained		
		Biomass C	Ground layer C	Soil C
A. marina	18.7	5 + 6*	3*	7
A. corniculatum	18.0	10 + 9*	3*	3*
K. candel	3.4	9 + 2*	3*	9
R. stylosa	2.7	2 + 5*	3*	3
S. caseolares	1.9	1 + 2*	3*	3*
A. marina + R. stylosa	3.8	3**	3*	3*
A. marina + A. corniculatum	7.2	3**	3*	3*
R. stylosa + K. candel-A. corniculatum + A. marina	4.6	3**	3*	3*
R. stylosa-A. corniculatum	2.7	3**	3*	3*
R. stylosa-A. corniculatum + A. marina	3.0	3**	3*	3*
B. gymnorrhiza + K. candel-A. corniculatum	2.6	3**	3*	3*
K. candel-A. corniculatum	9.0	3**	3*	3*
K. candel-A. corniculatum + A. marina	2.9	3**	3*	3*
S. apetala	0.1	3 + 8*	–	–
B. sexangula	0.3	2	–	–
B. gymnorrhiz	0.4	6 + 5*	–	–
Total	80.5	75 (27 + 24*+24**)	39*	49 (19 + 30*)

* sites sampled in the current study; **sites where we only surveyed the proportion of each species in a mixed forest; for numbers without *, data were obtained from published papers.