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Comparing carbon sequestration and stand structure of monoculture and mixed mangrove plantations of *Sonneratia caseolaris* and *S. apetala* in Southern China

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ABSTRACT

Mangroves are one of the most carbon-rich tropical ecosystems. Two fast-growing mangrove species of the genus *Sonneratia*, the native *S. caseolaris* and non-native *S. apetala*, have been widely used for mangrove reforestation in China; however their ability to sequester carbon is still unclear. The present study aimed to estimate the growth, carbon accumulation in biomass and carbon sequestration in sediments of these two species, in both mixed (50% *S. caseolaris*; 50% *S. apetala*) and monoculture plantations, in the intertidal zones of Shenzhen Bay, Guangdong Province, China. Twenty-five months of observation showed strong competition between the two species in the mixed plantation, with the native *S. caseolaris* outcompeting the non-native *S. apetala* due to a faster growth rate. Although *S. caseolaris* in the mixed plantation had lower carbon storage in biomass than in monoculture, carbon accumulation in sediment was higher in the mixed plantation. Thus, the relative advantage of the mixed plantation was in sequestering more carbon in sediment, as opposed to high carbon accumulation to biomass. These results indicated that the mixed plantation could be a good option for mangrove restoration and carbon sequestration of sediment. However, the two and a half years of this study may not indicate long-term trends, so more research on long-term species performance is essential for successful mangrove reforestation.

1. Introduction

"Blue carbon", as defined in a recent United Nations Environment Programme (UNEP) report, refers to carbon captured by living organisms and stored in sediments of coastal wetlands including mangroves, salt marshes and seagrasses (Nellemann et al., 2009). The global net primary production (NPP) of mangroves is estimated to be 218 Tg a^{-1} of carbon, accounting for nearly half of the total NPP of all coastal wetlands (Bouillon et al., 2008). Thus, mangroves are one of the most carbon-rich forest types in the tropics (Donato et al., 2011), in addition to supporting numerous important ecosystem services such as protecting coastlines and providing food or nursery grounds for birds and coastal animals (Chapman, 1976; Lin, 1988; Tomlinson, 1986). However, mangrove areas are becoming smaller or more fragmented, and their ecosystem services are functionally disappearing worldwide (Duke et al., 2007). Mangroves in China have likewise been degraded seriously with a great reduction in area during the last three decades due to human disturbance (Chen et al., 2009). The total mangrove area in China in 2002 was estimated at approximately 22,700 ha, less than 10% of the historical extent (Chen et al., 2009). Consequently, the Chinese government has invested greatly in mangrove reforestation since the 1990s.

In China, some non-native mangrove species have been used extensively in mangrove reforestation projects because of their high survival and fast growth rates (Chen et al., 2009). *Sonneratia apetala* Buch. Ham was introduced from Bangladesh in 1985 and has been planted in many locations along the coastline of China over the last three decades. The total area of *S. apetala* forests is estimated at more than 80% of the total area of mangrove plantations in China (Chen et al., 2009). *Sonneratia caseolaris* (Linn.) Engl., a congener of *S. apetala* indigenous to Hainan Province, China, has also been widely used in mangrove replanting projects not only in Hainan but also in other regions beyond its historical range, such as in Shenzhen Bay, Guangdong Province (Wang et al., 2002; Chen et al., 2008).

In forest ecosystems, the two largest carbon pools are the living tree biomass and organic matter stored in soil (Fahey et al., 2009;

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Sharma et al., 2010). Therefore, increased carbon sequestration in these two parts directly enhances the total carbon sequestration ability of the forest ecosystem. The productivity of mangrove forests (e.g., aboveground carbon) has been widely studied all over the world (reviewed in Komiyama et al., 2008). Belowground carbon in mangroves, on the other hand, is still quite uncertain, but the average for estuarine sites in general is 71–98% of total ecosystem carbon (Donato et al., 2011). As an important part of belowground carbon, the amount of carbon stored in belowground biomass varies greatly among species (Komiyama et al., 2008). Furthermore, forest plantations with different carbon sequestration rates resulted in different carbon gains in the soil (Fahey et al., 2009). The amount of carbon stored in sediments of the individual mangrove ecosystems varies greatly, from 0.5% to 40% (Kristensen et al., 2008; Laffoley and Grimsditch, 2009). The carbon can be derived from local mangrove production or imported by tide or rivers from adjacent coastal environments and deposited within mangroves (Bouillon et al., 2003; Laffoley and Grimsditch, 2009). Furthermore, mangrove afforestation not only results in direct carbon inputs of mangrove production to the sediment pool, but also increases sedimentation rates (Perry and Berkely, 2009). As sedimentation rates increase, more and more carbon from adjacent environments is deposited. Ren et al. (2010) concluded that the planting of non-native *S. apetala* in Leizhou, China, had great potential to sequester carbon in sediment. However, we know less about sediment carbon sequestration of the native *S. caseolaris*, although it has been shown to have higher aboveground productivity than *S. apetala* (Wang et al., 2002).

Although monoculture forests frequently have low biodiversity and ecological value (Sayer et al., 2004; Kelty, 2006), the vast majority of plantations globally are monocultures (FAO, 2001). In China, many mangrove reforestation programs likewise utilize a monoculture approach, aiming for simplicity of stand management and a homogenous appearance of the planted trees. Such programs include planting *S. apetala* in Guangdong and Fujian Provinces, and *Kandelia obovata* in Fujian Province (Chen et al., 2009). Mixed mangrove plantations have recently been recommended to increase biodiversity, food web connectivity and net ecosystem production (Alongi, 2011). For example, in a small-scale mangrove plantation program in China, the non-native *S. apetala* was planted together with native mangrove species, such as *S. caseolaris* (Zan et al., 2003). Both *Sonneratia* species have high tolerance to environmental stresses and can thrive in low inter-tidal zones where other indigenous species have difficulty surviving (Liao et al., 2004), however little is known about their effects on ecosystem biogeochemistry. In the present study, we set up a field manipulation experiment in both monocultures and a mixed plantation of these two *Sonneratia* species in an intertidal mudflat in Shenzhen Bay. We compared carbon accumulation and eco-physiological traits in order to test the hypothesis that the mixed plantation consisting of both *Sonneratia* species will exhibit strong inter-specific competition and will accumulate more carbon in both biomass and sediment compared to monocultures of either species. Such information will increase our knowledge of best practices for design and species selection in mangrove afforestation.

2. Materials and methods

2.1. Study site

The study was carried out in Futian Mangrove Nature Reserve (22°31′N, 114°05′E), located in Shenzhen Bay in Shenzhen City, Guangdong Province, China. The area is characterized by a subtropical monsoonal climate, with 1927 mm of annual precipitation and a rainy season from May to September. The mean annual relative humidity is approximately 80% and the mean air temperature is 22 °C, with a maximum average of 38.7 °C in July and minimum of 0.2 °C in January. Tides are irregular semidiurnal, with the average tidal range of 1.36 m and a spring tidal range of about 1.9 m. From 2005 to the end of 2007, climatic data such as air temperature and precipitation were obtained from the website of the Hong Kong Observatory, shown in Fig. 1.

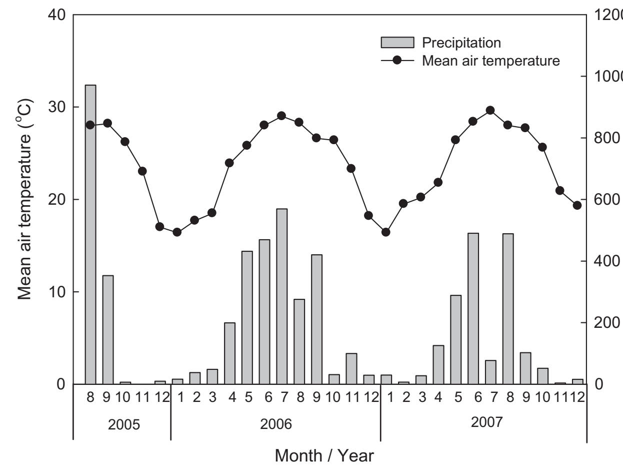

Fig. 1. Monthly precipitation and mean air temperature at Shenzhen during the 25 months of the experiment.

The sediment in the mangrove plantations studied was composed primarily of silt and sand (16.2% of sand, 82.3% of silt and 1.44% of clay in average) with a depth of 50–70 cm. The sediment had relatively high levels of organic material, and the humus content was about 3–5%. The pH of the seawater was 7.23–8.05 (average of 7.66). The average salinity of sediment was 25.6 PSU (practical salinity units).

2.2. Experimental design

Seedlings of *S. apetala* and *S. caseolaris* were cultured in a nursery near the study plots in the mudflats of Futian Mangrove Nature Reserve for 1 year before transplant. The average heights of *S. apetala* and *S. caseolaris* were 1.13 m and 1.14 m, respectively, at the time of planting.

In August 2005, we established three types of quadrats to study biomass, community structure and competition: a monoculture of *S. apetala*, a monoculture of *S. caseolaris*, and a 1:1 mixture of both species. We planted 100 seedlings in every 10 m × 10 m quadrat (density of one seedling m^{-2}), according to the replacement series (or substitutive) design (Vandermeer, 1989; Snaydon, 1991), where the mixture treatment was planted at the same density as the monoculture treatments. Four replicates were used for each treatment, for a total of twelve quadrats. The quadrats were established randomly in the mudflats of the mid intertidal zone with similar tidal inundation period and frequency, and retaining a buffer zone of no less than 10 m between each quadrat.

2.3. Sediment sampling

A soil cutting ring was used to collect a defined volume of surface (layer) sediment in each quadrat. Samples were oven-dried at 60 °C. Soil bulk volume was calculated as the ratio of soil dry weight to the soil cutting ring's volume. Soil bulk volume was measured before planting and after 2.5 years. The mean bulk volume of the surface layer sediment was 0.66 g cm^{-3} in all plots. Salinity of the surface layer of the sediment was 25.6 PSU (practical salinity units), as measured using an optical refractometer.