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REGULAR ARTICLE

Biomass accumulation and carbon storage of four different aged *Sonneratia apetala* plantations in Southern China

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Abstract The objectives of this study were to examine plant biomass accumulation and carbon (C) storage in four different aged *Sonneratia apetala* plantations in the Leizhou Bay in South China. The allometric equations using diameter at breast height (DBH) and height (H) were developed to quantify plant biomass. The total forest biomass (TFB) of *S. apetala* plantation at 4, 5, 8, and 10 years old was 47.9, 71.7, 95.9, and 108.1 Mg ha^{-1}, respectively. The forest biomass C storage in aboveground (AGB) and roots at 4, 5, 8, and 10-year plantation was 19.9, 32.6, 42.0, 49.0 Mg ha^{-1}, respectively. Soil organic C (SOC) on the top 20 cm of sediments increased by 0.3, 6.8, 27.4, and 35.0 Mg ha^{-1}after 4, 5, 8, and 10 years of reforestation, respectively. The average annual rate of total carbon storage (TCS) accumulation at 4, 5, 8, and 10-year *S. apetala* plantation was 5.0, 7.9, 8.7, and 8.4 Mg ha^{-1} yr^{-1}, respectively. The TCS values in this study were underestimated because we only estimated SOC storage on the top 20-cm sediments in these plantations. This study suggests these young S. *apetala* plantations have the characteristics of fast growth, high biomass accumulation, and high C storage capacity, especially in sediments. They sequestrated C at a high but varying rate over time. The large-scale reforestation of *S. apetala* plantations in the open coastal mudflats in southern China has great potential to sequestrate more C as well as restore the degraded coastal land. The potential ecological issues associated with the increasing monoculture plantations were discussed. More long-term monitoring and research are needed to further evaluate biomass and C accumulation of *S. apetala* plantations over time as well as how the increasing distribution of this monoculture plantation will influence the few native mangrove remnants.

Keywords *Sonneratia apetala* plantation · Mangrove forest · Biomass · C storage · Soil organic C · Southern China

Abbreviations

AGB	Aboveground biomass
AGCS	Aboveground C storage
BGB	Belowground biomass
BGCS	Belowground C storage
C	Carbon

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DBH	Diameter at breast height
H	Height
SOC	Soil organic C
TFB	Total forest biomass
TCS	Total carbon storage

Introduction

Mangrove ecosystems are forest associations of the intertidal zones at tropical and subtropical coastal areas (Lugo 1999) and play important ecological, social and economic roles. For example, mangrove forests support the marine biodiversity through food web and habitat and provide important regulatory functions such as coastal erosion and flooding control (Snedaker 1984; Field 1998; Macintosh et al. 2002). However, most native mangroves along the shorelines of China are threatened or degraded by clearance for shrimp ponds, over-cropping for timber, alteration of water flow patterns, environmental pollution, and increasing urbanization (Ren et al. 2008). Environmental degradation and the energy crisis in coastal land have stimulated an increased interest in establishing fast growing and high yielding plantations on degraded coast zone (Lin 1999; Ren and Peng 2001). The rationale for mangrove restoration has changed from mainly reforestation to recognition of diverse ecological services provided by mangroves. The term “restore” is meant the creation of a sustainable functioning mangrove ecosystem that may or may not resemble its precursor at the very same site (Bosire et al. 2008). One of ecological services mangrove forests provide is their significant capacity for carbon (C) sequestration (Twilley et al. 1992; Fujimoto 2004; Bouillon et al. 2008).

Mangrove forests currently cover an estimated 14.7 million ha of the tropical shorelines of the world (Wilkie and Fortuna 2003). This represents a decline from 19.8 million ha in 1980 and 15.9 million ha in 1990 (Bosire et al. 2008). Decline of mangrove forests was also observed in China. Most of the mangrove forests are distributed along the southeast coast of China. The total area of mangrove decreased from 50,000 ha in 1950 to 15,000 ha in 1990s due to the forest harvest, agriculture, and fish/shrimp pond development. In early 1990s, China initiated a 10-year mangrove reforestation project. The mangrove forests in China have increased to 22,000 ha since then (Wang and Wang 2007). According to the recent action plan of China Forestry Bureau (CFB), 2,000 ha mangroves have been planted each year during 2003–2007. Most of mangrove plantations have been established in South China. As one of the largest natural mangrove forests and plantations in China, the mangrove in Leizhou Bay of Zhangjiang City, South China, provides ecologists with an ideal place to explore community structure, function and succession of mangrove plantations (Lin et al. 2006).

Sonneratia apetala is one of the woody mangrove species with high adaptability and seed production. The species is naturally distributed in India, Bangladesh and Sri Lanka as a dominant species in local mangrove communities (Jayatissa et al. 2002). The species was introduced into China in 1985 for reforestation purposes and has been planted in more than 1,000 ha since 1991 (Ren et al. 2008). Due to its adaptability to poor habitat and fast growth, *S. apetala* has been recommended as a suitable species to restore the degraded coastal area. South China has about 1,135 km shoreline, which is suitable for the restoration of mangrove ecosystems. The establishment of *S. apetala* plantations in this region has the potential to sequestrate more C. However, the aboveground and belowground biomass accumulation and C storage of introduced mangrove *S. apetala* plantations in South China are largely unknown. Most studies focus on the morphology, biological characteristics and adaptability of ecological factors of *S. apetala* since the introduction of this species to South China (Snedaker 1984; Soares 1997; Formard 1998; Swamy et al. 2004; Soares and Nivelli 2005; Lin et al. 2006; Ren et al. 2008). Very few C storage data of mangrove forests including *S. apetala* plantations in China are available. Although the area covered by mangrove forests on the global scale represents only a small fraction of tropical and subtropical forests, their position at the terrestrial-ocean interface and potential exchange with coastal waters suggests these forests make a unique contribution to C biogeochemistry in coastal ocean (Twilley et al. 1992; Bouillon et al. 2008). The C storage data of mangrove forests in China is needed to better estimate the global C budget of mangrove forests.

We hypothesized that the biomass accumulation and C storage at both aboveground and belowground increased with plantation ages but belowground C accumulated at a faster rate than the aboveground C over time. The objectives of this study were to: 1) examine four different aged *S. apetala* plantation biomass accumulation in both aboveground plant components and roots in the Leizhou Bay in South China; 2) estimate C storage in plant biomass and sediments of the four different aged *S. apetala* plantations; and 3) discuss implications for C sequestration by restoring the degraded coastal area in southern China.

Materials and methods

The study area is situated in Leizhou Bay coast, about 20 km from Leizhou City (109°03'E, 20°30'N), Guangdong Province, southern China (Fig. 1). The annual average temperature is 22.9°C (28.4°C in July and 15.5°C in January) and the mean annual precipitation is 1,711 mm (about 73% in the rainy season from April to October and 27% in the dry season from November to March). The sediments in these mangrove forest plantations are acid soil with less bioturbation due to few activities of crab fauna. In the study area, a freshwater channel passes through the edge of the woodland and provides year-round fresh water from a sea-dike. The site is at the landward side of the intertide. Regular tides affect the stand greatly. The ground surface is about 1.5 m under water at high tide, and 0.6–1.2 m above water at low tide.

Extensive native mangroves historically covered the area. However, due to human disturbances, only small patches of natural stands remain. The area of mangroves in Leizhou Bay decreased by 1,676 ha during 1980–2005, mainly due to its transformation to aquatic farms, which plays an important role in the growth of local economy. In the 1990s, much of the mudflats and mangrove areas of Leizhou Peninsula were designed as mangrove reserves by the forestry sector. Restoration of mangroves has ever since been practiced. Native species such as *Kandelia candel* and *Avicennia marina* (Forsk.) Vierh were initially widely planted but most of them died. *S. apetala* was

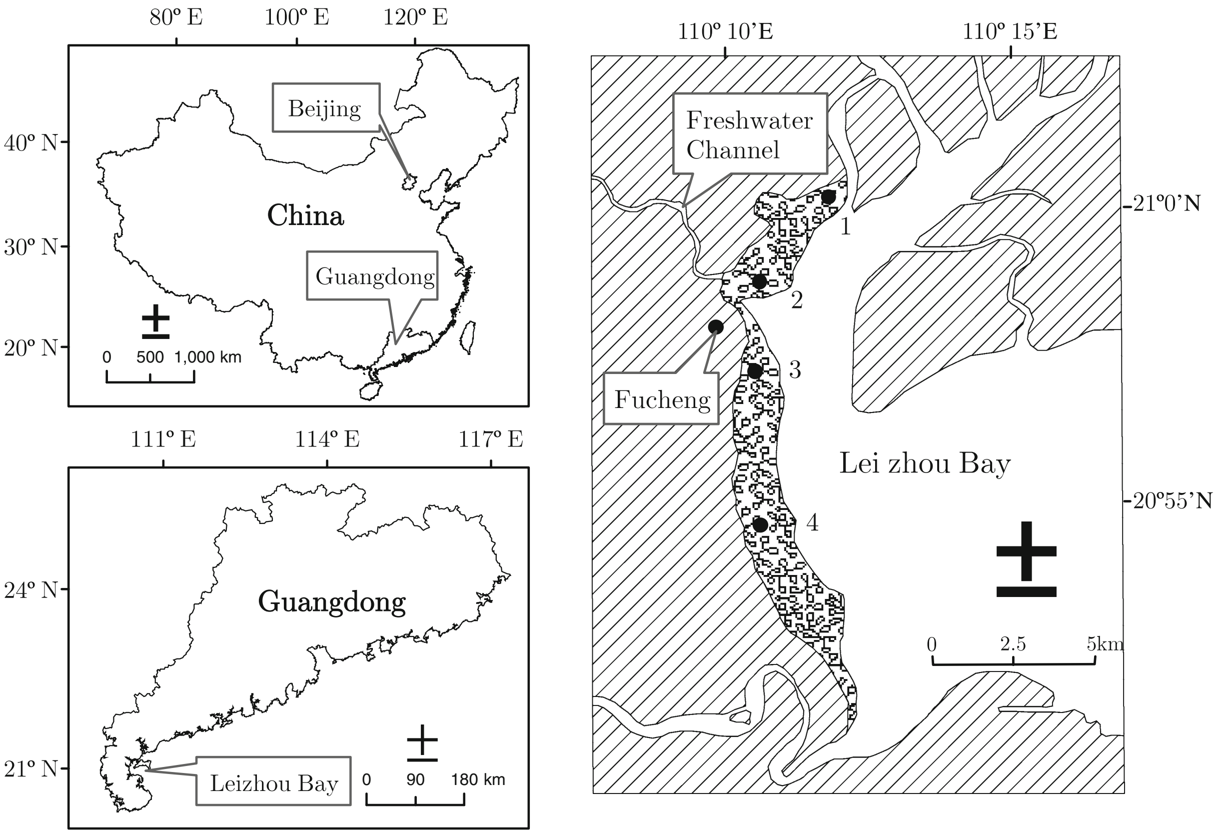

Fig. 1 The location of Leizhou Bay, Guangdong, South China and the study sites. The numbers represent: 1: 5 yr plantation; 2: 8 yr plantation; 3: 4 yr plantation;4: 10 yr plantation. (This figure is modified from the Fig. 1 in Ren et al. 2008)

introduced into Leizhou Bay in 1993. This species was highly adaptive, grew very fast in the area, and was extended broadly.

We conducted an investigation of *S. apetala* plantations established in 1995, 1997, 2000 and 2001, respectively. These plantations had an initial density of 1,667 seedlings/ha. Most seedlings survived and grew well but some seedlings of native mangrove species such as *Rhizophora stylosa* Griff, *K. candel* (Linn.) Druce, and *Aegiceras corniculatum* (Linn.) Blanco invaded those plantations but later died. We established four transects across the whole land-sea interface zone and various numbers of 10 m×10 m quadrates were placed along each transect depending on the length of each transect. For the 4, 5, 8, and 10-year plantation, there are 3, 7, 8, and 3 quadrates, respectively. In this study, only three quadrates were used. The species, tree height (H), tree diameter at breast height (DBH), and growth status (live or dead) of each individual were recorded at each quadrate (Table 1).

Tree height and DBH were measured for all the selected quadrates in each transect. The Mosaic Stratified Cutting Method was adopted for biomass study. In 2005, we stratified and harvested three individuals, including one standard tree (Norisade et al. 2005), one smaller tree than the standard tree, and one larger tree than the standard tree for each transect. We divided the aboveground of the sampling tree into trunk, branch, bark, leave, and flower and fruit component. An excavation method (Bledsoe et al. 1999) was used to estimate root biomass of the same three individual trees that were selected for aboveground biomass (AGB) and root biomass estimate. According to our observation, very few roots of these plantations were distributed deeper than 1 m in sediments. We also found canopy diameter of *S. apetala* trees in these plantations was usually smaller than 2 m. Most roots of this species were distributed within the projected canopy zone. Therefore, for belowground biomass (BGB, referring to root biomass in this study), we excavated all roots in 1 m depth within the radius of 1 m from the tree center, and then washed the roots. We excavated all the sediments within the sampling cylinder (2 m in diameter × 1 m in height) and washed them with a fine screen to collect all roots. The roots were sorted into four size classes: extreme fine roots (diameter <0.2 cm), fine roots (diameter 0.2–0.5 cm), small roots (diameter 0.5–1.0 cm), and coarse roots (diameter >1 cm). We did not separate live or dead roots. Root base were the root tip with about 30 cm length. Each tree organ was dried to a constant mass at 65°C using a dry oven. Thus, the AGB and BGB of the standard, smaller (than standard), and larger (than standard) tree were calculated at each plantation.

In order to estimate the total forest biomass (TFB), we used a relative growth relationship formula:

$$W = a\left(D^2H\right)^b$$

in which W is the organ or plant biomass (organ or plant biomass), D is the DBH (cm), H is the height (m), a and b are two parameters. The relative growth formula of every organ of *S. apetala* is based on the whole-harvest data acquired from samples of twelve harvested trees (4 different aged stands × 3 trees at each stand). From the biomass regression model for every component (Table 3), we calculated the total biomass (including stem, branch, bark, leaves and roots) of each tree using tree DBH and height data (Norisade et al. 2005). The TFB was scaled up by adding all individual tree biomass in the quadrates.

Tree organ samples of leaf, branch, bark, stem, root, flower and fruit were used at each plantation, respectively, for C concentration analysis. These samples were dried to a constant mass at 65°C first. Then they were ground in a Wiley mill and passed through a fine screen (1 mm). The C concentration was analyzed by potassium dichromate oxidation method (Sun 1996). For each stand, three replications were used for C concentration analysis. All the C concentration of roots reported in this study was ash-free values.

Table 1 The general status of four different aged *S. apetal* plantations in 2005 (mean ± SD)

Stand age (years)	Density (Trees/ha)	DBH (cm)	H (m)	Salinity (%)	pH
4	1,494	9.2±0.4	8.4±0.6	1.22	7.0
5	1,444	12.0±0.2	10.2±0.4	1.23	6.7
8	1,378	13.4±0.8	11.4±0.7	1.97	6.8
10	1,328	14.1±1.0	13.3±0.5	2.04	6.5

Soil/sediment samples at the top 20 cm were collected for soil organic carbon (SOC) and bulk density analysis. The first soil sampling was conducted prior to plantation establishment in 1995 and the second soil sampling was carried out in 2005. We collected and mixed three soil samples using a PVC tube 30 mm in diameter and 20 cm in depth in each transect each time. The soil samples were bulked mixed, and air dried. Plant residues including roots were sorted out. The soils were then milled to pass a sieve of 93,000 openings m^{-2}. SOC was determined using potassium dichromate oxidation method (Sun 1996). Roughly in parallel, soil bulk density was determined by samples taken from four subplots prior to and after planting. Undisturbed soil cores were taken from three randomly selected locations within each subplot using a stainless steel corer. All of the sample cores within each subplot were pooled together and oven-dried at 105°C to constant weights. Soil bulk density was calculated as the ratio of total dry weight to volume.

The relative growth relationship formula was developed by Excel. Statistical analyses were performed with SPSS11.5 for Windows (Norisade et al. 2005; Ren and Yu 2008). One-way ANOVA test was first used to examine C concentration of different plant organs and a LSD test was used to compare the means of C concentration of plant organs.

Results

Biomass of standard tree of *S. apetala*

The AGB and BGB of standard tree of *S. apetala* at different aged plantations are shown in Table 2. The average H and DBH of standard *S. apetala* trees increased with age (Table 1) and the biomass of every organ and the standard tree also increased with age (Table 2). The AGB of standard trees increased from 27.2 kg/individual at 4-year plantation to 79.0 kg/individual at 10-year plantation. The average individual tree biomass increased 2.9 times from 4-year plantation to 10-year plantation. Similarly, the root biomass of standard tree increased from 5.9 kg/individual at 4-year plantation to 21.0 kg/individual at 10-year plantation. The decreasing biomass order of those organs was trunk > branch > root > leaf > bark > flower & fruits. The average biomass of trunk, branch, root, leaf and bark of 10-year *S. apetala* standard tree was 53.3, 17.6, 21.0, 4.6 and 3.5 kg/individual, respectively.

Relative growth equation of *S. apetala* plantation

With data of biomass, DBH and H of standard trees, parameters of relative growth equations were developed using regressions (Table 3). The biomass of different parts was well fitted to the equations and all the regression models are significant ($p<0.05$). Most coefficient of determination of these models was above 0.96. The leaf biomass model can explain 91.3% variations of the biomass (Table 3). For bark component, the biomass model can explain 96.3% variations of the biomass. For other components such as stems and branches, the biomass models can explain more than 98% variations of the biomass. Similarly, the biomass models for the aboveground, belowground, and total can explain about 99% variations of the biomass.

AGB, BGB, and TFB of different aged plantations

AGB, BGB, and TFB at the *S. apetale* plantations markedly increased with stand age. The AGB and BGB of *S. apetala* plantation increased from 39.3 and

Table 2 The aboveground biomass (AGB) and belowground biomass (BGB) of standard tree of *S. apetala* plantations (unit: kg $tree^{-1}$)

Stand Age (yrs)	Trunk	Branch	Bark	Leaf	Flower and fruit	AGB Total	Stand Age (yrs)	Extreme fine roots	Fine roots	Small roots	Coarse roots	Root base	BGB Total
4	13.7	8.4	1.7	2.1	1.3	27.2	4	0.3	0.2	0.5	1.2	3. 7	5.9
5	24.3	15.1	2.0	2.7		44.1	5	0.4	0.2	1.0	2.1	5.4	9.1
8	38.3	18.1	3.0	3.3	2.8	65.5	8	0.7	0.3	1.0	3.7	9.2	14.9
10	53.3	17. 6	3.5	4.6		79.0	10	0.7	0.5	1.2	5.4	13.2	21.0

Extreme fine roots <0.2 cm; Fine roots:0.2–0.5 cm; Small roots: 0.5–1.0 cm; Coarse roots >1 cm

Table 3 The relative growth equations for *S. apetal* plantations

Components	Equation	r^2
Stem/trunk	$W=0.061\ (D^2H)^{0.821}$	0.997**
Branch	$W=0.205\ (D^2H)^{0.572}$	0.989*
Bark	$W=0.038\ (D^2H)^{0.564}$	0.963**
Leaves	$W=0.056\ (D^2H)^{0.536}$	0.913*
Aboveground subtotal	$W=0.280\ (D^2H)^{0.693}$	0.997*
Belowground subtotal	$W=0.038\ (D^2H)^{0.759}$	0.991*
Total	$W=0.312\ (D^2H)^{0.705}$	0.996*

$n=12$, $*p<0.05$ and $**p<0.01$

8.6 Mg ha^{-1} at 4-year stand to 82.1 and 26 Mg ha^{-1} at 10-year stand (Table 4). AGB accumulated at a rate of 9.8, 12.0, 9.6, and 8.2 Mg ha^{-1} yr^{-1} at the 4, 5, 8 and 10-year plantation, respectively. BGB accumulated at a slower rate. Root biomass accumulated at a rate of 2.2, 2.4, 2.4, and 2.6 Mg ha^{-1} yr^{-1} at the 4, 5, 8 and 10-year plantation, respectively. The TFB of *S. apetala* plantation increased from 47.9 Mg ha^{-1} at 4-year stand to 108.1 Mg ha^{-1} at 10-year stand (Table 4). The most rapid increase of biomass occurred from 4-year stand to 5-year stand. The accumulation rate of plantation biomass slowed down after 5 years of growth. The biomass of trunk and root accounted for more than 60% of total biomass. In these four different aged plantations, the proportion of trunk biomass was the largest and the flower & fruits biomass proportion was the smallest. The BGB/AGB ratio was 0.2, 0.2, 0.3, and 0.3 at the 4, 5, 8, and 10-year plantation, respectively.

C concentration of *S. apetala* tree organs

Significant differences in C concentration were observed among different organs of *S. apetala* tree (Table 5). Tree trunk had the highest C concentration with an average value of 46.8% at the four different aged stands. In contrast, leaf had the lowest C concentration with an average of 38.4%. The average C concentration of barks, roots, and branches was 42.8%, 43.3%, and 43.7%, respectively. No significant differences in C concentration were observed among these three organs. C concentration of tree organs did not change greatly with stand age. Coefficients of variation (CV) of C concentration were all less than 5%.

C storage in four different aged *S. apetala* plantations

Forest biomass C storage includes C storage in both AGB and root biomass. The forest biomass C storage at the *S. apetala* plantations markedly increased with stand age. The value was 19.9, 32.6, 42.1, 49.0 Mg ha^{-1} in the 4, 5, 8 and 10-year plantation, respectively (Table 6 and Fig. 2). Roots stored about 18%, 16%, 20%, and 24% of forest biomass C storage in these plantations. For the aboveground, most C stored in the trunks and branches, while leaves and barks only stored small amount of C. The annual rate of C accumulation in forest biomass at the 4, 5, 8 and 10-year plantation was 5.0, 6.5, 5.3, and 4.9 Mg ha^{-1} yr^{-1}, respectively (Fig. 3).

The SOC storage of the *S. apetale* plantations markedly increased with stand age. The SOC storage of the top 20 cm sediments was 27.7, 34.5, 56.0, 67.5 Mg ha^{-1} at the 4, 5, 8 and 10-year plantation, respectively (Table 6). After excluding the initial SOC storage, the SOC storage at these four stands increased by 0.3, 6.8, 27.4, and 35.0 Mg ha^{-1} since reforestation. The annual rate of SOC accumulation for these four plantations on average was 0.1, 1.4, 3.4, and 3.5 Mg ha^{-1} yr^{-1}, respectively (Fig. 3).

Total C storage (TCS) is defined as the summation of the aboveground C storage (AGCS) and belowground C storage (BGCS). BGCS includes C storage in roots and SOC storage. The TCS in the 4, 5, 8 and 10-year plantation was 47.6, 67.1, 98.1, and 116.5 Mg ha^{-1}, respectively (Fig. 2). The BGCS/AGCS ratio was 0.2, 0.4, 1.1, and 1.3 in 4, 5, 8 and 10-year stand, respectively. The average annual rate of TCS accumu-

Table 4 The biomass of four different aged *S. apetala* plantations (Mg ha^{-1})

Stand Age (yrs)	Trunk	Branch	Bark	Leaf	Flower and fruits	AGB	Root (BGB)	Total
4	20.2	11.7	2.5	3.1	1.8	39.3	8.6	47.9
5	32.4	20.7	2.8	3.7		59.6	12.1	71.7
8	42.8	23.9	3.5	4.0	2.2	76.4	19.5	95.9
10	49.8	24.2	3.9	4.2		82.1	26.0	108.1

AGB refers to aboveground biomass

Table 5 C concentration (%) of different organs of *S. apetala* plantations (Mean ± SD)[a]

Age (years)	Trunk	Branch	Bark	Leaf	Root[b]	Average
4	44.7±0.2	42.6±0.7	43.3±0.3	39.6±0.7	41.3±0.3	42.3±1.6
5	49.6±0.9	43.7±0.4	40.5±0.2	36.7±0.4	43.2±0.5	42.7±3.4
8	46.6±0.4	43.4±0.9	44.9±0.3	38.6±0.6	43.6±0.1	43.2±2.1
10	46.3±0.1	44.9±0.4	42.6±0.1	38.6±0.1	45.3±0.3	43.5±2.3
Average[c]	46.8±0.4[a]	43.7±0.6[b]	42.8±0.2[b]	38.4±0.4[c]	43.3±0.3[b]	43.0±2.3
CV[d]	4.4	2.1	4.2	3.2	3.8	1.3

[a] Each data point is the mean of 9 samples

[b] All the C concentration of roots reported in this study was ash-free values

[c] Means in a row followed by different letters are significantly different ($p<0.05$) according to a one-way ANOVA and an LSD test

[d] Coefficient of Variation, the ratio of standard deviation to the mean

lation for those plantations was 5.1, 7.9, 8.7, and 8.4 Mg ha^{-1} yr^{-1}, respectively (Fig. 3).

Discussion

High biomass accumulation in *S. apetala* plantations

Our study supports the hypothesis that biomass accumulation at both aboveground and belowground increased with plantation ages (Table 4). Although the accumulation rate of AGB slowed down after 5 years of growth, however, the accumulation rate of BGB show the trend of continuous increase during the first 10 years of growth. Moreover, the *S. apetala* plantations accumulated more biomass than many other secondary mangrove forests or plantations in China (Table 7). Miao et al. (1998) examined biomass of different mangrove forests in Gaoqiao, Guangdong. They found the TFB in 5-year *A. corniculatum*, *A. marina*, and *K. candel* forests was 5.5, 16.4, and 62.6 Mg ha^{-1}, respectively (Table 7), much smaller than the 71.7 Mg ha^{-1} reported in this study (Table 4). Similarly, the TFB in a 10-year *Bruguiera gymnorrhiza* secondary forest was 41.4 Mg ha^{-1} (Miao et al. 1998), a value much smaller than 108.2 Mg ha^{-1} in 10-year *S. apetala* plantation in this study. The biomass estimation methods in our study were very similar to the ones used in Miao et al. (1998). Liao et al. (1990) reported the AGB of a 5-year *S. caseolaris* secondary forest in Hainan was 47.2 Mg ha^{-1}, smaller than the AGB of 59.6 Mg ha^{-1} in this study (Table 4). Liao et al. (1999) investigated the AGB accumulation in three mangrove plantations and found that the AGB was 20.0, 38.5, and 29.4 Mg ha^{-1} in 6-year *S. caseolaris*, *S. caseolaris*/*K. candel*, and 11-year *K. candel* plantation, respectively. In contrast, the AGB in 5-year and 10-year *S. apetala* plantations was 59.6 and 82.1 Mg ha^{-1}, respectively. The TFB at our 10-year *S. apetala* plantation is lower than the TFB of 131.6 Mg ha^{-1} at a 12-year *Rhizophora mucronata* plantation in Kenya (Bosire et al. 2008). These biomass comparisons are reliable as the same biomass estimation method was used in these studies. This study indicates that *S. apetala* plantations can accumulate more biomass in both aboveground and

Table 6 C storage in biomass and SOC in four *S. apetala* plantation (Mg ha^{-1})

Age (yrs)	Trunk	Branch	Bark	Leaf	AGCS	Root	Total C in Biomass	SOC prior to planting (0–20cm)	Current SOC (0–20cm)
4	9.1	5.0	1.0	1.2	16.3	3.6	19.9	27.4	27.7
5	15.9	9.0	1.1	1.4	27.4	5.2	32.6	27.7	34.5
8	20.0	10.4	1.6	1.6	33.6	8.5	42.1	28.6	56.0
10	23.1	10.8	1.7	1.6	37.2	11. 8	49.0	32.5	67.5

SOC and AGCS refer to soil organic carbon and aboveground C storage, respectively

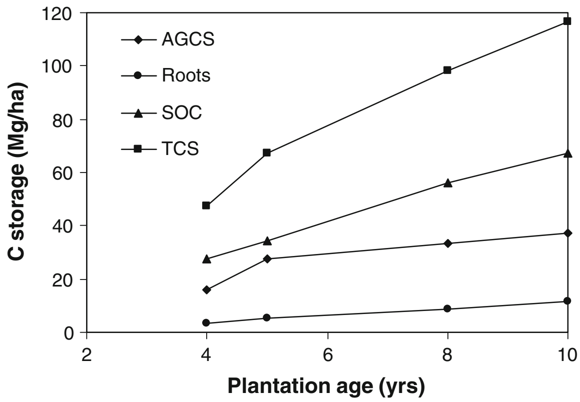

Fig. 2 Carbon storage at four different aged *S. apetala* plantations

belowground than many other mangrove forests in this region. Moreover, the high biomass accumulation was achieved under few management practices. Initial site preparation and planting probably were the only management measures applied in these plantations. No fertilization has ever been used in these plantations. *S. apetala* shows high adaptability in poor habitats, fast growth, and large biomass accumulation potentials in this region. This introduced species could be one of the suitable species to restore the degraded coastal area (Ren et al. 2008).

Mangrove forests accumulate large amounts of biomass in their roots. In this study, we found the averaged BGB/AGB ratio of the four *S. apetala* plantations was 0.3. This ratio is smaller than the values reported in several other mangrove biomass studies in China (Miao et al. 1998; Zan et al. 2001). Miao et al. (1998) studied the biomass accumulation in five different mangrove forests in Guangdong, China. For three 5-year mangrove secondary forests, the BGB/AGB ratio was 0.6, 0.7, and 0.8 in *Aegiceras corniculatu,,K. candel*, and *Avicennia marina*, respectively. The BGB/AGB ratio was 0.4 at a 10-year *Bruguiera gymmorrhiza* secondary forest and the ratio even reached as high as 1.2 at a 30-year *Rhizophora stylosa* secondary forest. Zan et al. (2001) reported a BGB/AGB ratio of 0.4 for a 6-year mixed plantation composed by *S. apetala*, *S. caseolaris* and *K. candel*. The differences of BGB/AGB ratio in these studies are probably due to species differences. In addition, we excavated all the roots in sediments up to 1 m deep in this study. This may underestimate root biomass by missing the roots that distribute more than 1 m deep in sediments despite most roots were distributed in top 1 m sediments in these four plantations. This partially explain why the BGB/AGB ratio in this study was lower than the ratios reported in Miao et al. (1998) and Zan et al. (2001) since both studies excavated roots up to the depth until no roots can be found. The excavation approach is better than soil core approach in estimating biomass of roots, especially small and coarse roots (Bledsoe et al. 1999; Tamooh et al. 2008).

The greater BGB/AGB ratio of mangrove forests suggests a large proportion of the forest biomass is accumulated in roots as crutch system of mangrove for its survival in the intertidal zone. This finding was consistent with mangrove forest studies conducted in other countries (Komiyama et al. 2008). Komiyama et al. (2008) reviewed 23 papers published in the past 50 years on the biomass of mangrove forests. Of these, only 9 papers included AGB and BGB data. The eighteen values of BGB/AGB ratio ranged from 0.2 to 1.4 with an average of 0.6 in these primary or secondary mangrove forests. The BGB/AGB ratio of mangrove forests is greater than the BGB/AGB ratio of upland forests (Jackson et al. 1996; Cairns et al. 1997), which helps to maintain a bottom-heavy mangrove tree form. The average BGB/AGB ratio of upland forests ranged from 0.2 (Jackson et al. 1996) to 0.3 (Cairns et al. 1997).

C storage in *S. apetala* plantations

Our study supports the hypothesis that C storage at both aboveground and belowground increased with plantation ages (Table 6 and Fig. 2). This trend is

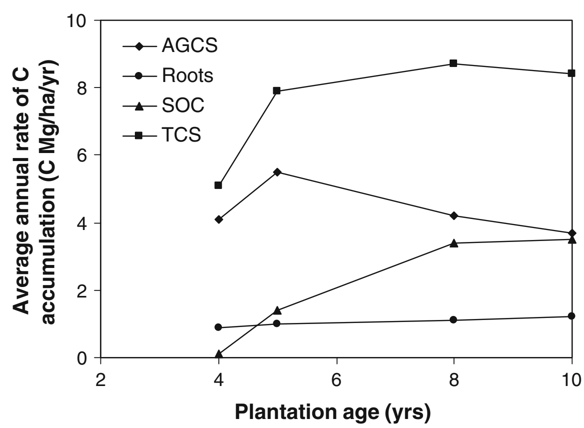

Fig. 3 Average annual rate of C accumulation of various C pools at four different aged *S. apetala* plantations

Table 7 Total biomass of main mangrove forests in China

Location	Dominant Species /Forest Type*	Age (yrs)	Biomass ($Mgha^{-1}$)	Reference
Wenchang, Hainan (19°15'N,110°47'E)	*S. caseolaris*/Secondary forest	5	47.2**	Liao et al. 1990
Qiongshan, Hainan (19°59'N,110°32'E)	*S. caseolaris* + *Kandelia candel*/Mixed plantation	6	38.5**	Liao et al. 1999
	S. caseolaris/Pure plantation	6	20.0**	
	K. candel/Pure plantation	11	29.4**	
Longhai, Fujiang (24°29'N,117°23'E)	*Kandelia candel*/Secondary forest	20	162.6	Lin 1999
Qiongshan, Hainan (20°00'N,110°41'E)	*Bruguiera sexangula*/Secondary forest	55	420.3	
Gaoqiao,Guangdong (21°30'N,109°42'E)	*Avicennia marina*/Secondary forest	5	16.4	Miao et al. 1998
	K. cande/Secondary forest	5	62.6	
	Aegiceras corniculatum/Secondary forest	5	5.5	
	Rhizophora stylosa/Secondary forest	30	96.1	
	Bruguiera gymnorrhiza/Secondary forest	10	41.4	
Beihai, Guangxi (21°28'N,109°43'E)	*Avicennia marina*/Secondary forest	30	52.7	Yin et al. 1993
Futian, Guangdong (22°32'N,114°03'E)	*S. apetala* + *S. caseolaris* + *K. Candel*/Mixed plantation	6	65.7	Zan et al. 2001

*Forest types include plantations and secondary forests originating from natural regeneration

**the biomass only includes the aboveground biomass

consistent with the pattern of biomass increase over time. The biomass C storage increased from 19.6 Mg C ha^{-1} at 4-year plantation to 49.0 Mg ha^{-1} at the 10-year plantation. The SOC storage at the 10-year plantation was more than two times of SOC storage at the 4-year plantation. The upward trend of C storage at different C pools, especially SOC and TCS, will likely continue over time due to the young ages of these plantations (Fig. 2). The *S. apetala* plantations in this study store more C than many other similar aged mangrove forests in China due to their higher biomass storage. Because of the lack of C storage data of other mangrove forests in China, we can not make a direct comparison as we did on biomass. Our study only partially supports the hypothesis that belowground C accumulated at a faster rate than the aboveground C in these plantations (Fig. 3). For example, belowground at 8- and 10-year *S. apetala* plantation accumulated C at a rate of 4.5 and 4.7 C Mg ha^{-1} yr^{-1} than 1.0 and 2.4 Mg ha^{-1} yr^{-1} at the aboveground, respectively. Similar pattern was not observed in the two younger plantations. For the 4 and 5-year *S. apetala* plantation, more C was accumulated at aboveground than belowground (Table 6 and Fig. 3). We predict that more C will likely be accumulated in BGCS such as SOC and roots than AGCS in older than 10-year *S. apetala* plantation since average annual rate of C accumulation in belowground is greater than the AGCS average annual rate of C accumulation. This high resiliency might be due to high annual rate of SOC accumulation in these mangrove plantations. Similar results were observed in other mangrove forest studies (Fujimoto 2004; Kristensen et al. 2008).

Sediments stored significant amount of SOC in these *S. apetale* plantations (Table 6 and Fig. 2). The SOC storage of the top 20 cm sediments was 27.7, 34.5, 56.0, 67.5 Mg ha^{-1} at the 4, 5, 8 and 10-year plantation, respectively (Table 6). The SOC storage in this study was underestimated, especially at the older stands, because we only sampled the top 20 cm sediments and the sediments at 8 and 10-year *S. apetale* plantation were deeper than 20 cm. Fujimoto (2004) reviewed SOC storages in sediments of mangrove forests in the Asia-Pacific region and reported that averaged SOC storage was 887 Mg ha^{-1} with a range of 220 to 4,200 Mg ha^{-1}. The sediments in many of the studies were sampled as deep as one meter and some even up to two meters (Fujimoto 2004). Kristensen et al. (2008) indicated organic-rich sediments may extend to several meters depth in primary mangrove forests. In our study, SOC accumulated at an annual rate of 0.1, 1.4, 3.4, and 3.5 Mg ha^{-1} yr^{-1} at the 4, 5, 8, and 10-year plantation, respectively. Fujimoto et al. (2000) reported an annual rate of SOC accumulation in the top 1 m of sediment was as high as 6.3 Mg ha^{-1} yr^{-1} in a 20-year *Rhizophora apiculata* plantation in southern Vietnam. The high SOC accumulation rate is likely due to the increasing input of dead roots over time (Fujimoto 2004; Kristensen et al. 2008) as well as the high rate of litterfalls (Zan et al. 2001). Although we did not measure litterfalls in this study, Zan et al. (2001) found the annual litterfalls was about 7.1 Mg C ha^{-1} (0.43 was used for biomass to C conversion) at a 6-year mixed plantation of *S. Apetala*, *S. caseolaris*, and *K. Candel* in the same region. The annual litterfalls of a pure 6-year *S. Apetala* plantation will likely be even higher. The slow decomposition of litters and organic matter in sediments also contributed to the high SOC accumulation (Zan et al. 2001; Kristensen et al. 2008). Thus, *S. apetale* plantations in this study could sequestrate significant amounts of C not only in forest biomass but also in sediments.

Implications for C sequestration by restoring the degraded coastal land in southern China

Fast-growing tree species have direct impact on the regional rate of C sequestration by incorporating C dioxide into plant biomass (Jandl et al. 2007). *S. apetala* is characterized with fast growth and high adaptability to poor habitats. Thus, from C sequestration perspective, it is recommended as key reforestation species for coastal land in Guangdong province as well as other coastal provinces in the southern China. To critically examine the impacts of developing large-scale *S. apetala* plantations on regional C sequestration, it is necessary to use processes-based biogeochemical models (Chen et al. 2006) because biomass accumulation and carbon storage in mangrove plantations are not homogenous due to variable climate, geomorphology, edaphic condition, and tide pattern (Soares 1997; Formard 1998; Swamy et al. 2004; Soares and Nivelli 2005). In order to preliminarily estimate the C sequestration by reforesting the degraded coastal land in southern China using *S. apetala* plantations, we can use averages of biomass C and SOC storage (Table 6). In the past 10 years, about 2,300 ha of *S. apetala* plantations with an average stand age of 8 years was established in southern China. Approximately 0.2 Tg of C was sequestrated in the reforestation over the past decade. At least about 7,300 ha of *S. apetala* will be planted over mudflats in southern China by 2015 according to the Mangrove Reforestation Plan (2006–2015) (GPG 2005). The reforestation using *S. apetala* will sequestrate about 0.5 Tg of C in southern China. Moreover, southern China has about 1,135 km shorelines, most of the coastal mudflats were once covered by native mangrove forests. The reforestation of *S. apetala* in 60% of the coastal mudflats (200 m in width) by 2020 could sequestrate about 1.0 Tg of C if the average stand age of these plantations is 8 years.

These results demonstrate that the establishment of *S. apetala* plantations has great potentials to sequester more C over the coming decades. This study indicated that the growth performance and C sequestration potentials of the exotic mangrove species, *S. apetala,* were better than many other mangrove species including native species such as *R.stylosa* and *K. candel* in the first 10 years after plantations. Most studies on *S. apetala* plantations were conducted in plantations younger than 10 years old (Zan et al. 2003, Ren et al. 2008, and this study). More long-term monitoring and research are needed to evaluate how the growth and C sequestration in this mangrove forest change in future.

Potential ecological issues related to large-scale *S. apetala* plantations

Widespread mangrove degradation coupled with the increasing awareness of the importance of these coastal forests has spurred many attempts to restore mangroves (Bosire et al. 2008). Most of the native mangroves along the shorelines of China have been deforested by clearance for shrimp ponds, over-cropping for timber, alteration of water flow patterns, and increasing urbanization (Ren et al. 2008). The restoration of large-scale native mangroves along the shorelines is difficult due to the habitat degradation. Many attempts to plant native mangrove in degraded coastal mudflats in southern China simply fail (Ren et al. 2008). Similar cases have been observed in many other countries. Most of these failed attempts were not based on well-understood ecological principles and well-defined aims (Field 1998; Bosire et al. 2008).

The successful introduction of exotic *S. apetala* may provide an opportunity for mangrove restoration. Our study indicates *S. apetala* shows high adaptability in poor habitats with fast growth and large C storage capacity in southern China. Moreover, C sequestration by *S. apetala* plantations can be achieved under little management. According to our preliminary estimate, the reforestation of 60% degraded coastal mudflats in southern China can accumulate at least 1.5 Tg C in these *S. apetala* plantations by 2020. As one of the important ecological services (Twilley et al. 1992; Fujimoto 2004; Bouillon et al. 2008), the C sequestration capacity of these plantations likely will enhance over time. Moreover, the C sequestration is accomplished at a low cost. The increasing biomass and C accumulation, especially the development of sediments, will further enhance other ecosystem functions such as nutrient cycling and biodiversity of the plantations (Kristensen et al. 2008; Ren et al. 2008).

The large-scale reforestation of exotic *S. apetala* in southern China may raise two potential ecological issues. Firstly, *S. apetala* is an invasive species (Wang et al. 2004). The large-scale reforestation of using this exotic species may further threat the few remaining native mangrove forests. This species shows high adaptability in poor habitats and fast growth. We need to learn more how this species interacts with native mangrove species. Invasion of this species into native mangrove forests in this region has not been observed yet. However, we found several native mangrove species such as *R. stylosa, K. Candel*, and *A. corniculatum* in 5-year *S. apetala* plantations. They all died later due to the rapid growth of *S. apetala*. Therefore, it is necessary to critically assess the ecological impacts of this species on native mangrove species in this region (Zan et al. 2003, Ren et al. 2008). Secondly, the species biodiversity is lower in *S. apetala* plantations than native mangrove remnants. The large-scale monoculture tree plantations are increasingly vulnerable to pests and diseases (Chapin et al. 2000), although no significant insect outbreaks or diseases have been occurred to these plantations so far.

Tree plantations have been received considerable attention as a forest restoration strategy. Plantations can facilitate secondary forest regrowth by providing an understory environment more favorable for native plant recruitment than unmanaged degraded habitats (Lugo 1997; Parrotta et al. 1997; Duncan and Chapman 2003; Ren et al. 2008). We could use *S. apetala* as a pioneer species to improve habitat quality by accumulating sediments and facilitate the reestablishment of native mangrove species. We observed several native mangrove species such as *R. stylosa, K. Candel*, and *A.corniculatum* "invade" in 5-year *S. apetala* plantations. The removal of the dominant *S. apetala* trees may enhance the restoration of native mangrove species. More studies are needed to understand the interaction between understory native mangrove species and the dominant *S. apetala* as well as the accumulation of sediments, which will facilitate the establishment of native mangrove species.

Conclusion

S. apetala plantations (4~10 years old) in Leizhou Bay could accumulate high biomass. The TFB of *S. apetala* plantation at 4, 5, 8, and 10-year stand was 47.9, 71.7, 95.9, and 108.1 Mg ha^{-1}, respectively, much greater than those under similar aged secondary mangrove forests or plantations in China. The SOC storage exceeded C storage in the TFB in the four plantations. The average annual rate of TCS accumulation at 4, 5, 8, and 10-year *S. apetale* plantations was 5.0, 7.9, 8.7, and 8.4 Mg ha^{-1} yr^{-1}, respectively, suggesting these plantations have great potential to sequestrate C. The TCS values in this study were underestimated because we only estimated the top 20 cm SOC storage in these plantations. The expansion of *S. apetala* plantations in the open coastal mudflats in southern China has great potential to sequestrate more C as well as restore the degraded coastal land, although more long-term monitoring and research are still needed to further evaluate biomass and C accumulation of *S. apetala* plantation over time as well as how the increasing distribution of this monoculture plantation will influence the native mangrove forests.

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