QUANTIFICATION OF SEDIMENTARY ORGANIC CARBON STORAGE AND TURNOVER OF TIDAL MANGROVE STANDS IN SOUTHERN CHINA BASED ON CARBON ISOTOPIC MEASUREMENTS

J P Zhang[1,2] • W X Yi[3,4] • C D Shen[3,5] • P Ding[3] • X F Ding[5] • D P Fu[5] • K X Liu[5]

ABSTRACT. Mangrove ecosystems are highly productive and play an important role in tropical and global coastal carbon (C) budgets. However, sedimentary organic carbon (SOC) storage and turnover in mangrove forests are still poorly understood. Based on C isotopic measurements of sediment cores of 2 mangrove stands in southern China, SOC density was 431.77 Mg ha^{-1} at site 1 (a *Aegiceras corniculatum*-dominated high tidal stand) and 243.65 Mg ha^{-1} in site 2 (a *Bruguiera gymnorrhiza + Kandelia candel*-dominated middle tidal stand). SOC δ^{13}C values at both mangrove sites ranged from –29.4‰ to –26.0‰. SOC δ^{13}C was enriched with depth at 20–50 cm at site 1, which possibly resulted from preferential microbial decomposition. SOC δ^{13}C at site 2 experienced frequent tidal flushing, and presented relatively stable values with depth. A bomb-^{14}C-based SOC turnover model indicated that turnover times of SOC at 20–50 cm at site 1 were 4.44–26.04 yr. Modern C input from abundant roots might account for the very short SOC turnover times at these subsurface layers. As a result, our study suggested that tidal processes had a great influence on SOC storage and turnover in mangrove forests.

INTRODUCTION

Wetlands represent perhaps the largest sinks of carbon (C) in terrestrial soils (Chmura et al. 2003; Choi and Wang 2004). Located at the intertidal zone, mangrove wetlands have the characteristics of high productivity and low ratio of decomposition to net primary production (Jennerjahn and Ittekkot 2002; Gonneea et al. 2004). Mangrove ecosystems, therefore, are regarded as efficient C sinks for atmospheric CO_2 (Choi and Wang 2004; Gonneea et al. 2004; Bouillon et al. 2008; Tamooh et al. 2008). Although understanding sedimentary organic carbon (SOC) dynamics in mangrove ecosystems will help us to better constrain global oceanic-C budgets (Bouillon et al. 2003, 2008; Kristensen et al. 2008), mangrove ecosystems have been ignored in most global C budgets. Chmura et al. (2003) estimated that the top 50 cm of global mangrove forest soils contains as much as 5 Pg C. SOC storage and dynamics in mangrove ecosystems therefore deserve our attention.

C isotopes are widely used to reconstruct ecological process and to trace ecological activity (Bouillon and Bottcher 2006; West et al. 2006), and the use of C isotopes has greatly improved our understanding of the C cycle in underground ecosystems (Staddon 2004). δ^{13}C combined with other indicators has been used to determine the sources (mangrove-derived, oceanic, or terrestrial) of organic C in mangrove wetlands (Bouillon et al. 2003; Gonneea et al. 2004). δ^{13}C is also useful in the study of SOC decomposition in different soil layers. However, there are few reports on the variations of SOC content and δ^{13}C with depth in mangrove ecosystems (Zhang et al. 2012), although such studies are common in terrestrial soils (Balesdent et al. 1993; Boutton 1996; Ehleringer et al. 2000; Wynn et al. 2006). ^{14}C serves as a powerful tool to study the C cycle. Based on bomb ^{14}C, produced by atmospheric thermonuclear weapons testing, many studies have modeled the turnover rates of C over decadal timescales in terrestrial ecosystems (Cherkinsky and Brovkin 1993; Townsend et al. 1995; Trumbore 1996; Chen et al. 2002; Telles et al. 2003). Using the bomb-^{14}C-based turnover

[1]Key Laboratory of Vegetation Restoration and Management of Degraded Ecosystems, South China Botanical Garden, Chinese Academy of Sciences, Guangzhou 510650, China.
[2]Graduate University of Chinese Academy of Sciences, Beijing 100039, China.
[3]Key Laboratory of Isotope Geochronology and Geochemistry, Guangzhou Institute of Geochemistry, Chinese Academy of Sciences, Guangzhou 510640, China.
[4]Corresponding author. Email: yiweixi@gig.ac.cn.
[5]State Key Laboratory of Nuclear physics and Technology, Peking University, Beijing 100871, China.

model (Harkness et al. 1986), Choi and Wang (2004) have found that turnover times of SOC in soil layers at 0–10 cm were 16–31, 18–57, and 10–38 yr in low, middle, and high tidal flats, respectively. Modeling SOC turnover in coastal wetlands, and especially in mangrove forests, has been carried out in some previous studies (Woodroffe 1992; Matsui 1998; Tam and Wong 1998; Middleton and McKee 2001; Jennerjahn and Ittekkot 2002; Gonneea et al. 2004; Khan et al. 2007; Zhang et al. 2007).

In this study, we estimated SOC storage and modeled SOC turnover in mangrove forests in southern China based on analyses of C and its isotopes. The specific objectives were to determine (1) SOC storage of high and middle tidal mangrove stands, (2) the variations of SOC $\delta^{13}C$ with depth at the 2 sites, and (3) SOC turnover rates in mangrove forests.

MATERIALS AND METHODS

Sites

The 2 study sites were located on the west coast of the Leizhou Peninsula, about 70 km northwest of Zhanjiang City, and are part of the Zhanjiang Mangrove National Nature Reserve, the largest mangrove reserve in China. Sediment cores were excavated in rarely disturbed natural mangrove forests (Figure 1), which had an area of approximately 270 ha and are more than 80 yr old. Site 1 was located at the high tidal flat and was dominated by a pioneer *Aegiceras corniculatum* community. Site 2 was located at the middle tidal flat and was dominated by a middle-to-late-stage *Bruguiera gymnorrhiza* and *Kandelia candel* community.
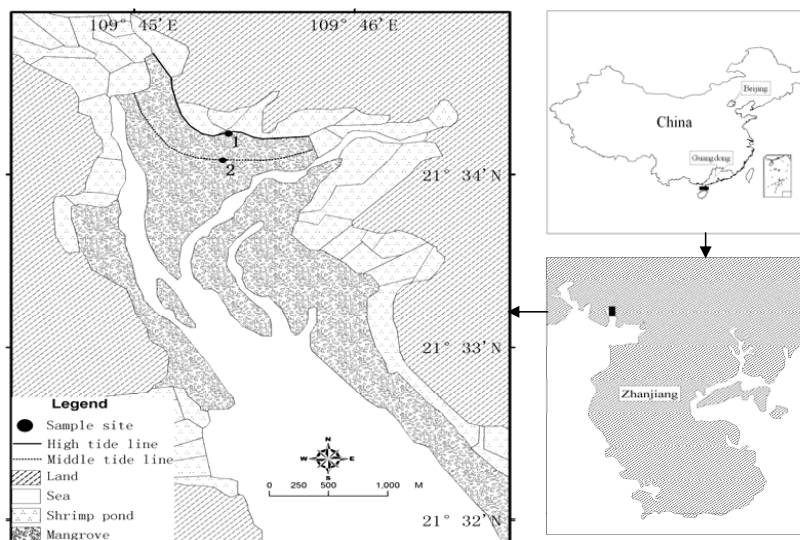

Figure 1 Locations of sediment cores at the 2 sites in mangrove forests, southern China: 1: *Aegiceras corniculatum* site; 2: *Bruguiera gymnorrhiza* + *Kandelia candel* site.

In 2005, we established three 10 × 10 m quadrants around each site for the study of community structure. Plant height and diameter at breast height (DBH) of each individual were recorded. Three 20-cm sediment cores were taken from each of the 10 × 10 m quadrats randomly to form a mixed sample. Salinity and pH were measured using an optical refractometer and a pH meter, respectively. Samples were oven-dried at 90 °C for 24 hr to remove water. Analysis of total N and total P followed

Arnold (1986) and Robert et al. (1997). Usually, Eh of the waterlogged mangrove sediment was less than or equal to 100 mV (McKee 1993). Table 1 summarizes the plant height and DBH, and properties of the top 20 cm of sediment at the 2 sites.

Table 1 Plant height, DBH, and properties of the top 20 cm sediment at 2 mangrove sites in southern China. Site 1 was located at the high tidal flat and was dominated by a pioneer *Aegiceras corniculatum* community. Site 2 was located at the middle tidal flat and was dominated by a middle-to-late-stage *Bruguiera gymnorrhiza* and *Kandelia candel* community.

| Site | Dominant species | Average height (cm) | Average DBH (cm) | Sediment property | | | |
				Salinity (‰)	pH	Total N (%)	Total P (%)
1	*A. corniculatum*	225	2.30	25.30	6.03	0.23	0.05
2	*B. ymnorrhiza*	220	5.60	27.50	6.10	0.18	0.06
	K. candel	270	3.70				

For both sites, the mean annual temperature is 22.9 °C, and the average temperature in the coldest month (January) is 15.5 °C. The annual average precipitation is 1711 mm, with the rainfall typically occurring from April to October. The average annual relative humidity is 80%. The tidal regime is diurnal, and the average tidal amplitude is 2.52 m, with a maximum of 6.25 m (He et al. 2007).

Sediment Sampling

During the ebb tide in June 2006, 1 sediment core (11 cm in diameter and 50 cm in length) was excavated from each site. Visible characteristics of the sediment are provided in Table 2. The cores were divided into segments based on depth and the characteristics of sediment and roots. The sampling interval was 2 cm for the surface 20 cm depth, and 5 cm for the 20–50 cm depth. These sediment segments were transported to the Carbon Isotope Laboratory of the Guangzhou Institute of Geochemistry, where they were frozen at –26 °C for later analyses.

Table 2 Visible characteristics of sediment cores at 2 mangrove sites, southern China. Site 1 was located at the high tidal flat and was dominated by a pioneer *Aegiceras corniculatum* community. Site 2 was located at the middle tidal flat and was dominated by a middle-to-late-stage *Bruguiera gymnorrhiza* and *Kandelia candel* community.

Site	Depth (cm)	Characteristics
1	0–20	Black sludge with high organic matter content, mixed with some red solid, granular structure, very loose, abundant plant debris and roots, full of crustacean and molluscan macrofauna
	20–50	Grayish black, half sludge, large roots (root amount decreasing with depth), less plant debris
2	0–25	Black, sludge, loose, abundant plant roots and macrofauna, occasionally brown solid
	25–50	Grayish black, half sludge, large roots

Carbon Isotope Analyses

The frozen sediment segments were thawed to room temperature. After visible roots and fragmentary stones were removed, a 20- to 35-g subsample of each segment was freeze-dried under vacuum for 48 hr, ground using a mortar and pestle, and then passed through a 1-mm screen to remove rootlets and coarse sand. The subsamples were acid-treated using 2M HCl to remove carbonate and then rinsed repeatedly with distilled water until a neutral pH was reached. Water was removed by oven-drying at 90 °C for 24 hr.

The subsamples for ^{13}C and ^{14}C analysis were then loaded into sealed, evacuated quartz tubes and combusted with CuO at 860 °C for 2 hr. The CO_2 generated was cryogenically purified with dry ice

and liquid nitrogen. SOC content was calculated from the quantity of CO_2 generated from the subsamples. SOC density was calculated by multiplying SOC content by the bulk density and thickness of sediment layer. According to Ren et al. (2008), the average bulk density used for the calculation of SOC density could be 2.6×10^3 kg m^{-3}.

Stable carbon isotope ratios in a portion of the generated CO_2 were determined using a Finnigan MAT-251 mass spectrometer with a precision of 0.2% at the State Key Laboratory of Loess and Quaternary Geology, CAS. Results were expressed as $\delta^{13}C$, in per mil deviations from the International Pee Dee belemnite (PDB) standard: $\delta^{13}C = [(^{13}C/^{12}C)_{\text{sample}} / (^{13}C/^{12}C)_{\text{standard}} -1] \times 1000$. The other portion of the generated CO_2 was catalytically reduced to graphite accelerator mass spectrometry (AMS) targets using the method of Vogel et al. (1987). The $^{14}C/^{12}C$ ratios were determined in the generated graphite using AMS at the Institute of Heavy Ion Physics of Peking University. ^{14}C data were all corrected for isotopic fractionation of ^{13}C of $-25‰$. Results were reported as $\Delta^{14}C$, in parts per thousand of the $^{14}C/^{12}C$ ratio from that of an absolute standard (oxalic acid decay-corrected to 1950) (Stuiver and Polach 1977): $\Delta^{14}C = [(^{14}C/^{12}C)_{\text{sample}} / (^{14}C/^{12}C)_{\text{standard}} -1] \times 1000$.

Bomb-^{14}C-Based SOC Turnover Model

For the samples with $\Delta^{14}C$ greater than zero, bomb ^{14}C can be used to trace short-term SOC turnover at decade scales (Cherkinsky and Brovkin 1993; Chen et al. 2002). The equations used to calculate the turnover rates are

$$\frac{I(1955)}{I_0} = \frac{m}{m + \lambda} \tag{1}$$

$$I(t) = I(t-1) - (m + \lambda) \cdot I(t-1) + m \cdot I_0(t) \tag{2}$$

where $I(1955)$ is the SOC ^{14}C activity in 1955, $I(t)$ is the SOC ^{14}C activity in the year of sampling $(t > 1955)$, $I(t-1)$ is the SOC ^{14}C radioactivity in year $(t-1)$, $I_0(t)$ is the ^{14}C activity in the atmosphere in year t, I_0 is the ^{14}C activity of oxalic acid II, λ is the ^{14}C decay constant (1/8267 yr^{-1}), and m is the SOC turnover rate (yr^{-1}).

Equation 1 describes the SOC ^{14}C activity of a stable and closed section. Equation 2 is a mathematical expression for the dynamics of ^{14}C activity of SOC that is exchanging carbon with atmospheric CO_2. The SOC ^{14}C activity in year t is determined by that in year $(t-1)$, the ^{14}C loss attributable to natural decay of ^{14}C and SOC decomposition, and the incorporation of ^{14}C from atmosphere in year t through formation of new organic matter.

Values of $I_0(t)$ in 1955–2006 were obtained from the previous studies (Hua and Barbetti 2004; Levin and Kromer 2004; Levin et al. 2008). During numerical simulation, 1 value of m was selected first, and then $I(1955)$ was calculated by Equation 1. The values for $I(1955)$ and m were then put into Equation 2, and the SOC ^{14}C activity in the sampling year (2006) was obtained by iterative calculation.

RESULTS

The *A. corniculatum*-Dominated High Tidal Stand (Site 1)

SOC content at site 1 increased from 5.4% at 0–2 cm to 6.4% at 6–8 cm, and then generally decreased with the increment of depth at 8–50 cm. The lowest SOC content was 1.3% at 40–50 cm (Figure 2a). The calculated SOC density to a depth of 50 cm at site 1 was 431.77 Mg ha^{-1}. SOC $\delta^{13}C$ values were relatively constant in the upper 20-cm layer, then became gradually less negative with

increasing depth at 20–50 cm. SOC δ^{13}C values throughout the sediment core ranged from –29.4‰ to –26.6‰ (Figure 2b).
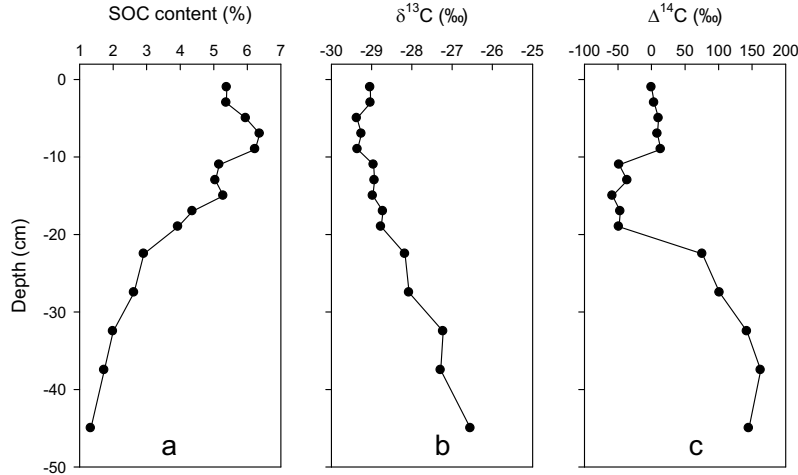

Figure 2 Vertical patterns in the sediment core from the *Aegiceras corniculatum* site (site 1): (a) SOC content; (b) SOC δ^{13}C; (c) SOC Δ^{14}C.

The curve describing the vertical distribution of SOC Δ^{14}C values could be divided into 3 sections. The first section covered the uppermost 10-cm sediment layer, with Δ^{14}C values gradually increasing from 0.1‰ at 0–2 cm to 13.8‰ at 8–10 cm. The second section was represented by the 10–20 cm sediment layer, with Δ^{14}C values varying between –58.1‰ and –36.0‰. The third section dominated the sediment at the 20–50 cm layer, presenting gradually increasing Δ^{14}C values with depth with 75.8‰ at 20–25 cm and 145.2‰ at 40–50 cm (Figure 2c). Reasonable values of SOC turnover rates for samples with Δ^{14}C greater than zero were shown in Table 3. Turnover rates ranged from 0.04 to 0.23 yr^{-1} at the 20–50 cm sediment layers.

Table 3 SOC turnover of the *Aegiceras corniculatum*-dominated high tidal stand (site 1), southern China.

Depth (cm)	Turnover rate (yr^{-1})	Turnover time (yr)
20–25	0.23	4.44
25–30	0.12	8.32
30–35	0.07	14.84
35–40	0.04	26.04
40–50	0.06	15.50

The *B. gymnorrhiza + K. candel*-Dominated Middle Tidal Stand (Site 2)

SOC content at site 2 was stable more or less throughout 0–50 cm, and covered 1.67–2.24% (Figure 3a). SOC density to a depth of 50 cm at site 2 was 243.65 Mg ha^{-1}. At site 2, SOC δ^{13}C values remained almost stable at 0–50 cm, although they fluctuated slightly in the top 20 cm. The mean SOC δ^{13}C value for 0–50 cm was –26.4‰ (Figure 3b). SOC Δ^{14}C values in all the sediment layers at site 2 were greater than zero, and gradually exhibited enrichment with depth from 19.5‰ at the surface 0–2 cm to 182.1‰ at the bottom 40–50 cm, with the exception of –17.5‰ at the 4–6 cm level and –13.4‰ at 6–8 cm, respectively (Figure 3c).
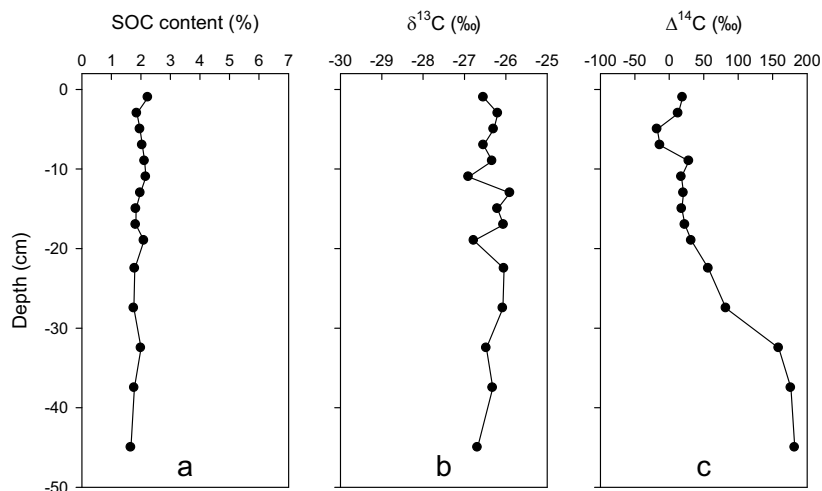
Figure 3 Vertical patterns in the sediment core from the *Bruguiera gymnorrhiza + Kandelia candel* site (site 2): (a) SOC content; (b) SOC δ^{13}C; (c) SOC Δ^{14}C.

DISCUSSION

Comparison of SOC Storage of High and Middle Tidal Mangrove Stands

There was a large difference in SOC storage between site 1 (high) and site 2 (middle) tidal mangrove stands. SOC density at site 2 (located at the middle tidal flat, 243.65 Mg ha^{-1}) was only 55.28% of that at site 1 (located at the high tidal flat, 431.77 Mg ha^{-1}). This difference was largely due to differences in SOC contents in the top 20 cm of sediment layers (see Figures 2a, 3a), with mean SOC contents of 5.31% and 2.02% at site 1 and site 2, respectively. The variability of the surface SOC contents probably resulted from tidal flushing effects.

SOC density in mangrove forests varies greatly at different sites. SOC densities at 0–100 cm depth were estimated to be 57.3 Mg ha^{-1} in Japan, 288.65 Mg ha^{-1} in Hong Kong, and 592 Mg ha^{-1} in Australia (Matsui 1998; Khan et al. 2007; Zhang et al. 2007). Factors such as mangrove species composition, tree density, root biomass, and sedimentary environments all may affect SOC density.

Vertical Patterns of SOC δ^{13}C of High and Middle Tidal Mangrove Stands

The variations of SOC δ^{13}C values as a function of depth differed greatly between the 2 sites in that SOC δ^{13}C values was relatively stable with depth at the middle tidal site but gradually presented enrichment with depth at the high tidal site (see Figure 2b, 3b). At the middle tidal site, frequent tidal actions played the role of averaging out the mangrove-derived organic matter over a wide area and mixing them with the ocean-derived organic matter.

SOC δ^{13}C at the surface 20 cm of the high tidal stand was relatively constant, reflecting the high productivity and rapid deposition of organic matter of mangrove forests (Woodroffe 1992; Jennerjahn and Ittekkot 2002; Gonneea et al. 2004). At the high tidal site, SOC δ^{13}C was enriched at 20–50 cm. This result agreed with those obtained in terrestrial forest ecosystems. In fact, the *A. corniculatum*-dominated high tidal stand (site 1) in this study lay beyond the regular reach of the tides, where they represented an environment not greatly different from that of a terrestrial forest (Hogarth 2007). Numerous studies have indicated that, with the exception of soils in peatlands, SOC δ^{13}C tended to

become enriched with soil depth (Balesdent et al. 1993; Boutton 1996; Ehleringer et al. 2000; Wynn et al. 2006). Several factors might explain this enrichment.

First, the relatively recent burning of large quantities of fossil fuels could have resulted in reduced $\delta^{13}C$ values near the surface, such that the $\delta^{13}C$ values deeper in the soil seem enriched in comparison. The burning of fossil fuels since the start of the Industrial Revolution has released large quantities of CO_2 with low $\delta^{13}C$ values (approximately –27‰) into the atmosphere, and the $\delta^{13}C$ of atmospheric CO_2 has been depleted by up to 1.3‰ during the past 200 yr. This CO_2 with low $\delta^{13}C$ values has been fixed by plants and added to the SOC as the plants died. Because this plant-derived SOC has been added relatively recently to the soil, it will be most abundant near the surface. It follows that the $\delta^{13}C$ value of the younger SOC near the surface will be more negative that of the older SOC in the deeper soil layers. Thus, the "enrichment" of SOC $\delta^{13}C$ with depth will be expected. However, SOC $\Delta^{14}C$ values at 20–50 cm were more than zero (see Figure 2c), indicating that SOC in these layers was formed only very recently, i.e. after the testing of atmospheric thermonuclear weapons and much later than the onset of the Industrial Revolution.

Second, roots generally have $\delta^{13}C$ values 1–3‰ higher than leaves (Vonfischer and Tieszen 1995). However, the surface litter decays rapidly and little is preserved into the deep layers, and most subsurface SOC is derived from roots in mangrove forests (Middleton and McKee 2001; Gleason and Ewel 2002; Jennerjahn and Ittekkot 2002). Therefore, it seems unlikely that the enrichment at the subsurface layers in this study was due to the $\delta^{13}C$ difference between roots and leaves.

Third, many studies have indicated that fractionation by microorganisms results in SOC $\delta^{13}C$ enrichment with depth (Agren et al. 1996; Schweizer et al. 1999; Santruckova et al. 2000; Powers and Schlesinger 2002). Microorganisms preferentially metabolize molecules containing the lighter ^{12}C, so that the remaining SOC tends to be ^{13}C enriched. Probably the enrichment in this study was attributable to this microbial fractionation.

SOC Turnover of High Tidal Mangrove Stand (Site 1)

In general, a bomb-^{14}C-based SOC turnover model was restricted to application in terrestrial ecosystems. Since the *A. corniculatum*-dominated high tidal stand in this study was only flooded occasionally, and the vertical distribution patterns of SOC content and $\delta^{13}C$ at the site did not differ greatly from those in terrestrial forests, we took sedimentary and pedogenic environment of the high tidal stand was aerobic and similar to terrestrial environment, so the model was tried for estimating SOC turnover rates at the high tidal mangrove site.

SOC $\Delta^{14}C$ values at all the sediment layers of the high tidal stand, with the exception of 10–20 cm, were greater than zero, indicating that SOC in these sections consisted of modern carbon polluted by atmospheric thermonuclear weapons testing. The bomb-^{14}C-based SOC turnover model indicated that SOC turnover times at the subsurface layers ranged from several years to decades (see Table 3).

There was bomb ^{14}C found as deep as 50 cm in this study. Previous studies have found that modern C is usually restricted to the top 25-cm soil layers (Bol et al. 1999; Wang et al. 2005). It is possible that modern C detected in this study was mainly derived from mangrove roots. Root biomass can account for half of the total biomass in mangrove forests (Briggs 1977), and fine-root biomass might account for 66% of the total root biomass (Komiyama et al. 1987). Mangrove roots, including pneumatophore and buttress-like roots, penetrated deep into the sediment and were the main input of the deep SOC (Fujimoto et al. 1999; Gleason and Ewel 2002). This hypothesis agrees with the root distribution in this study (see Table 2).

SOC turnover times at 20–50 cm of the *A. corniculatum*-dominated high tidal stand were 4.44–26.04 yr. In general, SOC turnover is much slower deeper in the sediment than near the surface. However, Fontaine et al. (2007) found that a fresh supply of organic C could provide an energy source for microorganisms at the subsurface layers. A fresh supply of organic C could, therefore, increase the rate of SOC turnover at the subsurface layers. In this study, we suspect that dead mangrove roots provided a fresh supply of organic C and shortened the SOC turnover time in these deeper sediment layers. SOC turnover times were years to decades in the subsurface sediment layers in the high tidal mangrove stand, which was largely different from conventional viewpoints that SOC turnover in mangrove forests is very slow irrespective of tidal location or local variability.

As for SOC of the middle tidal stand (site 2), the bomb-^{14}C turnover model could not be applied to the waterlogged sediment because the middle tidal flat was regularly flooded, and turnover there was primarily constrained by a lack of oxygen. We also suspect that the fresh supply of organic C by the dead mangrove roots result in increased Δ^{14}C values in the 20–50 cm layer of the middle tidal stand (Figure 2c).

CONCLUSIONS

The results of this paper, which are based on measurement of ^{14}C and ^{13}C isotopes in sediment cores, indicate that SOC storage and turnover were greatly constrained by tidal processes. SOC density was 431.77 Mg ha^{-1} for the high tidal stand and 243.65 Mg ha^{-1} for the middle tidal stand since the latter, but not the former forest experienced frequent tidal flushing of the surface sediment. SOC was δ^{13}C enriched with depth at the subsurface sediment layers of the high tidal stand, possibly due to preferential microbial decomposition.

A bomb-^{14}C-based turnover model was used to estimate SOC turnover times of the high tidal stand since the sedimentation environment there was similar to terrestrial soils and was suitable for the model. Turnover times were 4.44–26.04 yr for the subsurface SOC of the high tidal stand. Mangrove roots probably accounted for the shorter turnover times at the subsurface sediment layers. Tidal locations should be considered in the future study of SOC turnover. Also, further quantification of root dynamics and samplings of sediment cores are also required to increase our understanding of C turnover in the belowground mangrove ecosystem.

ACKNOWLEDGMENTS

REFERENCES

Agren GI, Bosatta E, Balesdent J. 1996. Isotope discrimination during decomposition of organic matter: a theoretical analysis. *Soil Science Society of America Journal* 60:1121–6.

Arnold K. 1986. *Methods of Soil Analysis. Part 1. Physical and Mineralogical Methods*. Madison: Soil Science Society of America.

Balesdent J, Girardin C, Mariotti A. 1993. Site-related δ^{13}C of tree leaves and soil organic-matter in a temperate forest. *Ecology* 74:1713–21.

Bol RA, Harkness DD, Huang Y, Howard DM. 1999. The influence of soil processes on carbon isotope distribution and turnover in the British uplands. *European Journal of Soil Science* 50:41–51.

Bouillon S, Bottcher ME. 2006. Stable isotopes in biogeosciences - preface. *Organic Geochemistry* 37: 1197–9.

Bouillon S, Dahdouh-Guebas F, Rao A, Koedam N, Dehairs F. 2003. Sources of organic carbon in mangrove sediments: variability and possible ecological implications. *Hydrobiologia* 495:33–9.

Bouillon S, Connolly RM, Lee SY. 2008. Organic matter exchange and cycling in mangrove ecosystems: recent insights from stable isotope studies. *Journal of Sea Research* 59:44–58.

Boutton TW. 1996. Stable carbon isotope ratios of soil organic matter and their use as indicators of vegetation and climate change. In: Boutton TW, Yamasaki S, editors. *Mass Spectrometry of Soils*. New York: Marcel Dekker. p 311–39.

Briggs SV. 1977. Estimates of biomass in a temperate mangrove community. *Australian Journal of Ecology* 2:369–73.

Chen QQ, Sun YM, Shen CD, Peng SL, Yi WX, Li Z, Jiang MT. 2002. Organic matter turnover rates and CO_2 flux from organic matter decomposition of mountain soil profiles in the subtropical area, south China. *Catena* 49(3):217–29.

Cherkinsky AE, Brovkin VA. 1993. Dynamics of radiocarbon in soils. *Radiocarbon* 35(3):363–7.

Chmura GL, Anisfeld SC, Cahoon DR, Lynch JC. 2003. Global carbon sequestration in tidal, saline wetland soils. *Global Biogeochemical Cycles* 17:1111, doi: 10.1029/2002GB001917.

Choi YH, Wang Y. 2004. Dynamics of carbon sequestration in a coastal wetland using radiocarbon measurements. *Global Biogeochemical Cycles* 18: GB4016, doi:10.1029/2004GB002261.

Ehleringer JR, Buchmann N, Flanagan LB. 2000. Carbon isotope ratios in belowground carbon cycle processes. *Ecological Applications* 10:412–22.

Fontaine S, Barot S, Barre P, Bdioui N, Mary B, Rumpel C. 2007. Stability of organic carbon in deep soil layers controlled by fresh carbon supply. *Nature* 450(7167): 277–80.

Fujimoto K, Imaya A, Tabuchi R, Kuramoto S, Utsugi H, Murofushi T. 1999. Belowground carbon storage of Micronesian mangrove forests. *Ecological Research* 14:409–13.

Gleason SM, Ewel KC. 2002. Organic matter dynamics on the forest floor of a Micronesian mangrove forest: an investigation of species composition shifts. *Biotropica* 34:190–8.

Gonneea ME, Paytan A, Herrera-Silveira JA. 2004. Tracing organic matter sources and carbon burial in mangrove sediments over the past 160 years. *Estuarine, Coastal and Shelf Science* 61:211–27.

Harkness DD, Harrison AF, Bacon PJ. 1986. The temporal distribution of 'bomb' [14]C in a forest soil. *Radiocarbon* 28():328–37.

He BY, Lai TH, Fan HQ, Wang WQ, Zheng HL. 2007.

Comparison of flooding-tolerance in four mangrove species in a diurnal tidal zone in the Beibu Gulf. *Estuarine, Coastal and Shelf Science* 74:254–62.

Hogarth P. 2007. *The Biology of Mangroves and Seagrasses*. Oxford: Oxford University Press. 273 p.

Hua Q, Barbetti M. 2004. Review of tropospheric bomb ^{14}C data for carbon cycle modeling and age calibration purposes. *Radiocarbon* 46(3):1273–98.

Jennerjahn TC, Ittekkot V. 2002. Relevance of mangroves for the production and deposition of organic matter along tropical continental margins. *Naturwissenschaften* 89:23–30.

Khan MNI, Suwa R, Hagihara A. 2007. Carbon and nitrogen pools in a mangrove stand of *Kandelia obovata* (S., L.) Yong: vertical distribution in the soil-vegetation system. *Wetlands Ecology and Management* 15: 141–53.

Komiyama A, Ogino K, Aksornkoae S, Sabhasri S. 1987. Root biomass of a mangrove forest in Southern Thailand. 1. Estimation by the trench method and the zonal structure of root biomass. *Journal of Tropical Ecology* 3:97–108.

Kristensen E, Bouillon S, Dittmar T, Marchand C. 2008. Organic carbon dynamics in mangrove ecosystems: a review. *Aquatic Botany* 89:201–19.

Levin I, Kromer B. 2004. The tropospheric $^{14}CO_2$ level in mid-latitudes of the Northern Hemisphere (1959–2003). *Radiocarbon* 46(3):1261–72.

Levin I, Hammer S, Kromer B, Meinhardt F. 2008. Radiocarbon observations in atmospheric CO_2: determining fossil fuel CO_2 over Europe using Jungfraujoch observations as background. *The Science of the Total Environment* 391:211–6.

Matsui N. 1998. Estimated stocks of organic carbon in mangrove roots and sediments in Hinchinbrook Channel, Australia. *Mangroves and Salt Marshes* 2:199–204.

McKee KL. 1993. Soil physicochemical patterns and mangrove species distribution—reciprocal effects? *The Journal of Ecology* 81(3):477–87.

Middleton BA, McKee KL. 2001. Degradation of mangrove tissues and implications for peat formation in Belizean island forests. *Journal of Ecology* 89:818–28.

Powers JS, Schlesinger WH. 2002. Geographic and vertical patterns of stable carbon isotopes in tropical rain forest soils of Costa Rica. *Geoderma* 109(1–2):141–60.

Ren H, Jian SG, Lu HF, Zhang QM, Shen WJ, Han WD, Yin ZY, Guo QF. 2008. Restoration of mangrove plantations and colonisation by native species in Leizhou bay, South China. *Ecological Research* 23:401–7.

Robert L, Morlang A, Gorman L. 1997. Monitoring the coastal environment. Part 2. Sediment sampling and geotechnical methods. *Journal of Coastal Research* 13:308–30.

Santruckova H, Bird MI, Lloyd J. 2000. Microbial pro-

cesses and carbon-isotope fractionation in tropical and temperate grassland soils. *Functional Ecology* 14: 108–14.

Schweizer M, Fear J, Cadisch G. 1999. Isotopic (^{13}C) fractionation during plant residue decomposition and its implications for soil organic matter studies. *Rapid Communications in Mass Spectrometry* 13:1284–90.

Staddon PL. 2004. Carbon isotopes in functional soil ecology. *Trends in Ecology & Evolution* 19:148–54.

Stuiver M, Polach H. 1977. Discussion reporting of ^{14}C data. *Radiocarbon* 19(3):355–63.

Tam NFY, Wong YS. 1998. Variations of soil nutrient and organic matter content in a subtropical mangrove ecosystem. *Water, Air, & Soil Pollution* 103:245–61.

Tamooh F, Huxham M, Karachi M, Mencuccini M, Kairo JG, Kirui B. 2008. Below-ground root yield and distribution in natural and replanted mangrove forests at Gazi bay, Kenya. *Forest Ecology and Management* 256:1290–7.

Telles EDC, de Camargo PB, Martinelli LA, Trumbore SE, de Costa ES, Santos J, Higuchi N, Oliveira RC. 2003. Influence of soil texture on carbon dynamics and storage potential in tropical forest soils of Amazonia. *Global Biogeochemical Cycles* 17(2):1040, doi: 10.1029/2002GB001953.

Townsend AR, Vitousek PM, Trumbore SE. 1995. Soil organic-matter dynamics along gradients in temperature and land-use on the island of Hawaii. *Ecology* 76: 721–33.

Trumbore SE. 1996. Applications of accelerator mass spectrometry to soil science. In: Boutton TW, Yamasaki S, editors. *Mass Spectrometry of Soils*. New York: Marcel Dekker. p 311–39.

Vogel JS, Nelson DE, Southon JR. 1987. ^{14}C background levels in an accelerator mass-spectrometry system. *Radiocarbon* 29(3):323–33.

Vonfischer JC, Tieszen LL. 1995. Carbon-isotope characterization of vegetation and soil organic-matter in subtropical forests in Luquillo, Puerto Rico. *Biotropica* 27:138–48.

Wang L, Ouyang H, Zhou CP, Zhang F, Song MH, Tian YQ. 2005. Soil organic matter dynamics along a vertical vegetation gradient in the Gongga Mountain on the Tibetan Plateau. *Journal of Integrative Plant and Biology* 47:411–20.

West JB, Bowen GJ, Cerling TE, Ehleringer JR. 2006. Stable isotopes as one of nature's ecological recorders. *Trends in Ecology & Evolution* 21:408–14.

Woodroffe C. 1992. Mangrove sediments and geomorphology. In: Robertson A, Alongi D, editors. *Tropical Mangrove Ecosystems*. Washington, DC: American Geophysical Union. p 7–41.

Wynn JG, Harden JW, Fries TL. 2006. Stable carbon isotope depth profiles and soil organic carbon dynamics in the lower Mississippi Basin. *Geoderma* 131:89–109.

Zhang HB, Luo YM, Wong MH, Zhao QG, Zhang GL. 2007. Soil organic carbon storage and changes with reduction in agricultural activities in Hong Kong. *Geoderma* 139:412–9.

Zhang JP, Shen CD, Ren H, Wang J, Han WD. 2012. Estimating change in sedimentary organic carbon content during mangrove restoration in southern China using carbon isotopic measurements. *Pedosphere* 22(1):58–66.