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Distribution Pattern and Influencing Factors for Soil Organic Carbon (SOC) in Mangrove Communities at Dongzhaigang, China

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ABSTRACT

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Mangrove wetlands constitute an important carbon pool and play an important role in the global carbon balance. Understanding the distribution and influencing factors for soil organic carbon (SOC) in different mangrove communities can improve the estimation of carbon sink capacity. The SOC content and physicochemical properties were investigated from six mangrove communities dominated by *Avicennia marina, Aegiceras corniculatum, Bruguiera sexangula, Sonneratia apetala, Rhizophora stylosa,* or *Ceriops tagal* in Dongzhaigang, Southern China. The SOC content ranged from 2.60 to 89.51 g kg^{-1} with a mean of 18.35 g kg^{-1}. The SOC content and density decreased with the depth from surface to bottom and with the tidal gradient from the low intertidal zone to the high intertidal zone except for the SOC density in the soils of the three arbor communities (*S. apetala, R. stylosa,* and *B. sexangula*). The SOC content was more related to soil nutrient elements such as total nitrogen, total phosphorus, and total potassium than to pH, bulk density, conductivity, and other soil environmental factors. Among these six mangrove plants, *R. stylosa* and *A. corniculatum* should be highly prioritized during mangrove restoration for the higher soil carbon sequestration rate and the stronger adaptive capacity.

ADDITIONAL INDEX WORDS: *Physicochemical property, correlation analysis.*

INTRODUCTION

Mangroves are unique vegetation communities found in the upper part of the tidal zone of tropical and subtropical regions. These systems have important ecological service functions, such as providing baits, refuge and feeding zones for marine organisms; contributing to coastline protection; and reducing the harm done by sea-level rise (Alongi, 2008; Holguin, Vazquez, and Bashan, 2001; Kauffman *et al.*, 2011). Mangroves are also important for mass exchange between ocean and land, linking the carbon cycles, and play an important role in global carbon balance (Dittmar *et al.*, 2006; Dittmar, Lara, and Kattner, 2001; Jennerjahn and Ittekkot, 2002; Kristensen *et al.*, 2008). Mangroves have high carbon concentration because of their high productivity, thick soils, and anaerobic conditions (Donato *et al.*, 2011).

Although the area of mangroves is less than 0.1% of the total land on Earth, the carbon stocks account for 10 to 11% of the total translocation from land to ocean, while about 15% of these translocations of carbon are accumulated in modern marine sediments (Bouillon *et al.*, 2008; Dittmar *et al.*, 2006; Jennerjahn and Ittekkot, 2002).When compared with other terrestrial ecosystems, mangroves soil carbon content is approximately four to eight times higher than that of tropical savanna and two to three times greater than that of forests (Donato *et al.*, 2012; Twilley, Chen, and Hargis, 1992). Moreover, mangrove wetlands are among the most productive types of wetlands on Earth, capable of fixing 2500 mg m^{-2} of carbon every day (Jennerjahn and Ittekkot, 2002). In the Pacific tropical region, the carbon stock in mangroves is 830 to 1218 Mg ha^{-1}, with 631 to 754 Mg stored in the soil, which is higher than the total carbon stock of other ecosystems (Donato *et al.*, 2012).

In mangrove ecosystems, 62 to 76% of the carbon is stored in the soil (Donato *et al.*, 2012). In the Indo-Pacific region, the carbon stock in the mangroves had an average of 1023 Mg ha^{-1} and accounted for 49 to 98% of carbon storage in soil from 0.5 to more than 3 m (Donato *et al.*, 2011). In the *Kandelia obovata* forest of the Manko wetland at Okinawa Island, Japan, the soil organic carbon (SOC) content within a depth of 1 m was 57.3 Mg ha^{-1}, almost equal to the storage of organic carbon (OC) in the mangrove plants (Khan, Suwa, and Hagihara, 2007). In the Hinchinbrook Channel of Australia, the OC content of mangrove soil from 0 to 50 cm was 296 t ha^{-1}, accounting for 64% of the total OC stock in this region (Matsui, 1998). In Micronesia, mangrove ecosystem carbon storage ranged from

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Figure 1. *A. marina* community in Dongzhaigang, Hainan Island. (Color for this figure is available in the online version of this paper.)

Figure 2. *S. apetala* community in Dongzhaigang, Hainan Island. (Color for this figure is available in the online version of this paper.)

479 to 1385 Mg ha^{-1}, and nearly 70% of the carbon was deposited in soil within a depth of 1 to 2 m (Kauffman *et al*., 2011). Overall, these findings indicate that mangrove forests are important surface carbon pools that vary greatly spatially and vertically (Kristensen *et al*., 2008).

The growth environment of mangroves is complex and diverse, resulting in diversified carbon storage (Kristensen *et al*., 2008). Previous studies indicated that the SOC of mangroves is influenced by plant types (Wang *et al*., 2013), soil depths (Donato *et al*., 2012), phenolic material concentration (Saraswati *et al*., 2016), and soil physical and chemical factors such as nitrogen (N; Batjes, 1996), phosphorus (P; Boto and Wellington, 1984), the carbon-to-nitrogen (C/N) ratio (Bouillon *et al*., 2003), potassium (K; Xin *et al*., 2014), pH (Tam and Wong, 1998), bulk density (Avnimelech *et al*., 2001), and water content (Wang *et al*., 2009). Even in the same area, the distribution of SOC is not homogeneous as a result of the different vegetation biomass and soil physicochemical properties (Huxham *et al*., 2010; Sherman, Fahey, and Martinez, 2003). At different positions of intertidal zone, the conditions of nutrient elements are different in both soil and plant organs, which generally increased along with the tidal elevation (He *et al*., 2007). Furthermore, the change of total ecosystem carbon pools, including carbon accumulated in both biomass and soil, was mainly influenced by the change of tidal elevation (Tam and Wong, 1998; Wang *et al*., 2013). These studies showed that the influencing factors of SOC distribution were complicated and that quantitative analysis of influencing factors for SOC accumulation is valuable and necessary for different areas.

In China, mangroves are naturally distributed along the coasts of the Hainan, Guangdong, Guangxi, and Fujian Provinces. Among them, the Dongzhaigang mangrove wetland in NE Hainan Island is the largest and earliest national mangrove nature reserve in China. However, stocks, distribution characteristics, and influencing factors of the mangrove SOC at Dongzhaigang have not been fully studied yet (Xin *et al*., 2014; Zhan *et al*., 2015). Therefore, the specific objectives of this study were to investigate the distribution of SOC in different mangrove communities and to reveal the relationship between the physicochemical properties of soil and the SOC. This will contribute to the estimation accuracy of the global coastal carbon pool and provide a scientific basis for wetland restoration along the China coast.

METHODS

This section introduces basic information, including geographical characteristics and species of the study area, the sampling scheme, the methods of sample treatment, and data analysis.

Study Area

Dongzhaigang National Mangrove Nature Reserve is located around the bay of NE Hainan Island, with a total area of about 1578.2 ha (Li and Lee, 1997). It is a semienclosed, muddy-bottom estuary formed by continental sink during the Great Qiongzhou Earthquake in 1605 and fed by four small rivers (Liao *et al*., 2009; Wang *et al*., 2009). The climate is tropical marine monsoon, with an average annual temperature of 23.3 to 23.8°C and rainfall of approximately 1700 mm. The reserve has an irregular semidiurnal tide, with an average tidal range of 1.1 m (Zhang *et al*., 1997). Dominant species in Dongzhaigang mangrove reserve include *Rhizophora stylosa* Griff., *Bruguiera sexangula* (Lour.) Poir., *Avicennia marina* (Forsk) Vierh., *Ceriops tagal* (Perr.) C. B. Rob., *Aegiceras corniculatum* (Linn.) Blanco., *Sonneratia apetala* Buch.-Ham., *Bruguiera gymnorrhiza* (Linn.) Sav., *B. sexangula* var. *rhynchopetala* Ko, *Kandelia obovata* Sheue *et al*., *Excoecaria agallocha* Linn., and *Acanthus lilcifolius* Linn., among a total of 35 species (Li and Lee, 1997).

Sampling

Based on remotely sensed data and a field survey, six mangrove communities dominated by *A. marina* (Figure 1), *B. sexangula, C. tagal, R. stylosa, A. corniculatum,* or *S. apetala* (Figure 2) were identified.

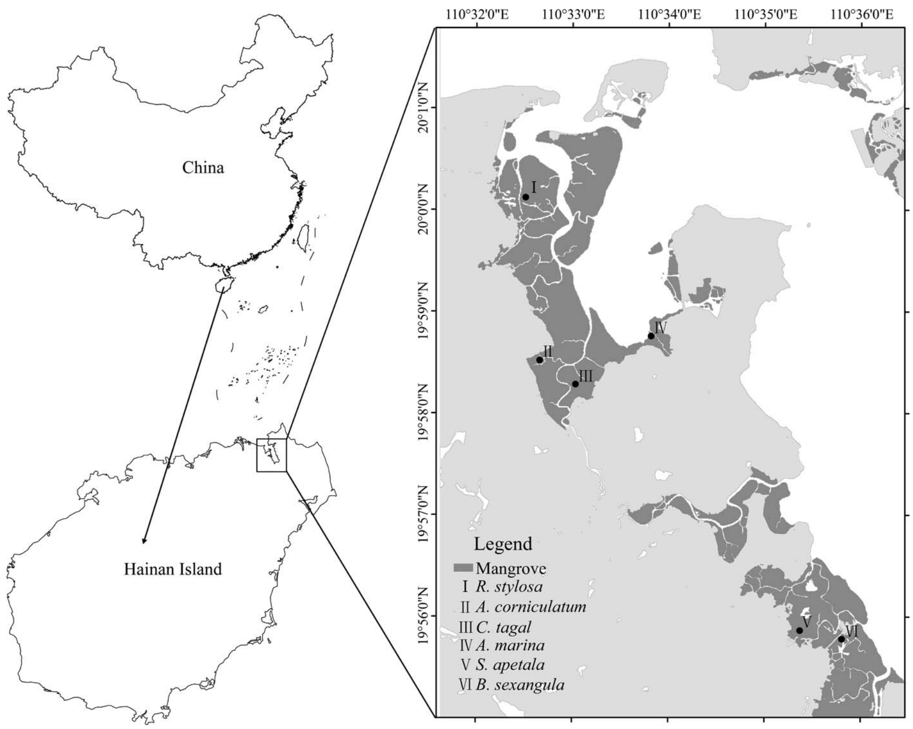

Figure 3. Sampling sites in the study area. Site I, *R. stylosa*: 20.002° N, 110.541° E; Site II, *A. corniculatum*: 19.975° N, 110.543° E; Site III, *C. tagal*: 19.971° N, 110.551° E; Site IV, *A. marina*: 19.978° N, 110.563° E; Site V, *S. apetala*: 19.930° N, 110.589° E; Site VI, *B. sexangula*: 19.929° N, 110.589° E.

From September to December 2013, six quadrats for six mangrove communities of Dongzhaigang were established (Figure 3). Quadrat size for arbors was 10 × 10 m and shrubs was 5 × 5 m. Within each quadrat, point information, species, number of each species, and tree height and diameter at the breast height 1.3 m (DBH) were recorded. Three core soil samples were collected from each quadrat with a depth of 0 to 100 cm using a stainless-steel soil sampler (inner diameter is 8 cm, and depth is 1.15 m) during ebb tide. Then, for each core soil sample, three parallel samples were collected from the layers of 0 to 20, 20 to 40, 40 to 60, 60 to 80, and 80 to 100 cm using a cutting ring. The samples were stored in clean, dry, labeled polyethylene plastic bags, sealed, and transported to the laboratory at normal temperature on the same day. The samples were dried in the open air in the laboratory.

The air-dried soil samples were mixed and sieved (0.15 mm) after sorting out the plant and animal residues and stones. Before laboratory analysis, all samples were stored in glass desiccators with desiccants. The soil properties analyzed included bulk density, water content, pH, conductivity, SOC content, total nitrogen (TN), total phosphorus (TP), and total potassium (TK). Soil bulk density was measured as the ratio of soil dry weight to the soil cutting ring's volume. Water content was measured using a drying oven (at 105°C). pH was measured with an IQ150 pH meter (IQ Scientific Instruments Inc., U.S.A.). Conductivity was measured with a Hydra Probe (Stevens Water Monitoring Systems Inc., U.S.A.). The SOC content was measured using the potassium dichromate outside heating method (Zhang *et al.*, 2014; Precision: ±0.001). The TN was measured with a Kjeltec 8400 system (Foss, Denmark). The TP was measured with the molybdenum-antimony antispectrophotometric method, and the TK was measured with flame photometry (Lu, 2000).

Data Analysis

SOC density was calculated using the following formula:

$$\mathrm{SOCD} = C_i D_i E_i (1 - G_i)/100 \qquad (1)$$

where, SOCD is SOC density (in kilograms per square meter), C_i is SOC content (in grams per kilogram), D_i is soil bulk density (in grams per cubic centimeter), E_i is soil depth (in centimeters), and G_i is the volume percentage of gravel with a size greater than 2 mm.

All data of the SOC and the environmental factors passed the nonparametric one-sample Kolmogorov-Smirnov test, which indicated that all data followed a normal distribution ($p > 0.05$, $n = 90$). The SOC content in different depths and soil physicochemical properties of mangrove communities was analyzed with the least significant difference method in one-way analysis of variance (ANOVA), and the significance was conducted at $p < 0.05$. Pearson's correlation analysis was used to delineate the pairwise relationships between SOC and soil physicochemical properties (Cheng and Wang, 2004). Regression analysis was then employed to deduce the regression equation describing the relationship between SOC and soil

Table 1. *Parameters of mangrove communities at Dongzhaigang, Hainan Island.*

Species Index	*R. stylosa* (mean ± SD)	*S. apetala* (mean ± SD)	*B. sexangula* (mean ± SD)	*A. marina* (mean ± SD)	*C. tagal* (mean ± SD)	*A. corniculatum* (mean ± SD)
Plants						
Height (m)	5.40 ± 0.71	11.90 ± 2.97	1.20 ± 0.41	1.90 ± 0.52	1.20 ± 0.16	1.56 ± 0.08
DBH (cm)	6.10 ± 0.21	14.40 ± 0.37	8.20 ± 0.12	3.40 ± 0.01	4.90 ± 0.04	3.50 ± 0.02
SOC content (g kg^{-1})	20.26 ± 15.52	14.89 ± 6.01	20.89 ± 6.41	17.39 ± 12.34	17.03 ± 18.63	19.65 ± 24.29
SOC density (kg m^{-2})	5.23 ± 3.49	4.11 ± 1.89	4.40 ± 0.96	4.99 ± 2.91	5.46 ± 6.52	5.83 ± 7.42

factors. All of these tests were accomplished using Statistical Product and Service Solutions (SPSS) version 18.0 software.

Moreover, the impact of soil physicochemical properties on the SOC content and density was determined by multivariate ordination analysis to sort the orders of the correlation degree using Canoco version 4.5 software. Detrended correspondence analysis indicated the use of redundancy analysis (RDA) was applicable because of predominantly linear relationships within all data according to the value of lengths of gradient. Significance of the first and other ordination axes was calculated with the Monte-Carlo significance test (ter Braak and Šmilauer, 2002).

RESULTS

In this section, the soil physicochemical properties and the distribution of SOC in Dongzhaigang mangrove communities were presented according to the results of the investigation. The relationships between SOC and physicochemical properties were also analyzed.

Soil Physicochemical Properties

In the six vegetation communities, the content of SOC ranged from 2.60 to 89.51 g kg^{-1} with an average of 18.35 g kg^{-1}, while the SOC density ranged from 0.81 to 27.68 kg m^{-2} with a mean value of 5.01 kg m^{-2}. The contents of SOC at different depths and communities are shown in Table 1.

Other physicochemical properties of different mangrove communities are shown in Table 2. Overall, the contents of TN and TP in the *B. sexangula* community were significantly higher than in the other communities except in the *C. tagal* community, while the C/N ratio, bulk density, and conductivity of *B. sexangula* community was significantly lower than the other communities. The significantly higher content of TK was found in the *R. stylosa* community, which also had the significantly highest value of pH. For the water content, it was found that *A. marina, A. corniculatum,* and *C. tagal* communities were significantly higher than *R. stylosa, B. sexangula,* and *S. apetala* communities.

Vertical Distribution of SOC

In *R. stylosa* (Figure 4b), *A. marina* (Figure 4d), *S. apetala* (Figure 4a), and *C. tagal* (Figure 4e), the highest content of SOC was found with a depth of 0 to 20 cm, which occurred in the following order: *C. tagal* (51.9 ± 10.2 g kg^{-1}) > *R. stylosa* (45.0 ± 1.9 g kg^{-1}) > *A. marina* (40.7 ± 1.2 g kg^{-1}) > *S. apetala* (21.2 ± 3.6 g kg^{-1}). In general, the SOC content decreased as the soil depth increased in the *R. stylosa, A. marina, S. apetala,* and *C. tagal,* but this trend was not remarkable in *B. sexangula* and *A. corniculatum*. Besides, as shown in Figure 4, SOC content had great variation in different communities within 0 to 100 cm. Overall, SOC content of *R. stylosa, A. marina,* and *C. tagal* communities from 0 to 20 cm was significantly higher than that at other depths. There were no significant differences among 0 to 20, 20 to 40, and 80 to 100 cm in the SOC content of *S. apetala* community, but it was significantly higher than that with 40 to 60 and 60 to 80 cm. For the *B. sexangula* community (Figure 4c), the maximum SOC content was 29.7 ± 2.6 g kg^{-1}, which was observed with a depth of 60 to 80 cm and was significantly higher than that with the other depths except 40 to 60 cm. For the *A. corniculatum* community (Figure 4f), the maximum SOC content was observed from 20 to 40 cm with an average of 52.4 g kg^{-1}, which was significantly higher than that with the other depths of 40 to 60, 60 to 80, and 80 to 100 cm except 0 to 20 cm.

The vertical distribution of SOC density of six communities in Dongzhaigang also had great variation within 0 to 100 cm, as shown in Table 1 and Figure 5. In general, there is no obvious trend for the SOC density of all mangrove communities with soil depth. In *R. stylosa* (Figure 5b), *A. marina* (Figure 5d), *C. tagal* (Figure 5e), and *A. corniculatum* (Figure 5f) communities, the SOC densities decreased with increasing soil depth. The highest SOC densities in the *R. stylosa* (9.6 kg m^{-2}), *A. marina* (10.4 kg m^{-2}), and *C. tagal* (17.7 kg m^{-2}) communities

Table 2. *Physicochemical properties of mangrove communities at Dongzhaigang, Hainan Island.*

Species Index	*R. stylosa* (mean ± SD)	*S. apetala* (mean ± SD)	*B. sexangula* (mean ± SD)	*A. marina* (mean ± SD)	*C. tagal* (mean ± SD)	*A. corniculatum* (mean ± SD)
TN (g kg^{-1})	0.53 ± 0.47†	0.42 ± 0.24†	2.48 ± 1.22*	0.26 ± 0.29†	0.15 ± 0.07†	0.24 ± 0.07†
TP (g kg^{-1})	0.67 ± 0.04*	0.66 ± 0.11*	0.53 ± 0.06†	0.67 ± 0.05*	0.54 ± 0.03†	0.65 ± 0.06*
TK (g kg^{-1})	13.55 ± 0.52*	12.60 ± 0.80*, †, ‡	11.52 ± 0.38‡	11.90 ± 3.42†, ‡	11.96 ± 0.64†, ‡	12.91 ± 2.09*, †
C/N ratio	45.63 ± 16.10‡, §	40.83 ± 19.09‡, §	9.27 ± 2.72§	101.20 ± 48.92*, †	146.71 ± 132.19*	71.49 ± 79.07†, ‡
Bulk density (g cm^{-3})	1.38 ± 0.20*, †, ‡	1.38 ± 0.19*	1.08 ± 0.14§	1.51 ± 0.13*, †	1.49 ± 0.14†, ‡	1.48 ± 0.18‡, §
Conductivity (μs cm^{-1})	603.33 ± 108.54†	384 ± 137.67‡	402 ± 173‡	636 ± 243.89†	656 ± 344.71†	978 ± 396.76*
pH	8.11 ± 0.11*	4.78 ± 0.15††	6.9 ± 0.09§	7.46 ± 0.32†	7.33 ± 0.14‡	6.40 ± 0.04**
Water content	0.70 ± 0.01†	0.69 ± 0.04†	0.60 ± 0.06‡	0.76 ± 0.05*	0.79 ± 0.02*	0.76 ± 0.02*

*, †, ‡, §, **, †† Different symbols from each row indicate significant differences ($p < 0.05$) among different species according to the one-way ANOVA, which means that if the symbols of any two species in the same row are the same, the difference between the index of these two species is not significant.

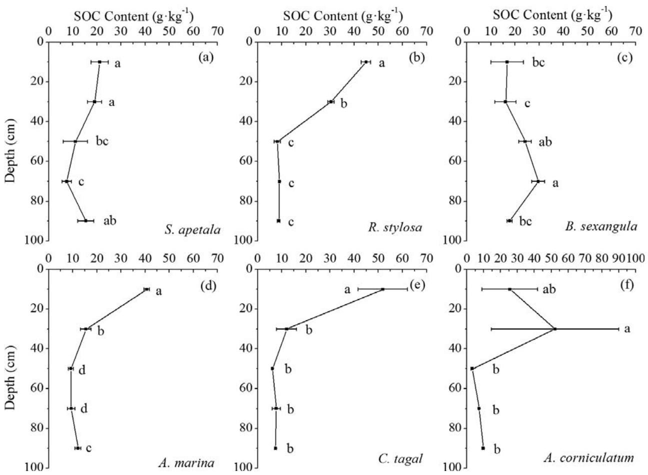

Figure 4. Distribution of SOC content at different depths in the six mangrove communities at Dongzhaigang, Hainan Island. (a) to (d) Significant difference ($p < 0.05$) among different depths according to the one-way ANOVA.

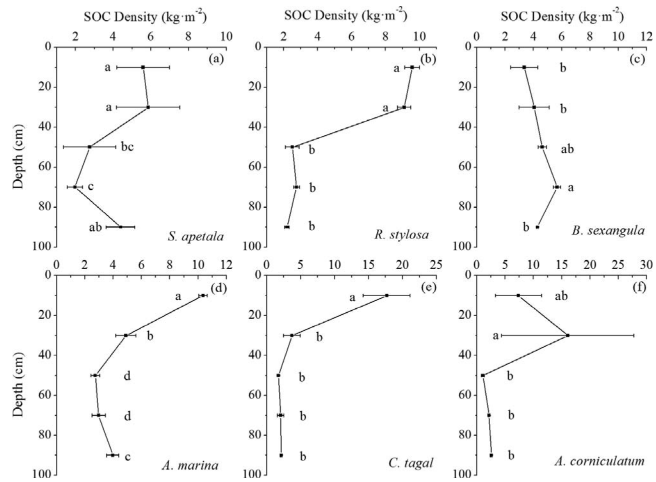

Figure 5. Distribution of SOC density at different depths in the six mangrove communities at Dongzhaigang, Hainan Island. (a) to (d) Significant difference ($p < 0.05$) among different depths according to the one-way ANOVA.

were found with depths of 0 to 20 cm, while those of the *A. corniculatum* community (16.8 kg m^{-2}) appeared from 20 to 40 cm. But in *B. sexangula* (Figure 5c), SOC density increased with increasing soil depth, with the highest value found with a depth of 60 to 80 cm (5.7 kg m^{-2}) and the minimum value with a depth of 0 to 20 cm (3.4 kg m^{-2}).

Horizontal Distribution of SOC

The average SOC content for the whole (0–100 cm) soil layer of the six communities is as follows: *B. sexangula* community (20.89 g kg^{-1}) > *R. stylosa* community (20.26 g kg^{-1}) > *A. corniculatum* community (19.65 g kg^{-1}) > *A. marina* community (17.39 g kg^{-1}) > *C. tagal* community (17.03 g kg^{-1}) > *S. apetala* community (14.89 g kg^{-1}). The order for the SOC density was slightly different: *A. corniculatum* community (5.98 kg m^{-2}) > *C. tagal* community (5.46 kg m^{-2}) > *R. stylosa* community (5.23 kg m^{-2}) > *A. marina* community (4.99 kg m^{-2}) > *B. sexangula* community (4.40 kg m^{-2}) > *S. apetala* community (4.11 kg m^{-2}). As shown in Figure 6, SOC content and density decreased with the tidal gradient from the high intertidal zone to the low intertidal zone for the three mangrove shrubs, with the overall levels occurring as follows: *A. marina* community < *C. tagal* community < *A. corniculatum* community. The SOC content showed the same trend for arbors, with levels occurring as follows: *S. apetala* community < *R. stylosa* community < *B. sexangula* community. However, SOC density in arbors showed little difference with SOC content, with levels occurring as follows: *S. apetala* community < *B. sexangula* community < *R. stylosa* community.

Relationships between SOC and Soil Physicochemical Properties

Figure 7 shows the ordination diagram of a RDA, which was calculated for the environmental variables (physicochemical properties of soils) and the SOC content and density as species variables. Eigenvalues of the RDA showed that 40 and 1.2% of the total variance within the SOC content and density were explained by the first and second ordination axes, respectively. High species–environment relationships indicated a strong relationship (species–environment correlation = 0.64) between physicochemical properties of soils and SOC. The result of RDA (Figure 7) indicated that SOC content and density were positively correlated to TN, TP, pH, C/N ratio, and bulk density and negatively correlated to TK, conductivity, and water content. But the p values between SOC and TN, TP, TK, and water content were less than 0.05, while the p values between SOC and C/N ratio, pH, bulk density, and conductivity were higher than 0.05. The result of RDA also showed that the total variance of TN, TP, TK, C/N ratio, and water content was 36.7% on the first ordination axis, which explained most information of environmental variables. Besides, the results of Pearson's correlation analysis indicated that SOC content had a significantly positive correlation with TN, TP, and C/N ratio but a significantly negative correlation with TK and water content. No significant correlation was found between SOC and pH, bulk density, or conductivity. Therefore, it could be

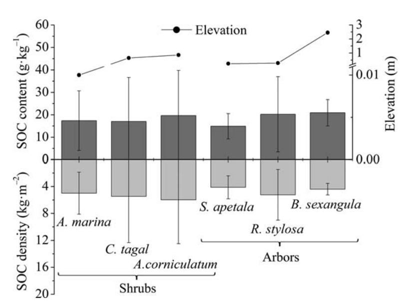

Figure 6. Distribution of SOC content and density for different mangrove communities at Dongzhaigang, Hainan Island.

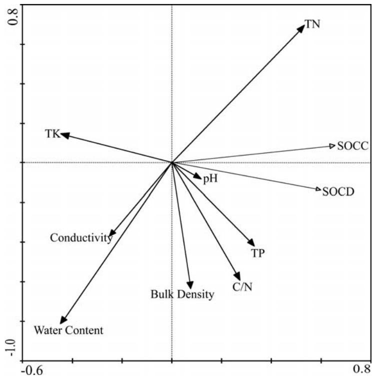

Figure 7. Ordination diagram of the RDA between the SOC content and density and the different soil physicochemical properties. SOCC, SOC content; SOCD, SOC density.

considered that the SOC content was more closely related to soil nutrient elements than to other environmental factors.

The regression equation was further developed with regression analysis. With a 0- to 20-cm depth, the regression equations between SOC and physicochemical properties fit better than in other depths. Thus, the data with depths of 0 to 20 cm were chosen to establish the regression equation between SOC and physicochemical properties. To find a general model, five groups of data from five communities were used to establish the regressions, while the data from the remaining community were used for verification. Regression equations are shown in Table 3.

For C/N ratio, the content of N had been calculated with TN, while for water content, it had been used in calculating bulk density. Therefore, C/N ratio and bulk density were not used to avoid increasing the weight values of N and water content in the regression equations. From the seven equations in Table 3, a universal regression model between SOC and soil physicochemical properties can be established:

$$Y = k - a{*}X_1 + b{*}X_2 - c{*}X_3 - d{*}X_4 + e{*}X_5 - f{*}X_6 \quad (2)$$

where, X_1 to X_6 represent TN, TK, TP, conductivity, pH, and water content, respectively; k ranges from –9.11 to 142.64; a is from 10.74 to 57.72; b is from 5.84 to 10.12; c is from 20.37 to 69.70; d is from 0.03 to 0.04; e is from 14.76 to 21.05; and f is from 10.27 to 122.59. In these equations, all values of R^2 were less than 0.95, indicating that other factors influenced the distribution of SOC in mangrove soils besides the factors presented in the equations.

DISCUSSION

In the following section, the distribution characteristics and influencing factors of SOC in Dongzhaigang mangrove communities were discussed according to the results of this study. The results were also compared with other studies with similar conditions in the world.

Distribution of SOC

In this study, the content of SOC was lower than that in Yingluo Bay, Guangdong Province, China (Wang *et al.*, 2013). Compared with other ecosystems in Hainan Island, the average SOC content of Dongzhaigang mangrove wetland in this study is 6.8 times, 3.8 times, and 1.1 times higher than that of the tropical rubber plantations (Zhang, Ding, and Meng, 2010), the mango plantations (Zheng *et al.*, 2013), and the tropical rain forest on the same island (Zhang *et al.*, 2014), respectively. The density of SOC in this study was similar to that of the Sanya mangrove of China (5.6 kg m^{-2}; Ren *et al.*, 2010), which was higher than that in the mangrove in Sundarbans of India (0.61–1.55 kg m^{-2}; Mitra, Banerjee, and Sett, 2012), the *K. obovata* community of the Jiulong River Estuary of China (1.51–1.70 kg m^{-2}; Alongi *et al.*, 2005), and the Manko wetland of Japan (0.57 kg m^{-2}; Khan, Suwa, and Hagihara, 2007) but lower than that in the Hinchinbrook Channel mangroves of Australia (29.6 kg m^{-2}; Matsui, 1998). These differences of SOC content and density in different mangrove ecosystems were mainly caused by differences of biomass, which is further influenced by site condition, species composition, and primary productivity of each species (Lovelock *et al.*, 2010; Sebastian and Chacko, 2006). Wang *et al.* (2013) found that biomass and SOC concentration had significantly positive correlation in the Yingluo Bay mangrove forest of South China. Ren *et al.* (2008) found that the high amount of dead roots resulted in the large vegetation biomass input and caused the high SOC density in the Leizhou Bay mangrove forest of Southern China.

SOC entering mangroves can be derived from autochthonous carbon, such as litter from trees and roots, or imported by tides or rivers from outside (Bouillon *et al.*, 2003; Kristensen *et al.*, 2008). Mangroves are shallow-root plants, with root systems mainly within a depth of 0 to 90 cm and usually not more than 120-cm deep (Boto and Wellington, 1984; Duke, Ball, and Ellison, 1998; Youssef and Saenger, 1996). Different communities may have different root structures; for example, *R. stylosa* has stilt roots, *A. marina* and *S. stylosa* have pneumatophores, and *B. sexangula* has knee roots (Srikanth, Lum, and Chen, 2016; Youssef and Saenger, 1996). This may affect the differences of the distribution of SOC in different

Table 3. *The regression equation between SOC and soil physicochemical properties with a depth of 0 to 20 cm.*

	Regression Equation*	R^2	F	p
Without *R. stylosa*	$Y = -44.35 - 57.72X_1 + 10.12X_2 - 33.78X_3 - 0.05X_4 + 18.20X_5 - 107.27X_6$	0.91	12.71	0.001
Without *S. apetala*	$Y = -44.11 - 55.71X_1 + 9.87X_2 - 59.87X_3 - 0.04X_4 + 19.83X_5 - 106.79X_6$	0.90	11.34	0.002
Without *B. sexangula*	$Y = 142.64 - 107.40X_1 + 9.81X_2 - 69.70X_3 - 0.04X_4 + 21.05X_5 - 327.32X_6$	0.86	8.22	0.004
Without *A. marina*	$Y = 4.18 - 54.71X_1 + 5.84X_2 - 27.94X_3 - 0.04X_4 + 17.75X_5 - 116.10X_6$	0.88	9.79	0.003
Without *C. tagal*	$Y = -20.75 - 48.76X_1 + 7.88X_2 - 20.37X_3 - 0.03X_4 + 15.48X_5 - 112.71X_6$	0.84	6.90	0.008
Without *A. corniculatum*	$Y = -10.70 - 50.45X_1 + 7.97X_2 - 40.22X_3 - 0.03X_4 + 14.76X_5 - 102.70X_6$	0.94	19.64	0.000
Total	$Y = -9.11 - 57.70X_1 + 8.64X_2 - 40.90X_3 - 0.04X_4 + 17.22X_5 - 122.59X_6$	0.88	13.91	0.000

* Y = SOC; X_1 = TN; X_2 = TK; X_3 = TP; X_4 = conductivity; X_5 = pH; X_6 = water content.

mangrove communities. In this study, it was found that SOC content and density in different mangrove communities decreased with increasing depth in most sampling sites generally, which was found to be similar in the Yap state of the Federated States of Micronesia, the Republic of Palau, and the Manko wetlands of Okinawa Island, Japan (Donato *et al.*, 2012; Khan, Suwa, and Hagihara, 2007).

In the horizontal direction, SOC content and density varied with the tidal gradient. The SOC content and density for the three mangrove shrubs and SOC content for the three mangrove arbors in Dongzhaigang decreased with the tidal gradient from the high intertidal zone to the low intertidal zone. A similar result was found in Yingluo Bay, Guangdong, Southern China, which was attributed to the diversities of the vegetation biomass and net primary production in different mangrove communities (Wang *et al.*, 2013). In other studies, Zhang *et al.* (2009) reported that in the mangrove of the Pearl River Estuary, the SOC content near the estuary was significantly higher than that in the more salinized coast, and Tam and Wong (1998) found that the content of OC in sediments decreased as the distance from land to the sea decreased. These differences of SOC in different mangrove communities indicated that the distributions of SOC was influenced by various factors, such as location, species composition, primary productivity, and stages of forest (Lovelock *et al.*, 2010; Sebastian and Chacko, 2006). Therefore, it is necessary to conduct further investigation on the aboveground and underground biomass of mangrove communities at different locations and forest ages in Dongzhaigang.

Besides, in the process of afforestation practices, some mangrove plants, such as *R. stylosa, A. corniculatum, A. marina,* and *S. apetala,* are commonly used in China. *R. stylosa, A. corniculatum,* and *A. marina* have strong adaptability to temperature, salinity, and tide. They also have developed strong root systems that can resist wind and waves (He *et al.*, 2007). *S. apetala* is a highly adaptive and fast-growing exotic species introduced into Dongzhaigang in 1985 from Bangladesh (Wang *et al.*, 2013). However, according to the results of carbon sequestration ability in this study, native species *R. stylosa* and *A. corniculatum* should be highly prioritized during mangrove restoration.

Relationship between SOC and Soil Physicochemical Properties

In this study, the correlations between mangrove SOC content and soil nutrient elements were found to be higher than those between SOC and other environmental factors. The SOC showed positive correlations with TN, TP, and C/N ratio, which was consistent with the results of previous studies (Boto and Wellington, 1984; Bouillon *et al.*, 2003; Soto-Jiménez, Páez-Osuna, and Ruiz-Fernández, 2003), indicating that N, P, and K were the major elements influencing plant growth and standing biomass (Boto and Wellington, 1984). Bouillon *et al.* (2003) found that a lower C/N ratio is associated with a lower SOC content in mangroves, because high N content could stimulate the decomposition of soil organic matter and thus lower the content of SOC (Batjes, 1996; Soto-Jiménez, Páez-Osuna, and Ruiz-Fernández, 2003). The SOC displayed a negative correlation with TK in this study. According to the results by Wang and Hong (2005), the number of bacteria was decreased when TK was high, while bacteria can process most of the energy flow and nutrients and provide more organic matter in soils (Holguin, Vazquez, and Bashan, 2001).

For pH, it was found that pH and SOC have a significantly negative correlation in *C. tagal* of this study, which was similar to the results presented for the mangroves of Hong Kong and Hainan Island (Tam and Wong, 1998; Xin *et al.*, 2014). This might be related to the microbial activity under different pH values; when extreme pH values of more than 8.5 or less than 5.5 inhibited microbial activity, the decomposition rate of OC would be affected (Alongi, Boto, and Tirendi, 1989; Holguin, Vazquez, and Bashan, 2001). Usually, when the pH is close to neutral, the microbial activity is the strongest (Xin *et al.*, 2014). Bulk density has the great influence on soil solute transport, water-holding capacity, permeability, and mineralization rate, which affect the accumulation of SOC (Avnimelech *et al.*, 2001). The total SOC content of the six mangrove communities tended to decrease as bulk density increases significantly in *A. marina, B. sexangula,* and *R. stylosa*. Avnimelech *et al.* (2001) also found that SOC content is inversely proportional to soil bulk density in Israel, Alabama, Egypt, and three other areas. Although SOC was not significantly correlated with conductivity in this study, the influence of conductivity on SOC should not be ignored, because it is the index of soil water-soluble salt, while salinity has a significant impact on plant growth, biomass, and soil microbial activities (Lacerda, Ittekkot, and Patchineelam, 1995; Li *et al.*, 2010; Mitra, 2011). In mangrove wetlands, the excessive salinity would inhibit mangrove growth, biomass, and carbon accumulation (Mitra, 2011). There was a significantly negative correlation between SOC and water content (50–82%, $p < 0.05$). Based on the control experiment, Wang *et al.* (2010) found that the mineralization rate of peat wetland increased with increasing water content, with the maximum value being observed at a water content of 60%. The average water content of Dongzhaigang was 71% (>60%), because mangrove communities are growing under long-term flooding.

These aforementioned relationships between SOC and soil physicochemical properties indicated that the impact factors of SOC were complicated and heterogeneous because of the special growth environment of mangroves, according to the RDA and Pearson's correlation analysis in this study. Besides, many other factors might influence the SOC, such as temperature (Melillo *et al.*, 2002), tidal differences (Bouillon *et al.*, 2003; Lallier-Verges *et al.*, 1998; Yuan *et al.*, 2014), microorganisms (Holguin, Vazquez, and Bashan, 2001), enzyme activity (Acosta-Martínez *et al.*, 2007), and human disturbance (Matsui *et al.*, 2010). Therefore, to better understand mangrove OC storage, further study about the influence of other factors on the OC should be conducted in the future.

Moreover, vegetation litter and root systems are not only the main source of SOC but also the main components of vegetation biomass (Kristensen *et al.*, 2008; Lawson *et al.*, 2015). Foody *et al.* (2001) found that normalized difference vegetation index (NDVI) was highly correlated with vegetation biomass. However, in this study, when NDVI was added into the SOC regression equation, R^2 values did not improve significantly. NDVI can only reflect the information provided by the vegetation canopy; however, canopy litter can be easily transported to other places by the tide, while the trunk and underground biomass cannot be reflected by the NDVI (Donato *et al*., 2011; Li *et al*., 2007). Therefore, it is necessary to explore other methods to reveal the relationship between vegetation biomass and SOC in mangroves.

Climate warming could stimulate plant growth, promote nutrient absorption, and increase the absorption of carbon dioxide released from soils (Lal, 2005). Thus, global warming caused by the influence of greenhouse gases may lead to a change of carbon storage in wetland soils (Chmura *et al*., 2003). Sea-level rise is an important consequence of global climate change, while in mangrove coast, Alongi (2008) found that the sediment deposition rate was approximately equivalent to the rate of sea-level rise and the carbon sequestration capacity of mangrove ecosystem was important for global carbon cycling.

CONCLUSION

The distribution and influencing factors of SOC in the Dongzhaigang mangrove were investigated in this study. In the vertical profile of 1 m, SOC decreased with soil depth from 33.5 ± 15.2 to 11.9 ± 4.0 g kg^{-1}. Horizontally, with the increase of tidal influence, the SOC content and density in the shrub communities of *A. marina, C. tagal,* and *A. corniculatum* and the SOC content in the arbor communities of *S. apetala, R. stylosa,* and *B. sexangula* showed an increasing trend. In the soils of different mangrove communities, SOC content was more correlated with soil nutrient elements than with soil environmental factors. But the intrinsic relationships among the various factors and the mechanisms of these factors influencing the SOC need further investigation. Besides, for carbon sequestration among the six mangrove communities in Dongzhaigang, Hainan Island, China, native species such as *R. stylosa* and *A. corniculatum* should be highly prioritized in the coastal ecosystem restoration, rather than the exotic species *S. apetala*. The relative carbon sequestration ability for native and exotic species needs verification at specific sites.

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