Acta Oceanol. Sin., 2018, Vol. 37, No. 12, P. 85–91
DOI: 10.1007/s13131-018-1290-5
http://www.hyxb.org.cn
E-mail: hyxbe@263.net

Ecosystem carbon stock of a tropical mangrove forest in North Sulawesi, Indonesia

CHEN Shunyang[1], CHEN Bin[1], SASTROSUWONDO Pramudji[2], DHARMAWAN I Wayan Eka[2, 3], OU Danyun[1], YIN Xijie[1], YU Weiwei[1], CHEN Guangcheng[1]*

[1] Third Institute of Oceanography, Ministry of Natural Resources, Xiamen 361005, China

[2] Research Center for Oceanography, Indonesian Institute of Sciences, Jakarta 14430, Indonesia

[3] Technical Implementing Unit Marine Life Conservation Biak, Indonesian Institute of Sciences, Biak 98152, Indonesia

Received 15 June 2017; accepted 12 March 2018

Abstract

Recent studies have highlighted the valuable role played by mangrove forests in carbon sequestration and storage. Although Indonesia accounts for a large proportion of global mangrove area, knowledge on the carbon stock and sources in the Indonesian mangrove is still limited. In this study, we quantified the ecosystem organic carbon (OC) stock and its spatial variation at an oceanic mangrove in Wori, North Sulawesi, Indonesia. The sources of soil OC were also investigated. The results showed that the mangrove soil had a substantial OC stock containing 15.4 kg/m^2 (calculated by carbon) in the top 50 cm soil, and represented the majority of the ecosystem OC stock at the Wori mangrove. The mangrove biomass and ecosystem OC stock were 8.3 kg/m^2 and 23.7 kg/m^2, respectively. There was no significantly difference in the soil OC stock among the stations with difference distances offshore, while the highest mangrove biomass OC stock was found at the seaward station. Isotope mixing calculations showed that the rich OC in mangrove soils was attributed to the accumulated autochthonous mangrove source while the suspended organic matter in tidal water and the mangrove-adjacent seagrass contributed less than 20% to the soil OC. The results further demonstrated the importances of the oceanic mangrove in carbon storage and the mangrove plants in contributing OC to their soils.

Key words: mangrove, carbon stock, biomass, soil, stable isotopes, Indonesia

Citation: Chen Shunyang, Chen Bin, Sastrosuwondo Pramudji, Dharmawan I Wayan Eka, Ou Danyun, Yin Xijie, Yu Weiwei, Chen Guangcheng. 2018. Ecosystem carbon stock of a tropical mangrove forest in North Sulawesi, Indonesia. Acta Oceanologica Sinica, 37(12): 85–91, doi: 10.1007/s13131-018-1290-5

1 Introduction

Although mangrove forests occupy only 2% of the world's coastal ocean area, they account for around 5% of net primary production, 12% of ecosystem respiration and 30% of carbon burial on all continental margins in subtropical and tropical seas (Alongi and Mukhopadhyay, 2015). Recently, numerous studies have highlighted the importance of mangrove ecosystems in carbon stock (Donato et al., 2011; Keith et al., 2009; Alongi, 2014), because the mangrove plants are highly productive (Alongi, 2014) and the anoxic condition in their highly saturated or flooded soils limits the decomposition of organic carbon (OC) in soil (Armentano and Menges, 1986; Alongi, 1998, 2009). Globally, the mangrove ecosystem stores an OC pool three times more than the typical upland tropical forests and the ecosystem OC stocks can even be up to 1 023 Mg/hm^2 in certain mangroves (Donato et al., 2011). However, regional assessments of carbon stocks are still limited and should be viewed for the accuracy of global budget, due to the great geographic variation in carbon stock in mangrove wetlands. Such information is also important for the inventory of national greenhouse gases emissions from mangrove wetlands because loss of their carbon stock due to human activities is equivalent to relevant carbon dioxide emission to atmosphere (Hiraishi et al., 2014).

Soil pool is the majority of ecosystem carbon stock in mangroves (Donato et al., 2011; Alongi et al., 2016), and the soil stock accounts for 49%–98% of the ecosystem stock in some tropical mangrove wetlands (Donato et al., 2011). The soil OC comprises the organic matter derived from mangrove, benthic algae, and allochthonous sources including suspended organic matter (SPOM) and adjacent seagrass (Wooller et al., 2003; Kristensen et al., 2008). Although mangrove derived OC generally accounts for the majority of the soil OC in mangrove wetlands (Kristensen et al., 2008), non-mangrove sources could also dominate the OC sources in some mangrove wetlands (Wooller et al., 2003). The source of OC is an important factor determining the soil carbon sequestration because different sources have variable carbon concentrations (Chen et al., 2017); however, sources of OC in mangrove soils have rarely been studied in details.

Indonesia with a total mangrove area of 2.9×10^6 hm^2, has the largest extent of mangroves around the world and accounts for around half the Asian mangrove area (FAO, 2007). Although some studies have suggested that the Indonesian mangrove wet-

Foundation item: The China-Indonesia Ecological Station Establishment and Marine Biodiversity Investigation in North Sulawesi Sea; the Development and Implement Ocean Strategic Planning and Policy supported by Ministry of Natural Resources, PRC; the National Natural Science Foundation of China under contract Nos 41606105 and 41776102.
*Corresponding author, E-mail: gc.chen@tio.org.cn

lands are globally significant carbon sink and stock (Donato et al., 2011; Murdiyarso et al., 2015; Alongi et al., 2016), currently only a few studies reported the mangrove ecosystem carbon stocks in Indonesia (Donato et al., 2011; Murdiyarso et al., 2015, Alongi et al., 2016). These data are very limited for the knowledge and accurate estimation of the national mangrove carbon stock in Indonesia. The present study studied the ecosystem carbon stock and its spatial variation pattern with tidal elevation in a North Sulawesi mangrove, and the soil OC sources were also investigated via isotopic analysis.

2 Materials and methods

2.1 *Study area*

The present study was conducted at an oceanic mangrove forest in Wori (1°35′44.16″N, 124°50′48.97″E), North Sulawesi, Indonesia. The North Sulawesi had a typical equatorial climate, and the mean temperatures at sea level are uniform, varying by only a few degrees throughout the region and throughout the year, from 20°C to 28°C. Tides in this area were mixed and mainly semi-diurnal, and fluctuate slightly with an annual tidal range of 2.4 m. The mangrove forest consisted of *Rhizophora apiculata*, *Avicennia lanata*, *Bruguiera gymnorrhiza* and *Sonneratia alba*, and seagrass meadow occurred at the seaward fringe of the mangrove forest, which was dominated by *Halodule pinifolia*, *Cymodocea rotundata* and *Thalassia hemprichii* (Chen et al., 2017).

2.2 *Vegetation investigation*

Three sampling stations were established at the landward (LW), middle zone (MZ) and the seaward (SW) zones at the Wori mangrove. At each station, three 10 m×10 m plots were randomly setup for vegetation investigation. Within each plot, the species and canopy height of all trees and saplings were recorded. Breast height diameters (DBH) of *S. alba*, *A. lanata* and *B. gymnorrhiza* were measured at the height of 1.3 m. DBH of *R. apiculata* was measured above the highest prop-root when the prop roots were developed over 1.3 m. Senescent mangrove leaves (with a yellowish color) of the dominant species were collected at each sampling station by gently shaking the branches.

The aboveground biomass (AGB) and belowground biomass (BGB) were estimated using the common allometric equations with tree diameter DBH and wood density (ρ) as the independent variables for each tree species.

For *R. apiculata*, $AGB=0.235\times DBH^{2.420}$; $BGB=0.063\,9\times DBH^{2.546}$ (Ong et al., 2004).

For other species: $AGB=0.251\times\rho\times DBH^{2.460}$; $BGB=0.019\,9\times\rho^{0.899}\times DBH^{2.220}$ (Komiyama et al., 2005).

The ρ were 0.699 g/cm^3, 0.506 g/cm^3 and 0.475 g/cm^3 for *B. gymnorrhiza*, *A. lanata* and *S. alba*, respectively (Komiyama et al., 2005).

Total biomass OC stock (BOS) was calculated using the following formula:

$$BOS=AGB\times C_{\mathrm{AG}}+BGB\times C_{\mathrm{BG}},$$

where C_{AG} and C_{BG} were the OC proportions of the aboveground biomass and belowground biomass, respectively, and their respective values were 0.47 and 0.39 (Murdiyarso et al., 2015).

2.3 *Soil samples collection*

Soil samples were collected from each sampling plot using a PVC corer (inner diameter of 7.0 cm) with a cutter at the bottom. The sampling depth was 50 cm at the LW and MZ stations, and was limited to 20 cm at the SW station. The sediment cores were sliced into subsections by 10 cm intervals. Each of these subsections was weighted and then divided into two halves, with one half oven-dried under 60°C to achieve the water content of these fresh samples and estimate the bulk density. Another half was then air-dried for later analysis of soil OC concentration and δ^{13}C after the visible benthic animals, plant residues and stones (>2 mm) were removed.

2.4 *Soil and plant samples analyses*

The OC and δ^{13}C in soil and plant samples were measured using a Thermo Flash EA 1112 HT-Delta V Advantages system. For isotopic analysis of soils, air-dried subsamples were placed into silver cups, acidified with diluted HCl (5%) and then oven-dried at 40°C to remove the carbonates. Mangrove leaves were not treated with HCl because no carbonate was expected to be present. The stable carbon isotopic composition was reported in the δ notation as the ratio of the heavy to the light stable isotope in the sample (R_{sample}) relative to that of a standard (R_{standard}), i.e., $\delta_{\mathrm{sample}}=1\,000\times[(R_{\mathrm{sample}}/R_{\mathrm{standard}})^{-1}]$, with standard=Vienna Pee Dee Bellemnite (VPDB) and $R={}^{13}C/{}^{12}C$. The reproducibility of OC and stable isotopic analysis were <0.6% and <0.2‰, respectively.

2.5 *Statistical analyses and estimation of soil OC sources*

The normality of variables was checked using Kolmogorov–Smirnov test. The results showed that the distribution patterns of all soil parameters were distributed normally ($p>0.05$), so no transformation of data was performed. The differences in plant biomass and the biomass OC stock among the stations were compared using one-way analysis of variance (ANOVA). Two-way ANOVAs was used to test the differences in soil parameters with the sampling station and soil depth as factors. If the difference was significant ($p<0.05$), a post-hoc Tukey test was used to determine the difference. All statistical analyses were performed using SPSS 17.0 for Windows (SPSS Inc., USA).

The relative contributions of three potential sources, mangrove OC, SPOM and seagrass OC, to the soil OC at the Wori mangrove were examined using the IsoSource software (Phillips and Gregg, 2003), which provided the ranges of source proportional contributions to a mixture when the number of sources was too large to permit a unique solution (>number of isotope systems+1).

3 Results

3.1 *Vegetation biomass*

The dominant species was *R. apiculate* at the Wori mangrove and *S. alba* also co-dominated the landward station (Table 1). The three stations had similar plant densities, ranging from 1 967 stem/hm^2 to 2 500 stem/hm^2. Higher DBH of *R. apiculata* was measured at the SW station than other two stations, resulting in higher aboveground and belowground biomasses, and a consequential total biomass than those at the other two stations ($p<0.05$). There was no significant difference in biomass between the LW and MZ stations.

3.2 *Soil carbon stock and carbon source*

Soil bulk density, OC concentration and carbon density at the Wori mangrove were 0.31–0.48 g/cm^3, 65.97–90.58 mg/g and 25.85–38.05 mg/cm^3, respectively (Fig. 1). For the soil cores down to 50 cm collected at the LW and MZ stations, neither sampling station (LW vs. MZ) nor soil depth had a significant effect on the soil bulk density, OC concentration and carbon density at these

Table 1. Community structure, vegetation biomass and carbon stock of different sampling stations

Station	Species	DBH/cm	Tree density/ stem·hm^{-2}	AGB/t·hm^{-2}	BGB/t·hm^{-2}	TB/t·hm^{-2}
LW	*Sonneratia alba*	2.55–21.96	1 033±153	52.79±15.70	23.83±6.89	76.63±22.54
	Rhizophora apiculata	1.59–14.06	1 433±1 069	44.84±32.28	16.01±11.41	60.85±43.68
	Subtotal	–	2 433±1 210^{a}	97.64±16.81^{a}	39.85±5.05^{a}	137.48±21.77^{a}
MZ	*Avicennia lanata*	5.09–16.23	233±115	12.42±17.23	5.62±7.43	18.05±24.23
	Rhizophora apiculata	2.86–18.46	1 867±472	81.03±22.64	29.66±8.48	110.69±31.12
	Bruguiera gymnorrhiza	2.55–5.73	333±251	1.29±0.71	0.77±0.43	2.06±1.14
	Sonneratia alba	13.37–15.60	67±58	5.76±5.25	2.58±2.33	8.35±7.58
	Subtotal	–	2 500±897^{a}	100.51±24.79^{a}	38.64±9.52^{a}	139.15±34.30^{a}
SW	*Rhizophora apiculata*	4.14–37.88	1 867±577	161.05±52.77	60.64±20.05	221.68±72.82
	Bruguiera gymnorrhiza	8.28–27.37	100±100	29.77±48.85	11.47±18.51	41.25±67.36
	Subtotal	–	1 967±600^{a}	190.82±42.40^{b}	72.11±16.15^{b}	262.93±58.56^{b}

Note: DBH represents breast height diameters, AGB aboveground biomass, BGB belowground biomass, TB total biomass, LW landward, MZ middle zone, and SW seaward. In each column, different letters indicate a significant difference among the three sampling stations.

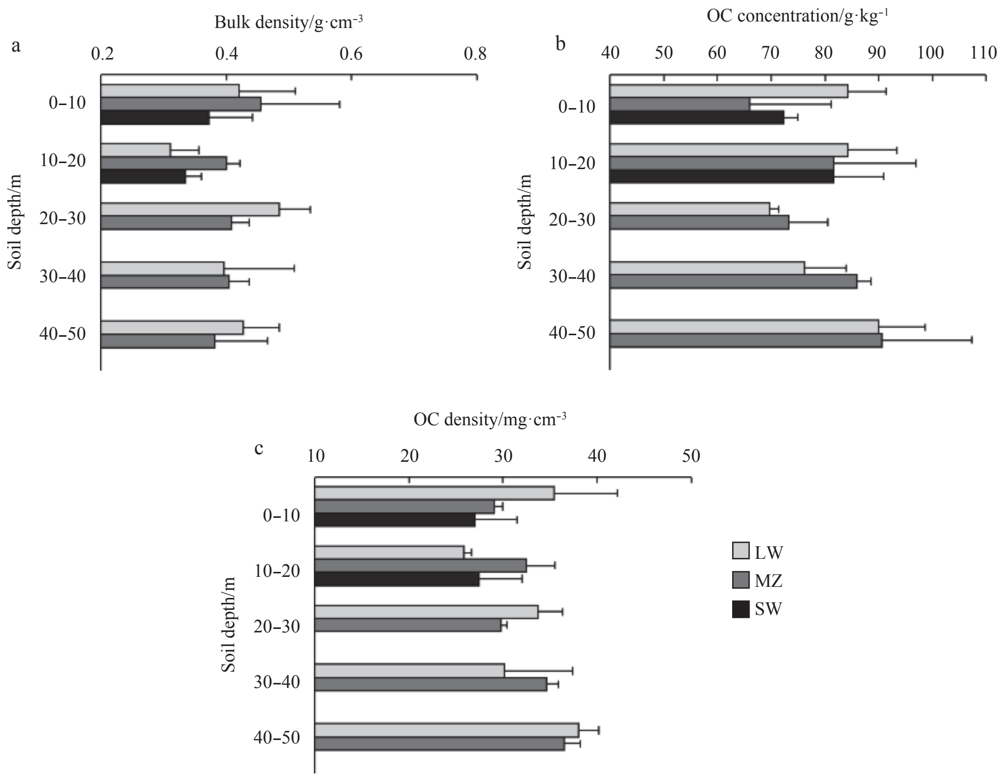

Fig. 1. Soil bulk density (a), organic carbon (OC) concentration (b) and density (c) at the Wori mangrove in North Sulawesi (mean and standard deviation of three replicates are shown). LW represents landward station, MZ middle station, and SW seaward station.

Table 2. Two-way ANOVA test of the effects of station and depth on LW and MZ soil columns

	Bulk density	OC concentration	OC density	δ^{13}C
Station	0.057	0.106	0.005	135.706***
Depth	1.225	2.340	1.719	1.627
Interaction	0.887	1.210	1.521	4.511*

Note: * and *** indicate significant effects at p<0.05 and p<0.001, respectively.

Table 3. Two-way ANOVA test of the effects of station and depth on surface 20 cm soil properties

	Bulk density	OC concentration	OC density	δ^{13}C
Station	1.261	1.089	0.559	106.234***
Depth	2.952	1.777	0.406	0.717
S×D	0.349	0.587	1.946	1.222

Note: *** indicates a significant effects at p<0.001.

two stations (Fig. 1 and Table 2). Comparisons of the soil bulk density, OC and OC density of the top 20 cm soil layer among the three sampling stations showed that the values were similar among the three stations or between the two sampling depths (0–10 cm vs. 10–20 cm, Fig. 1 and Table 3).

Mangrove plant had the most ^{13}C-depleted OC in this study with a mean value of (–29.5±0.7)‰, and its OC concentration was (44±2)%. The δ^{13}C of seagrass and SPOM were (–11.1±0.7)‰ and (19.5±0.8)‰, respectively.

The soil δ^{13}C values at the LW and MZ stations showed a spatial variation while the variation was depth-specific (Fig. 2, Table 2). Soil ^{13}C was more depleted in the top 40 cm soil at the LW station than the MZ station, and the soil δ^{13}C in the 40–50 cm soil was similar between the two stations. In the top 20 cm soil, the OC was more enriched in ^{13}C at the SW station (>–28‰) than the other stations, and the δ^{13}C significantly decreased toward landward, with a value <–28.7‰ at the LW station (Fig. 2, Table 3).

δ^{13}C analysis revealed that mangrove OC was the major source of the soil OC (contributing 81% to 95%) at the Wori mangrove, while its contribution slightly decreased from the landward toward the sea (Table 4). The marine source (including SPOM and seagrass) contributed only 0%–19%, and the seagrass had less contributions than SPOM.

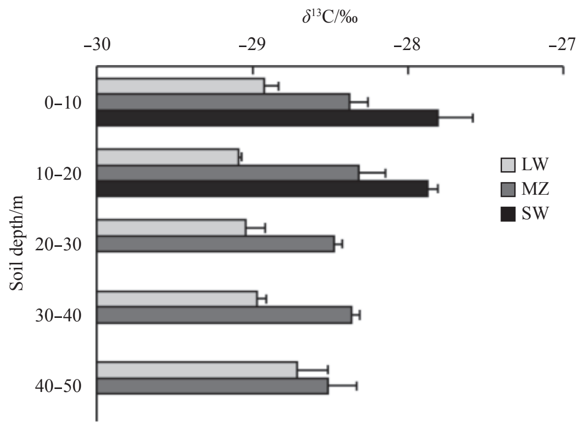

Fig. 2. δ^{13}C of soil organic carbon at the Wori mangrove in North Sulawesi (mean and standard deviation of three replicates are shown). Abbreviations same as Fig. 1.

Table 4. Ranges of proportional contributions of the three potential sources to the organic carbon in surface soil (0–20 cm) at Wori mangrove

Station	Mangrove/%	Seagrass/%	SPOM/%
LW	92–96	0–4	0–8
MZ	86–92	0–7	1–14
SW	81–89	0–10	1–19

Note: SPOM represents suspended organic matter.

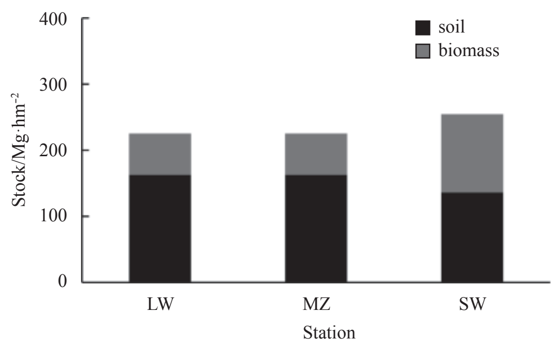

Fig. 3. Ecosystem OC stock of the Wori mangrove in North Sulawesi. Data are the mean of the three replicates. Abbreviations same as Fig. 1.

3.3 *Ecosystem carbon stock*

Soil OC stocks were 16.3 kg/m^2 and 16.2 kg/m^2 in the top 50 cm soil at the LW and MZ stations (Fig. 3), respectively. Considering that no significant difference in soil OC density was observed with soil depth down to 50 cm at these two stations and the OC stocks in the top 20 cm soil (6.1 kg/m^2 for LW and 6.2 kg/m^2 for MZ) accounted for ~40% of the total stocks in the top 50 cm soil, we further estimated the soil OC stock in the top 50 cm soil as 13.6 kg/m^2 at the SW station from the top 20 cm stock using a conversion factor 2.5 .

Mangrove biomass OC stocks were 60, 60 and 164 Mg/hm^2 at the LW, MZ and SW stations, respectively (Fig. 3) and the value was higher at the SW station (p<0.05). The ecosystem OC stock as the sum of mangrove biomass stock and soil stock (in top 50 cm soil) was 22 kg/m^2 at the LW and MZ station, while the SW station had a higher stock. The mean ecosystem OC stock, biomass OC stock and soil OC stock were 23.7, 8.3 and 15.4 kg/m^2, respectively at the Wori mangrove, and soil OC stock accounted for 65% of the ecosystem OC stock.

4 Discussion

Previous studies have suggested mangrove wetlands as substantial carbon stocks and the soil OC pool generally represented the majority of ecosystem OC stock (Twilley et al., 1992; Donato et al., 2011; Murdiyarso et al., 2015; Rovai et al., 2018). In the present study, the OC stocks were quantified in the top 50 cm soil and the values ranged from 137 to 164 Mg/hm^2 at the Wori mangrove in North Sulawesi, Indonesia. Here we normalized the soil OC stock obtained at the Wori mangrove and those previously reported at other worldwide mangroves at various soil depths (Table 5) to make comparisons, on bias of the previous finding that soil OC density did not differ significantly with depth in mangrove forest (Murdiyarso et al., 2015). Murdiyarso et al. (2015) suggested that the decrease in soil OC concentration with depth was compensated by the increased bulk density (Murdiyarso et al., 2015). The top 1 m soil OC stock at Wori mangrove, equivalent to 274–328 Mg/hm^2, fell into the range reported in other mangrove wetlands (Fig. 4). The Wori mangrove also had similar OC stocks in the top 1 m soil to those obtained from other Indonesian mangroves ranging from 270 to 530 Mg/hm^2, and had comparable soil OC concentrations to most of the values at these Indonesian mangroves (Murdiyarso et al., 2015). The mean soil OC concentration in present study (79.85 g/kg) was higher than the global median value (20 g/kg) for mangroves (Kristensen et al., 2008), further indicated the Wori mangrove as a substantial soil carbon stock.

The soil carbon stock changed as a function of soil carbon concentration, bulk density and the total depth. By comparing the soil OC stock from various tropical mangroves, Donato et al. (2011) concluded that soil carbon concentration was lower in estuarine sites (with a mean of 7.9 %) than in oceanic (with a mean of 14.6 %) sites, and the mean C densities was also lower in estuarine (0.038 g/cm^3) than in oceanic soils (0.061 g/cm^3). However, the low OC density of estuarine mangrove soil was compensated by their deeper alluvial soil deposits, resulting in the comparable soil stocks between these two geomorphic settings (Donato et al., 2011). A later review by Breithaupt et al. (2012) also indicated no statistical difference in soil carbon burial rate, which was related to the soil OC sequestration capacity, between the estuarine/riverine and oceanic mangroves. These results suggested that mangroves under these two geomorphic sets are both important in the soil carbon stock and sequestration.

The mangrove soil carbon stock was influenced by the tidal

Table 5. Summary of ecosystem carbon stocks in various mangrove forests worldwide

Mangroves	Coordinate	OC stock/Mg·hm^{-2}			Bulk density/g·cm^{-3}	OC content/%	References
		Ecosystem	Soil	Biomass			
Bintuni, Indonesia	2°10′12"S, 133°32′09"E	1 396.9	1 014.8 (2.65 m)	382.1	0.63	7.22	Murdiyarso et al. (2015)
Cilacap, Indonesia	7°43′25"S, 108°57′29"E	592.8	571.6 (2.11 m)	21.2	0.50	5.64	Murdiyarso et al. (2015)
Mui Ca Mau National park, Vietnam	8°32′N, 104°44′E	762.0	623.0 (2.5 m)	140.0	0.72	2.00	Tue et al. (2014)
Sulawesi, Indonesia	1°22′N, 124°33′E	2 203.0	2 064.0 (3.0 m)	139.0	0.40	18.10	Donato et al. (2011)
Bugtong-Bato, Philippines	11°49′26"N, 122°08′46"E	562.0	275.0 (1.5 m)	287.0	–	2.80	Thompson et al. (2014)
Dominican Republic	18°45′N, 71°00′W	922.0	753.0 (1.95 m)	169.0	0.30	17.50	Kauffman et al. (2014)
Bomeo	2°44′N, 111°41′E	1 246.0	1 059.0 (3.0 m)	187.0	0.32	9.30	Donato et al. (2011)
Mozambique	20°11′S, 34°45′E	219.0	160.0 (1.0 m)	59.0	1.08	1.50	Sitoe et al. (2014)
Sundarbans, Bangladesh	21°30′N, 89°00′E	259.8[1)]	–	–	–	–	Rahman et al. (2015)
Sundarbans	21°32′N, 88°55′E	80.0	26.0 (0.3 m)	54.0	–	0.60	Ray et al. (2011)
Ganges-Brahmaputra Delta, Bangladesh	22°15′N, 89°37′E	566.0	439.0 (3.0 m)	127.0	0.92	1.70	Donato et al. (2011)
Java, Indonesia	9°33′N, 138°11′E	587.0	572.0 (2.11 m)	15.0	0.50	5.60	Donato et al. (2011)
Zambezi River Delta, Mozambique	18°36′S, 35°51′E	483.0	283.0 (2.0 m)	200.0	0.83	1.71	Stringer et al. (2015)
Kubu Raya, Indonesia	0°40′33"S, 109°21′41"E	794.0	620.9 (1.36 m)	173.1	0.61	8.40	Murdiyarso et al. (2015)
Teminabuan, Indonesia	1°37′24"S, 131°48′35"E	910.9	660.5 (1.54 m)	250.4	0.53	9.93	Murdiyarso et al. (2015)
Sembilang, Indonesia	2°04′28"S, 104°28′09"E	1 319.1	979.5 (1.83 m)	339.6	0.60	9.43	Murdiyarso et al. (2015)
Tanjung Putting, Indonesia	2°51′30"S, 111°42′02"E	1 240.0	1 059.2 (3.0 m)	180.8	0.32	9.74	Murdiyarso et al. (2015)
Timika, Indonesia	4°51′41"S, 136°47′18"E	1 275.2	965.1 (2.09 m)	310.1	0.56	10.15	Murdiyarso et al. (2015)
Yinluo Bay, China	20°14′N, 109°40′E,	323.7	243.2 (1.0 m)	80.5	–	–	Wang et al. (2013)
Bunaken, Indonesia	1°17′17"N, 124°30′37"E	938.4	811.6 (1.17 m)	126.8	0.49	15.63	Murdiyarso et al. (2015)
Sulawesi, Indonesia	1°17′N, 124°30′E	950.0	574.0 (0.87 m)	126.0	0.50	15.10	Donato et al. (2011)
Pedada, Philippines	11°04′05"N, 122°57′25"E	331.0	138.0 (1.5 m)	193.0	–	1.30	Thompson et al. (2014)
Madagascar	13°26′S, 48°30′E	499.0	429.0 (1.5 m)	70.0	0.91	3.00	Jones et al. (2014)
Caribbean, Mexican	19°20′N, 88°00′W	713.0	596.0 (1.0 m)	117.0	–	21.70	Adame et al. (2013)
Kosrae, Micronesia	5°17′N, 162°54′E	1 188.0	762.0 (2.01 m)	426.0	0.43	13.50	Donato et al. (2011)
Palau, Micronesia	7°21′N, 134°32′E	707.0	521.0 (1.17 m)	184.0	0.25	18.40	Donato et al. (2011)
Yap, Micronesia	7°21′N, 134°32′E	1 177.0	754.0 (1.62 m)	313.0	0.35	10.50	Kauffman et al. (2011)

Note: Values in brackets were the depths of soil sampled for soil OC stock estimation in each study. [1)] The OC stock of the top 1 m soil was included; – not available.

gradient, vegetation biomass and production, species composition and input of allochthonous sources (Gleason and Ewel, 2002; Sherman et al., 2003; Cerón-Bretón et al., 2011). Some estuarine mangrove showed spatial variations in soil OC concentrations and stock, with values increasing from the lower tidal elevation zone toward the land (Chen et al., 2012; Wang et al., 2013). This maybe partially due to the higher biomass and production at the higher-tidal-elevation zone that provide more dead roots and litter into the soil (Wang et al., 2013). Moreover, heavy siltation occurs in the estuarine mangrove resulting in an extensive gradual intertidal slope, and the reduced wave energy and current velocity at the station proximal to the land would facilitate the burial of particular organic matter, and reduce the loss of litter carbon from the mangrove floor. However, there was no significant difference in soil OC concentration and stock among the three sampling stations in this study. This is similar to the finding by Donato et al. (2011) that soil OC density was not variable with the distance from the seaward edge in oceanic mangrove sites. The results further suggested that the spatial variation of soil OC stock was different between the oceanic and estuarine mangroves.

A wide range of mangrove ecosystem OC stocks has been reported worldwide with soil OC stock at various depths combined, from 80.0 Mg/hm^2 in Sundarbans in Bangladesh to 1 396.9 Mg/hm^2 in Bintuni in Indonesia (Table 5). The ecosystem carbon stocks including the top 1 m soil stock varied from 140. 7 to 874.8 Mg/hm^2 and showed higher values in the tropic mangroves than the subtropics (Fig. 4). This was coincided with the previous finding that primary or mature mangrove forests in the tropics in low latitudes had much higher biomass than those in temperate areas on a global scale (Komiyama et al., 2008). The production of mangrove has also been found to exhibit a pronounced geographical trend, with highest litter fall rates measured near the equator and decreased with increasing latitude (Alongi, 2002; Bouillon et al., 2008). Moreover, our results further prove that soil pool was the majority of ecosystem carbon stock (Donato et al., 2011; Alongi et al., 2016) and the soil OC stock (in the top 1 m) accounted for

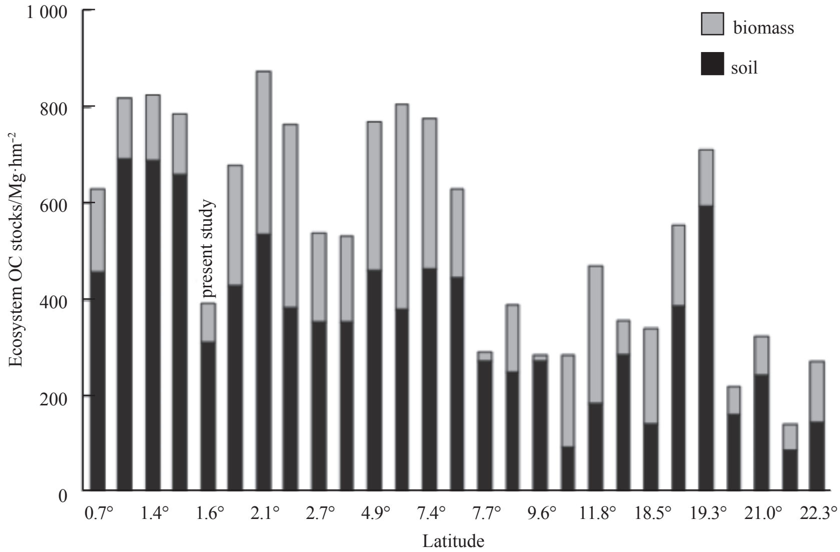

Fig. 4. Change in biomass, soil and ecosystem OC stocks in world wide mangroves with latitude. Ecosystem carbon stocks were sum of the biomass OC stock and the normalized OC stock in the top-1 m soil. Data of the biomass OC stock and soil OC stock at various depths were provided in Table 5.

76% of the ecosystem OC stock at the Wori mangrove. The mean ecosystem OC stock, 391.4 Mg/hm^{2}at the Wori mangrove was lower than other mangroves with similar latitudes, due to the lower biomass OC stock at Wori (Fig. 4). The biomass carbon stock in present study, with an average of 83.4 Mg/hm^2 was much less than most of the values reported in other Indonesian mangroves (Fig. 4).

Mangrove derived OC were generally the major source of the carbon accumulated in mangrove soils, while allochthonous organic matter may increase in importance when high rate of input from riverine or tidal sources were presented (Jennerjahn and Ittekkot, 2002). In the present study, the mangrove soil was depleted in ^{13}C and the $\delta^{13}C$ was around –28‰. The isotope mixing calculations showed that the rich OC in soil was attributed to the accumulated autochthonous mangrove source. The mangrove contribution (81%–96%) was much higher those reported in other mangrove forests (Gonneea et al., 2004; Muzuka and Shunula, 2006; Ranjan et al., 2011; Tue et al., 2011). For example, Alongi et al. (1998) reported that mangrove carbon represented only 56% of the total OC input to Hinchinbrook Channel while in a lagoon-fringe mangrove the contribution of mangrove OC was found <80% for the soil OC. Although seagrass meadow occurred at the seaward edge of the Wori mangrove, the seagrass derived OC contributed a negligible proportion to the mangrove soil OC in this area, and even if at the seaward station adjacent to seagrass the contribution of seagrass was less than that of SPOM. This was contrarily to previous finding that seagrass could be an important OC input to mangrove soil (Wooller et al., 2003; Walton et al., 2014). Wooller et al. (2003) found that the source of OC in a mangrove soil was primarily allochthonous including seagrass material, and in the Arabian Gulf in-welling of seagrass production balanced the out-welling of mangrove production in the arid mangrove forest (Walton et al., 2014). These findings suggested that the OC flux between mangrove and seagrass could be geographically variable, and the mechanism driving such variation deserved further studies.

Acknowledgements

The authors are grateful to Asep Rasyidin, Mochtar Djabar and Liang Cuicui for their assistance with field sampling and laboratory analysis.

References

Adame M F, Kauffman J B, Medina I, et al. 2013. Carbon stocks of tropical coastal wetlands within the Karstic Landscape of the Mexican Caribbean. PloS One, 8(2): e56569, doi: 10.1371/journal.pone.0056569

Alongi D M. 1998. Coastal Ecosystem Processes. Boca Raton, Fla: CRC Press

Alongi D M. 2002. Present state and future of the world’s mangrove forests. Environmental Conservation, 29(3): 331–349

Alongi D M. 2009. The Energetics of Mangrove Forests. Netherlands: Springer

Alongi D M. 2014. Carbon cycling and storage in mangrove forests. Review of Marine Science, 6(1): 195–219, doi: 10.1146/annurev-marine-010213-135020

Alongi D M, Ayukai T, Brunskill G J, et al. 1998. Sources, sinks, and export of organic carbon through a tropical, semi-enclosed delta (Hinchinbrook Channel, Australia). Mangroves and Salt Marshes, 2(4): 237–242, doi: 10.1023/A:1009927611025

Alongi D M, Mukhopadhyay S K. 2015. Contribution of mangroves to coastal carbon cycling in low latitude seas. Agricultural and Forest Meteorology, 213: 266–272, doi: 10.1016/j.agrformet.2014.10.005

Alongi M D, Murdiyarso D, Fourqurean J W, et al. 2016. Indonesia’s blue carbon: a globally significant and vulnerable sink for seagrass and mangrove carbon. Wetlands Ecology and Management, 24(1): 3–13, doi: 10.1007/s11273-015-9446-y

Armentano T V, Menges E S. 1986. Patterns of change in the carbon balance of organic soil-wetlands of the temperate zone. Journal of Ecology, 74(3): 755–774, doi: 10.2307/2260396

Bouillon S, Borges A V, Castañeda-Moya E, et al. 2008. Mangrove production and carbon sinks: a revision of global budget estimates. Global Biogeochemical Cycles, 22(2): GB2013

Breithaupt J L, Smoak J M, Smith III T J, et al. 2012. Organic carbon burial rates in mangrove sediments: Strengthening the global budget. Global Biogeochemical Cycles, 26(3): GB3011

Cerón-Bretón J G, Cerón-Bretón R M, Rangel-Marrón M, et al. 2011. Determination of carbon sequestration rate in soil of a mangrove forest in Campeche, Mexico. WSEAS Transactions on Environment and Development, 7(2): 55–64

Chen Guangcheng, Azkab M H, Chmura G L, et al. 2017. Mangroves as a major source of soil carbon storage in adjacent seagrass meadows. Scientific Reports, 7: 42406, doi: 10.1038/srep42406

Chen Guangcheng, Tam N F Y, Ye Yong. 2012. Spatial and seasonal variations of atmospheric N_2O and CO_2 fluxes from a subtropical mangrove swamp and their relationships with soil characteristics. Soil Biology and Biochemistry, 48: 175–181, doi: 10.1016/j.soilbio.2012.01.029

Donato D C, Kauffman J B, Murdiyarso D, et al. 2011. Mangroves among the most carbon-rich forests in the tropics. Nature Geoscience, 4(5): 293–297, doi: 10.1038/ngeo1123

FAO. 2007. The World'S Mangrove 1980–2005. Rome: FAO

Gleason S M, Ewel K C. 2002. Organic matter dynamics on the forest floor of a micronesian mangrove forest: an investigation of species composition shifts. Biotropica, 34(2): 190–198, doi: 10.1111/btp.2002.34.issue-2

Gonneea M E, Paytan A, Herrera-Silveira J A. 2004. Tracing organic matter sources and carbon burial in mangrove sediments over the past 160 years. Estuarine, Coastal and Shelf Science, 61(2): 211–227, doi: 10.1016/j.ecss.2004.04.015

Hiraishi T, Krug T, Tanab, K, et al. 2014. 2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands. Switzerland: IPCC

Jennerjahn T C, Ittekkot V. 2002. Relevance of mangroves for the production and deposition of organic matter along tropical continental margins. Naturwissenschaften, 89(1): 23–30, doi: 10.1007/s00114-001-0283-x

Jones T, Ratsimba H, Ravaoarinorotsihoarana L, et al. 2014. Ecological variability and carbon stock estimates of mangrove ecosystems in northwestern Madagascar. Forests, 5: 177–205, doi: 10.3390/f5010177

Kauffman J B, Heider C, Cole T G, et al. 2011. Ecosystem carbon stocks of Micronesian mangrove forests. Wetlands, 31: 343–352, doi: 10.1007/s13157-011-0148-9

Kauffman J B, Heider C, Norfolk J, et al. 2014. Carbon stocks of intact mangroves and carbon emissions arising from their conversion in the Dominican Republic. Ecological Applications, 24: 518–527, doi: 10.1890/13-0640.1

Keith H, Mackey B G, Lindenmayer D B. 2009. Re-evaluation of forest biomass carbon stocks and lessons from the world's most carbon-dense forests. Proceedings of the National Academy of Sciences of the United States of America, 106(28): 11635–11640, doi: 10.1073/pnas.0901970106

Komiyama A, Ong J E, Poungparn S. 2008. Allometry, biomass, and productivity of mangrove forests: a review. Aquatic Botany, 89(2): 128–137, doi: 10.1016/j.aquabot.2007.12.006

Komiyama A, Poungparn S, Kato S. 2005. Common allometric equations for estimating the tree weight of mangroves. Journal of Tropical Ecology, 21(4): 471–477, doi: 10.1017/S0266467405002476

Kristensen E, Bouillon S, Dittmar T, et al. 2008. Organic carbon dynamics in mangrove ecosystems: a review. Aquatic Botany, 89(2): 201–219, doi: 10.1016/j.aquabot.2007.12.005

Murdiyarso D, Purbopuspito J, Kauffman J B, et al. 2015. The potential of Indonesian mangrove forests for global climate change mitigation. Nature Climate Change, 5(12): 1089–1092, doi: 10.1038/nclimate2734

Muzuka A N N, Shunula J P. 2006. Stable isotope compositions of organic carbon and nitrogen of two mangrove stands along the Tanzanian coastal zone. Estuarine, Coastal and Shelf Science, 66(3–4): 447–458

Ong J E, Gong W K, Wong C H. 2004. Allometry and partitioning of the mangrove, *Rhizophora apiculata*. Forest Ecology and Management, 188(1–3): 395–408

Phillips D L, Gregg J W. 2003. Source partitioning using stable isotopes: coping with too many sources. Oecologia, 136(2): 261–269, doi: 10.1007/s00442-003-1218-3

Rahman M M, Khan M N I, Hoque A K F, et al. 2015. Carbon stock in the Sundarbans mangrove forest: spatial variations in vegetation types and salinity zones. Wetlands Ecology Management, 23: 269–283, doi: 10.1007/s11273-014-9379-x

Ranjan R K, Routh J, Ramanathan A L, et al. 2011. Elemental and stable isotope records of organic matter input and its fate in the Pichavaram mangrove-estuarine sediments (Tamil Nadu, India). Marine Chemistry, 126(1–4): 163–172

Ray R, Ganguly D, Chowdhury C, et al. 2011. Carbon sequestration and annual increase of carbon stock in a mangrove forest. Atmospheric Environment, 45: 5016–5024, doi: 10.1016/j.atmosenv.2011.04.074

Rovai A S, Twilley R R, Castañeda-Moya E, et al. 2018. Global controls on carbon storage in mangrove soils. Nature Climate Change, 8(6): 534–538, doi: 10.1038/s41558-018-0162-5

Sherman R E, Fahey T J, Martinez P. 2003. Spatial patterns of biomass and aboveground net primary productivity in a mangrove ecosystem in the Dominican Republic. Ecosystems, 6(4): 384–398, doi: 10.1007/s10021-002-0191-8

Sitoe A A, Mandlate L J C, Guedes B S. 2014. Biomass and carbon stocks of Sofala Bay mangrove forests. Forests, 5: 1967–1981, doi: 10.3390/f5081967

Stringer C E, Tretin C C, Zarnoch S J, et al. 2015. Carbon stock of mangrove within the Zamberzi River Delta Mozambique. Forests Ecology and Management, 354: 139–148, doi: 10.1016/j.foreco.2015.06.027

Thompson B S, Clubbe C P, Primavera J H, et al. 2014. Locally assessing the economic viability of blue carbon: a case study from Panay Island, the Philippines. Ecosystem Services, 8: 128–140, doi: 10.1016/j.ecoser.2014.03.004

Tue N T, Dung L V, Nhuan M T, et al. 2014. Carbon storage of a tropical mangrove forest in Mui Ca Mau National Park, Vietnam. Catena, 121: 119–126, doi: 10.1016/j.catena.2014.05.008

Tue N T, Hamaoka H, Sogabe A, et al. 2011. Sources of sedimentary organic carbon in mangrove ecosystems from Ba Lat Estuary, Red River, Vietnam. In: Omori K, Guo Xinyu, Yoshie N, et al., eds. Interdisciplinary Studies on Environmental Chemistry-Marine Environmental Modeling & Analysis. Terrapub: Center for Marine Environmental Studies, 151–157

Twilley R R, Chen R H, Hargis T. 1992. Carbon sinks in mangroves and their implications to carbon budget of tropical coastal ecosystems. Water, Air, and Soil Pollution, 64(1–2): 265–288

Walton M, Al-Maslamani I, Skov M W, et al. 2014. Outwelling from arid mangrove systems is sustained by inwelling of seagrass productivity. Marine Ecology Progress Series, 507: 125–137, doi: 10.3354/meps10827

Wang Gang, Guan Dongsheng, Peart M R, et al. 2013. Ecosystem carbon stocks of mangrove forest in Yingluo Bay, Guangdong Province of South China. Forest Ecology and Management, 310: 539–546, doi: 10.1016/j.foreco.2013.08.045

Wooller M, Smallwood B, Jacobson M, et al. 2003. Carbon and nitrogen stable isotopic variation in *Laguncularia racemosa* (L.) (white mangrove) from Florida and Belize: implications for trophic level studies. Hydrobiologia, 499(1–3): 13–23