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Variability in the organic carbon stocks, sources, and accumulation rates of Indonesian mangrove ecosystems

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ABSTRACT

Mangrove ecosystems are an important natural carbon sink that accumulate and store large amounts of organic carbon (C_{org}), in particular in the sediment. However, the magnitude of carbon stocks and the rate of carbon accumulation (CAR) vary geographically due to a large variation of local factors. In order to better understand the blue carbon sink of mangrove ecosystems, we measured organic carbon stocks, sources and accumulation rates in three Indonesian mangrove ecosystems with different environmental settings and conditions; (i) a degraded estuarine mangrove forest in the Segara Anakan Lagoon (SAL), Central Java, (ii) an undegraded estuarine mangrove forest in Berau region, East Kalimantan, and (iii) a pristine marine mangrove forest on Kongsi Island, Thousand Islands, Jakarta. In general, C_{org} stocks were higher in estuarine than in marine mangroves, although a large variation was observed among the estuarine mangroves. The mean total C_{org} stock in Berau (615 ± 181 Mg C ha^{-1}) is twice as high as that in SAL (298 ± 181 Mg C ha^{-1}). However, the Segara Anakan Lagoon displayed large within-system variation with a much higher C_{org} stock in the eastern (483 ± 124 Mg C ha^{-1}) than in the central lagoon (167 ± 36 Mg C ha^{-1}). The predominant accumulation of autochthonous mangrove organic matter likely contributed to the higher C_{org} stocks in Berau and the eastern SAL. Interestingly, the CAR distribution pattern in SAL is opposite to that of its C_{org} stocks. The central SAL that receives high sediment inputs from the hinterland has a much higher CAR than the eastern SAL (658 ± 311 g C m^{-2} yr^{-1} and 194 ± 46 g C m^{-2} yr^{-1}, respectively), while Berau has one of the highest CAR (1722 ± 183 g C m^{-2} yr^{-1}) ever measured. It appears that these large differences are driven by the environmental setting and conditions, mainly sediment dynamics and hydrodynamics, landform, and vegetation conditions. It is inferred that quantifying carbon accumulation in sediments is a useful tool in estimating the present-day carbon storage of mangrove ecosystems. This is a precondition for taking measures under REDD+ (Reducing Emissions from Deforestation and Forest Degradation and the role of conservation, sustainable management of forests and enhancement of forest carbon stocks in developing countries) schemes.

1. Introduction

Situated in the transition zone between land and ocean, mangrove ecosystems are one of the most biogeochemically active areas in the biosphere due to permanent exchange of nutrients and organic matter with adjacent ecosystems. Although mangrove forests occupy only a small fraction of the global coastal area, they are highly productive, with a net primary production rate of 92–280 Tg C yr^{-1} (Twilley et al., 1992; Jennerjahn and Ittekkot, 2002; Bouillon et al., 2008), and they contribute up to 15% of the total carbon accumulation in marine sediments (Jennerjahn and Ittekkot, 2002). Mangrove ecosystems are also among the most carbon-rich ecosystems in the tropics (Donato et al., 2011). They sequester and store high amounts of organic carbon in plant biomass and sediment, which makes them an important natural

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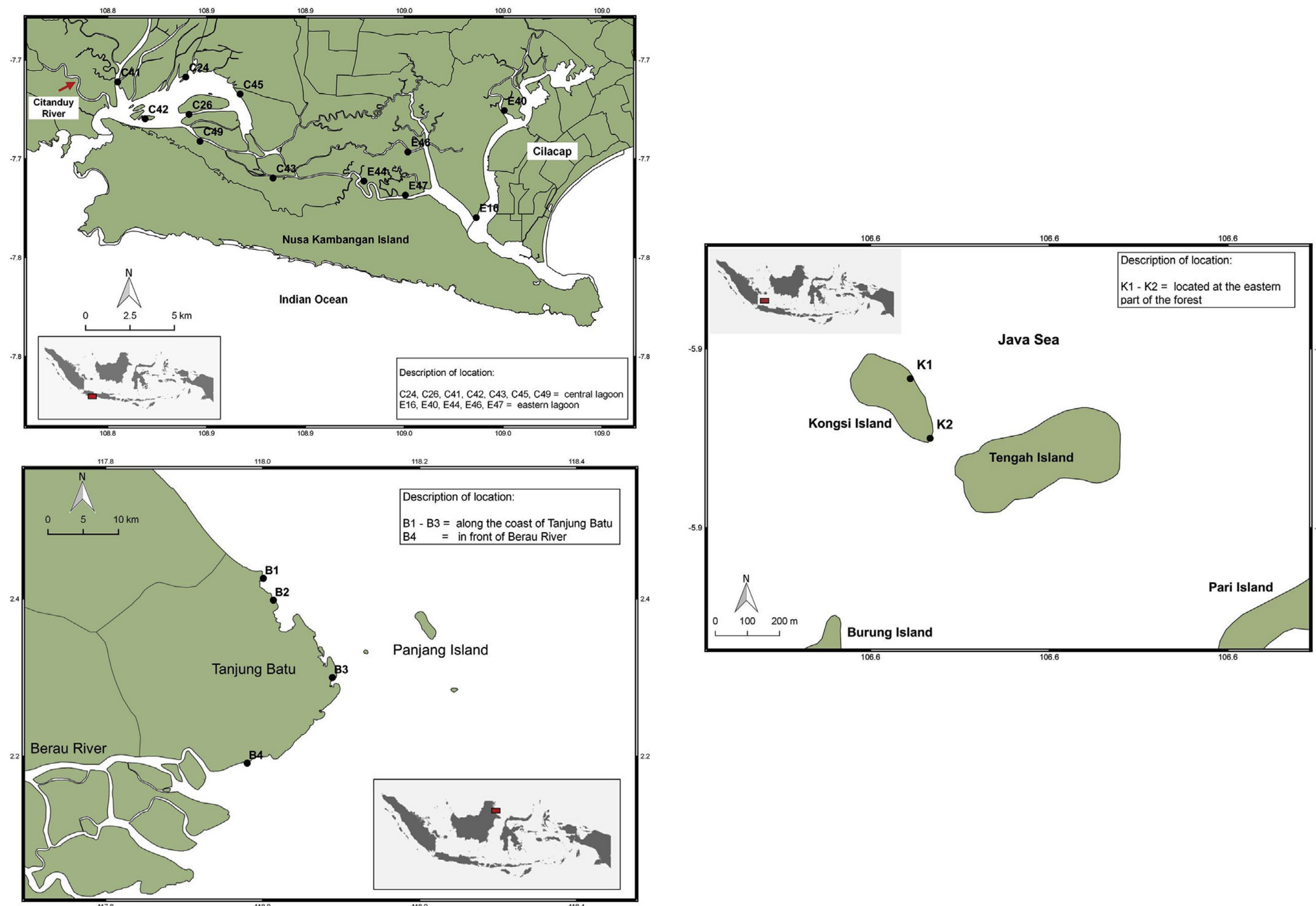

Fig. 1. Maps of the study sites: (left-above) Segara Anakan Lagoon, (left-below) Berau Regency, (right) Kongsi Island.

carbon sink (Twilley et al., 1992; Jennerjahn and Ittekkot, 2002; Bouillon et al., 2008). The mean global carbon stock of mangrove ecosystems is estimated at 956 Mg C ha^{-1}, which is much higher than those of rainforests, peat swamps, salt marshes, and seagrass meadows (Alongi, 2014). Their advantage over terrestrial forests is their much higher carbon accumulation in sediments/soils which is mainly due to high autochthonous and allochthonous inputs and low decomposition rates of organic matter because of the mostly anoxic conditions in the sediment (Donato et al., 2011; Kristensen, 2000). The rate of organic carbon accumulation in mangrove ecosystems is estimated to be around 20–24 Tg C yr^{-1} (Twilley et al., 1992; Jennerjahn and Ittekkot, 2002; Duarte et al., 2004).

However, climate change and anthropogenic disturbances can strongly impair the ecosystem service of sequestering and storing carbon (Grellier et al., 2017; Jennerjahn et al., 2017; Pérez et al., 2017). Over several decades, mangrove areas have been declining worldwide mainly due to deforestation and land use change (Valiela et al., 2001; Alongi, 2002). The impacts are not only the loss of biodiversity and coastal protection, but also the loss of the carbon sink function (Nellemann et al., 2009). Thus, preventing mangrove loss is considered an effective strategy for climate change mitigation (Pendleton et al., 2012; Murdiyarso et al., 2015).

While it is commonly accepted that mangrove ecosystems are a carbon sink, there are large uncertainties in the magnitude of this sink with a global carbon stock estimated at 4–20 Pg (Donato et al., 2011). The magnitude of carbon storage in mangrove ecosystems varies geographically, which is largely determined by the type of environmental setting (Twilley et al., 1992; Woodroffe, 1992; Saintilan et al., 2013; Rovai et al., 2018). Initially, Thom (1982) defined five common environmental settings which were later described in more detail by Woodroffe (1992); these are (i) river-dominated, (ii) tide-dominated, (iii) wave-dominated, (iv) composite river and wave dominated, (v) drowned bed rock valley, and (vi) carbonate settings. Each of these settings contains suites of landforms and physical processes which control the distribution of mangrove species, transport and deposition of sediment, and the biogeochemical conditions. These processes thus influence the efflux, accumulation, storage, and composition of sediment organic matter (Thom, 1982; Woodroffe, 1992; Saintilan et al., 2013; Rovai et al., 2018). Given the large differences between environmental settings and the high within-system spatial variability of environmental conditions of mangrove ecosystems, it is conceivable that these uncertainties are to a large extent related to the scarce data base on carbon storage and the lack of knowledge on the underlying mechanisms.

Moreover, identification of organic matter (OM) sources is important for evaluating the effectiveness of the 'blue carbon' sink in mangrove ecosystems, as various OM contribute differently to carbon sequestration, and their distribution and deposition vary geographically (Saintilan et al., 2013; Watanabe and Kuwae, 2015). Furthermore, with regard to the CO_2 sink function of mangrove ecosystems and the estimation of the global carbon budget, identification of the origin of allochthonous OM inputs will help to determine whether the OM is produced from newly fixed CO_2 or relocated “old” OM from terrestrial or marine reservoirs.

In order to better understand the spatial pattern of mangrove carbon storage and composition, we measured organic carbon stocks (aboveground and sediment) and accumulation rates, and we identified the sources of organic matter in three Indonesian mangrove ecosystems

Table 1
Summary of site characteristics.

Location	Mangrove extent	Mangrove condition	Hydrodynamics	Sedimentation
Segara Anakan Lagoon	ca. 9000 ha	● degraded (mainly in the central area) ● plant density and diversity are higher in the eastern than in the central area ● the central area is dominated by understorey plants; while the eastern area is dominated by true mangrove species	river-dominated in the central area; tide-dominated in the eastern area (tidal range ~1.5 m)	the central area receives high sediment inputs from the Citanduy River, and part of the sediment is retained in the lagoon; while the eastern area receives terrigenous sediment inputs only during rainy season
Berau	ca. 80,000 ha	● mature forests ● relatively undisturbed	tide-dominated along the coast of Tanjung Batu (salinity ~35); river-dominated near Berau River (salinity ~25)	mangrove forests receive sediments from the rivers and sea (tidal range ~3 m), and part of the sediments are re-distributed along the coast and form vast mudflats seawards
Kongsi Island	ca. 10 ha	● dense forest; ● good condition/pristine; ● dominated by *Rhizophora*	no river; tide-dominated; strong wave action	the island is affected by abrasion

with different environmental settings and conditions: (i) a degraded estuarine mangrove forest in the Segara Anakan Lagoon, Central Java, (ii) an undegraded estuarine mangrove forest in the Berau region, East Kalimantan, and (iii) a pristine marine mangrove forest on Kongsi Island, Thousand Island Marine National Park, Jakarta. We hypothesize that the total organic carbon stock is higher in the undegraded than in degraded mangrove ecosystems.

2. Materials and methods

2.1. Study area

The Segara Anakan Lagoon (SAL) is a mangrove-fringed shallow coastal lagoon located in southern Central Java (108°46′E − 109°03′E, 8°35′S – 8°48′S; Fig. 1), which is separated from the Indian Ocean by the rocky mountainous Nusakambangan Island (Yuwono et al., 2007). The lagoon receives water input from the rivers in the west and by tidal exchange with the Indian Ocean through two channels in the western and eastern parts (Table 1). The extensive mangrove forest surrounding the lagoon, with a total area of approximately 9000 ha (Ardli and Wolff, 2009), is the largest remaining single mangrove forest in the south coast of Java, which is inhabited by 21 mangrove species and 5 understorey genera (Hinrichs et al., 2009). Mangrove density and diversity are higher in the eastern than in the central part of the lagoon, mainly as a consequence of environmental degradation due to high sedimentation, overexploitation of natural resources and land use conversion (Hinrichs et al., 2009; Lukas, 2017). The lagoon became narrower and shallower due to heavy sedimentation from several rivers, mainly the Citanduy River (Yuwono et al., 2007). Because of large differences in hydrodynamics and sediment dynamics, flora and fauna composition, and redox conditions and porewater nutrient biogeochemistry in sediments, the Segara Anakan Lagoon is considered to be consisting of two parts in our study, the western and central part (collectively named central part in the following) vs. the eastern part (Table 1; Hinrichs et al., 2009; Holtermann et al., 2009; Jennerjahn et al., 2009).

The Berau Regency is located in East Kalimantan (118°05′E, 2°25′N; Fig. 1). This region has a unique coastal system that displays a good example where mangroves, seagrasses and corals interact. In 2005, the Berau Marine Protected Area ($1321*10^6$ ha) was established, which has the second highest coral reef biodiversity in Indonesia and the most extensive remaining mangrove forest in Kalimantan covering an area of 80,277 ha (Bengen et al., 2003; Wiryawan et al., 2005). Mangrove forests are found along the mainland coast (Tanjung Batu to Biduk-Biduk) and surrounding the Berau River estuary (Tomascik et al., 1997; Hoekstra et al., 2007). The forests are relatively undisturbed. Although some area near the estuary has been cleared for aquaculture, these activities are still in an early development stage. The hinterland is characterized by tropical rainforest, which has been partly converted into palm oil plantations. The hydrodynamics of the Berau coastal area are driven by rivers in the west, mainly the Berau River, and strong currents in the east influenced by the Indonesian Throughflow (ITF) that connects the Pacific and Indian Oceans through the Makassar Strait, with a tidal range of up to 3 m (Gordon, 2005; Wiryawan et al., 2005; Hoekstra et al., 2007). The rivers carry a considerable amount of sediments that are dispersed along the coast by the tidal and longshore currents, and form elongated mudflats seawards of the river mouth (Table 1; Tomascik et al., 1997; Hoekstra et al., 2007).

Kongsi Island is a pseudo atoll and forms part of the Pari Island cluster (106°36′E, 5°51′S; Fig. 1), situated in the Thousand Islands Marine National Park. The Thousand Islands are a group of small islands located in the Java Sea, approximately 40 km northwest of Jakarta Bay, in which 13 rivers debouch after passing Jakarta city (Damar, 2003). The hydrodynamics of the island is tidal-dominated. The mangrove forest stretches along the northern and eastern part of the coast and occupies up to 80% (807 m) of the coastline (Salim and Ahmad, 2013). It is a typical marine mangrove ecosystem with a microtidal reef setting, and due to a lack of rivers, mangroves receive no or minimum allochthonous input from the hinterland. Mangroves grow densely and are still in a good condition. However, the island is affected by abrasion due to strong wave actions (Salim and Ahmad, 2013), which may wash off the autochthonous organic matter, and thus will affect sediment accumulation.

2.2. Field sampling and measurement

A sampling campaign was conducted from October to December 2016 in the Segara Anakan Lagoon and on Kongsi Island, while sampling in Berau was conducted in May 2013. In Segara Anakan, data and sample collection were undertaken at 12 stations, with seven stations located in the central area (C24, C49, C45, C41, C26, C42, C43) and five stations located in the eastern area (E40, E46, E44, E47, E16). These stations had been established during previous studies (Hinrichs et al., 2009; Jennerjahn and Yuwono, 2009). On Kongsi Island, data and samples were collected at two stations (K1 and K2), while in Berau, data and samples were collected at four stations located along the coast of Tanjung Batu (B1, B2, B3) and the Berau estuary (B4).

2.2.1. Aboveground tree biomass

At each station, a 100 m transect was laid from the water edge perpendicular towards the mangrove forest. Square plots sized 10 × 10 m were set along the transect in 10 m intervals (5 plots in total). Mangrove plants inside the plots were identified at species level (species identification based on Noor et al., 1999), counted, and diameter at breast height (DBH) of each tree was measured for the estimation of aboveground biomass.

2.2.2. Sediment

Sediments were collected with a 1 m long semi-cylindrical auger. The sediment corer was inserted vertically into the sediment, twisted several times to cut through any fine roots, and then gently pulled out. Sediments were sampled only down to 1 m depth. After the sediment was successfully extracted, it was, sampled in 5 cm intervals, collected into plastic bags, and then preserved in a coolbox before the samples were transferred to the laboratory.

2.3. Analyses

2.3.1. Elemental C, N and stable carbon isotope analysis

All samples were dried at 60 °C for 48–72 h, weighed, ground to fine powder and then flash-combusted in an elemental analyzer (Eurovector EA3000 Elemental Analyzer) to obtain the total C content, total N content and organic carbon (C_{org}) content. The C_{org} content was determined after removing carbonate carbon by acidification with hydrochloric acid and subsequent drying at 40 °C. The samples were then measured for the stable carbon isotope composition ($\delta^{13}C_{org}$) using a Thermo Finnigan Delta plus mass spectrometer coupled to a Flash EA1112 Elemental Analyzer. All data were expressed in a conventional delta (δ) notation, where the isotopic ratio of $^{13}C/^{12}C$ was reported relative to the international VPDB standard as defined below:

$$\delta\ (‰) = [(Ratio_{sample} - Ratio_{standard})/(Ratio_{standard})] \times 1000$$

The precision of instruments was determined by replicate analysis of the standards which resulted in standard deviations as follows: C = ± 0.04%, N = ± 0.006%, $\delta^{13}C_{org}$ = ± 0.08‰.

2.3.2. Stable isotope mixing model

The stable carbon isotope composition ($\delta^{13}C_{org}$) was used to identify the sources of organic matter in the mangrove sediment. The natural variation in the isotope composition of organic matter occurs as a consequence of distinct photosynthetic pathways by different groups of plants; the C3, C4 and CAM plants (Smith and Epstein, 1971; Fry, 2006). However, due to a strong overlap of $\delta^{13}C$ between C4 vegetation and marine-derived organic matter, $\delta^{13}C$ was used in combination with the carbon to nitrogen (C/N) ratio to distinguish organic matter (Bouillon et al., 2003; Fry, 2006; Khan et al., 2015). The C/N ratio can be used to distinguish aquatic from terrestrial organic matter due to a higher relative N content of aquatic organic matter (Tyson, 1995).

The Bayesian isotopic modeling package, Stable Isotope Mixing Model in R (SIMMR) was used to estimate the proportional contribution of potential sources to sedimentary organic carbon based on their isotopic and elemental signatures. The SIMMR model is an updated version of the SIAR package (Parnell et al., 2010), which has been used elsewhere to analyze source contribution of organic matter in coastal ecosystems (Sarma et al., 2014; Watanabe and Kuwae, 2015). This model uses the Markov Chain Monte Carlo (MCMC) algorithm to determine the probability of source proportions to the observed mixture while incorporating the uncertainty for correction (e.g. isotopic fractionation, concentration-dependency, residual error, etc.). Two variables ($\delta^{13}C_{org}$ and C/N atomic) were used and five endmembers (mangrove root and leaf litter, general C3 plants, soils, riverine surface sediment, and coastal Particulate Organic Matter = POM) were considered in this study. The number of endmembers was selected carefully in order to maximize the estimation of source contribution by checking a diagnostic matrix plot of proportional source contributions. The isotopic fractionation and concentration-dependency were set to zero, assuming that the early degradation of organic matter in mangrove sediment does not significantly alter the stable isotope composition (Meyers, 1994; Khan et al., 2015). A model was run through 1×10^3 iterations, and the results are presented using a boxplot which depicts the 50% credibility interval.

The endmember's signatures were taken from region-relevant literature, e.g. mostly collected from Segara Anakan such as mangrove leaf litter (Herbon and Nordhaus, 2013; supplementary information in Nordhaus et al., 2017), surface sediment from the Citanduy River and rice field soils (Yuwono et al., 2007). In addition, data from other areas were also used, for surface sediment from the Berau River (Weiss et al., 2016), for coastal POM from Madura Strait, Indonesia (Jennerjahn et al., 2004), for land plants from Trang, Thailand (Kuramoto and Minagawa, 2001), and for mangrove roots (fresh and decomposed) from Segara Anakan and a Kenyan mangrove forest (Huxham et al., 2010; Weiss et al., 2016). We found that the values of $\delta^{13}C_{org}$ and C/N ratio between mangrove leaf litter and dead roots were overlapping, therefore, we did not separate these endmembers.

2.3.3. Biomass and carbon stocks

Tree biomass was determined by using published allometric equations (Table 2). The aboveground C_{org} stock was then calculated by multiplying the biomass of the individual tree by their specific C_{org} content. For sediment, carbon density of the sediment was determined by multiplying sediment dry bulk density with C_{org} content (wt%) at a specific depth. Dry bulk density was obtained by dividing the mass of the dried sample by the initial volume of the sample. The sediment C_{org} stock per sampled depth interval was then calculated as follows:

$$C_{org}\ \text{stock (Mg C ha}^{-1}) = C_{org}\ \text{density (g cm}^{-3}) * \text{depth interval (cm)}$$

The total sediment C_{org} stock from one core was determined by summing up C_{org} stocks at all depth intervals from the entire core (to 1 m depth).

2.3.4. Radionuclide analyses

Natural and artificial gamma emitting radionuclides were analyzed in three sediment cores, C24 (central SAL), E40 (eastern SAL) and B2 (Berau) in order to estimate sediment accumulation rates. Their activity concentrations were determined by reverse electrode coaxial HPGe detector (Canberra Industries, 50% rel. efficiency) with a carbon-

Table 2
Allometric equations used in this study to determine aboveground biomass (D is tree DBH in cm; ρ is wood density in g cm^{-3}).

Species	Equation	Reference	Wood density (ρ)[a]
Aegiceras corniculatum	$0.251*\rho*D^{2.46}$	Komiyama et al. (2005)	0.5967
Aegiceras floridum	$0.251*\rho*D^{2.46}$	Komiyama et al. (2005)	0.76
Avicennia alba	$0.251*\rho*D^{2.46}$	Komiyama et al. (2005)	0.6987
Bruguiera gymnorhiza	$0.0754*\rho*D^{2.505}$	Kauffman and Cole (2010)	0.741
Bruguiera parviflora	$0.0754*\rho*D^{2.505}$	Kauffman and Cole (2010)	0.8427
Ceriops decandra	$0.251*\rho*D^{2.46}$	Komiyama et al. (2005)	0.725
Ceriops tagal	$0.251*\rho*D^{2.46}$	Komiyama et al. (2005)	0.8859
Heritiera littoralis	$0.251*\rho*D^{2.46}$	Komiyama et al. (2005)	0.8847
Lumnitzera littorea	$0.251*\rho*D^{2.46}$	Komiyama et al. (2005)	0.83
Lumnitzera racemosa	$0.251*\rho*D^{2.46}$	Komiyama et al. (2005)	0.88
Rhizophora apiculata	$0.043*D^{2.63}$	Amira (2008)	0.8814
Rhizophora mucronata	$0.128*D^{2.60}$	Fromard et al. (1998)	0.8483
Rhizophora stylosa	$0.105*D^{2.68}$	Clough and Scott (1989)	0.94
Scyphiphora hydrophyllacea	$0.251*\rho*D^{2.46}$	Komiyama et al. (2005)	0.685
Sonneratia alba	$0.3841*\rho*D^{2.101}$	Kauffman and Cole (2010)	0.6443
Sonneratia caseolaris	$0.251*\rho*D^{2.46}$	Komiyama et al. (2005)	0.5337
Xylocarpus granatum	$0.1832*D^{2.2}$	Tarlan (2008)	0.6721
Xylocarpus moluccensis	$0.251*\rho*D^{2.46}$	Komiyama et al. (2005)	0.6535

Note.
[a] World Agroforestry Centre (2017).

composite window housed in a 10 cm Pb shielding with Cu, Cd and plastic lining. Dry samples were pressed into pellets with a diameter of 35 mm, placed on a polystyrene dish without a lid and sealed using radon-tight aluminum barrier foil. Before measurement, they were stored for a minimum of 3 weeks to establish equilibrium between ^{226}Ra and ^{222}Rn and its daughters to prevent underestimation of "supported" ^{210}Pb (Pittauerová et al., 2011). The counting times ranged from a minimum of 24 h to almost 7 days for samples with low radionuclide concentrations. Spectra were analyzed in Genie 2000 software and the efficiency calibration was performed with the inbuilt LabSOCS (Laboratory SOurceless Calibration System) for a characterized detector.

The values for "supported" ^{210}Pb ($^{210}Pb_{sup}$) were derived from the concentrations of ^{226}Ra, determined via its daughter product ^{214}Pb. Only the peak area of the strongest and cascade correction free gamma line at an energy of 352 keV was used. "Excess" ^{210}Pb ($^{210}Pb_{xs}$), e.g. the part of ^{210}Pb originating from the atmospheric deposition, was calculated for each sample by subtracting the $^{210}Pb_{sup}$ from the total ^{210}Pb measured via its 46 keV gamma line. ^{137}Cs was determined using the peak area of the ^{137m}Ba line at 662 keV. In most of the samples, no ^{137}Cs could be detected and the decision threshold varied depending on measurement times and sample masses. Spectra were also analyzed for ^{241}Am (59 keV), which can sometimes be used as a marker for bomb test fallout. However, no traces of ^{241}Am could be detected.

The carbon accumulation rate (CAR) was calculated by multiplying the sediment accumulation rates with sediment dry bulk density (BD) and organic carbon content (C_{org} content) as follows:

$$CAR\ (g\ m^{-2}\ yr^{-1}) = \text{sedimentation rate}\ (cm\ yr^{-1}) * BD\ (g\ cm^{-3}) * C_{org}\ (\%) * 100$$

2.3.5. Statistical analysis

The differences of a single variable (C_{org} content, N content, bulk density and $\delta^{13}C_{org}$) between areas (SAL East, SAL Central, Berau, Kongsi), and their differences with depth were analyzed by using a one-way ANOVA. The normality of data distribution was tested using Shapiro-Wilk prior to statistical analysis. If the data were not normally distributed, the respective variables were log-transformed to fit a normal distribution when testing linear models. The analyses were performed in R programming (R Core Team, 2017).

3. Results

3.1. Elemental and isotopic composition of sediment organic matter

On average, the highest bulk density was measured in marine mangroves on Kongsi Island (1.35 ± 0.18 g cm^{-3}). It was lower in the estuarine mangroves in Berau (1.20 ± 0.36 g cm^{-3}) and in the Segara Anakan Lagoon (0.62 ± 0.11 g cm^{-3} in the east, 0.74 ± 0.11 g cm^{-3} in the central area). While C_{org} and N contents were higher in the estuarine than in the marine mangroves, $\delta^{13}C_{org}$ was higher in marine mangroves than in estuarine mangroves (Table 3).

3.2. Radionuclides and accumulation rates

$^{210}Pb_{xs}$ in core C24 decreased with depth (Fig. 2). The mass accumulation rate was calculated using the Constant Flux - Constant Sedimentation (CF-CS) model (e.g., Appleby and Oldfield, 1983; Sanchez-Cabeza and Ruiz-Fernández, 2012), using a single exponential fit, for which all samples were considered. No mixing was assumed in this model, as there was neither a direct observation of it, nor an indirect proof in a form of a deep penetration of a shorter lived radioisotope excess ^{228}Th (Pittauerová et al., 2014), which can be used as a mixing

Table 3
Mean values (± SD) of sediment dry bulk density, elemental C_{org} and N content, atomic C/N ratio and $\delta^{13}C_{org}$ from all locations.

Location	Bulk density	C_{org}	N	C_{org}/N	$\delta^{13}C_{org}$
	(g cm^{-3})	(%)	(%)		(‰)
SAL	0.69 ± 0.12	4.6 ± 3.0	0.22 ± 0.05	22.8 ± 11.9	−27.2 ± 0.6
- East	0.62 ± 0.11	7.7 ± 1.8	0.26 ± 0.04	34.7 ± 8.8	−27.6 ± 0.4
- Central	0.74 ± 0.11	2.4 ± 0.8	0.19 ± 0.04	14.3 ± 2.5	−26.9 ± 0.6
Berau	1.20 ± 0.36	5.7 ± 3.7	0.17 ± 0.08	37.1 ± 6.4	−27.8 ± 0.1
Kongsi Island	1.35 ± 0.18	0.8 ± 0.2	0.05 ± 0.01	20.8 ± 0.6	−24.2 ± 0.5

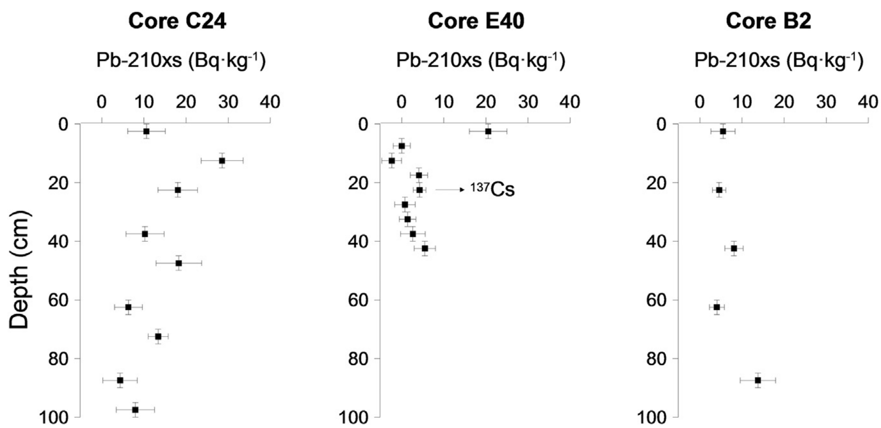

Fig. 2. Distribution of $^{210}Pb_{xs}$ activity concentrations in mangrove sediment cores from Segara Anakan Lagoon and Berau. Horizontal error bars mark the combined counting and calibration uncertainties (± SD), vertical error bars mark the sampling interval.

Table 4
Estimate values (± SD) of mean mass accumulation rates and sedimentation rates.

Core	Accumulation rate ($g{\cdot}cm^{-2}yr^{-1}$)	Sedimentation rate ($mm{\cdot}yr^{-1}$)	$^{210}Pb_{xs}$ inventory ($kBq{\cdot}m^{-2}$)
C24	2.4 ± 1.4	36 ± 22	14 ± 9[a]
E40	≥0.2	≥3.3	~1.1
B2	≥1.6	≥18	~5.7[b]

[a] Estimated using an extrapolation of the exponential fit. In the measured part of the core down to the depth of 100 cm there was about 6.5 $kBq{\cdot}m^{-2}$.
[b] Estimated between 0 and 90 cm, there is probably more $^{210}Pb_{xs}$ below this depth.

indicator. The average mass accumulation rate was estimated to be 2.4 ± 1.4 g cm^{-2} yr^{-1} (Table 4). High fluctuation of values around the model is responsible for high uncertainty of the mean accumulation rate. No ^{137}Cs could be detected with a decision threshold between 0.50 and 1.25 Bq·kg^{-1}. Detailed results of radionuclide analyses are presented in Table S1.

The $^{210}Pb_{xs}$ depth profile of core E40 is less regular and does not allow the use of the CF-CS model. A single positive value of artificial ^{137}Cs was detected at the depth of 22.5 cm (equivalent to the cumulative mass depth of 14.8 g cm^{-2}, Fig. 2). In all other layers ^{137}Cs was below the decision threshold (0.3–1.2 Bq·kg^{-1}). The radioisotope ^{137}Cs was introduced in the environment globally mainly through the atmospheric nuclear testing. Therefore, we can assume this layer younger than 1950 and the estimated average mass accumulation rate is > 0.2 g cm^{-2} yr^{-1}. This is also consistent with the fact that in the deeper layers (27 g cm^{-2}) $^{210}Pb_{xs}$ was still present, marking the layers likely younger than 100 years. In the rest of the core, below 30 g cm^{-2}, ^{210}Pb activities were very low, not detectable by the gamma spectrometry setup.

In core B2, $^{210}Pb_{xs}$ is present in the entire core and does not show any trend with depth. At the cumulative mass depth of 80 g cm^{-2} the $^{210}Pb_{xs}$ concentration did not decrease in comparison to the top of the core, so the sediment is very likely younger than 50 years, assuming the top is recent. The mass accumulation rate is therefore > 1.6 g·cm^{-2}yr^{-1}, possibly much larger than that and likely accompanied with significant reworking. Similar with core C24, ^{137}Cs was not detected (decision threshold 0.3–1.3 Bq·kg^{-1}), which might be a result of dilution due to large mass accumulation.

3.3. Carbon accumulation rates (CAR)

The highest carbon accumulation rate (CAR) was measured in the mature and undisturbed forest in Berau (B2: 1722 ± 183 g C m^{-2} yr^{-1}), followed by a disturbed forest that receives high sediment input from river discharge in the central SAL (C24: 658 ± 311 g C m^{-2} yr^{-1}). The lowest was measured in the eastern SAL (E40: 194 ± 46 g C m^{-2} yr^{-1}) which does not receive significant input from the hinterland. No CAR could be calculated for Kongsi Island as radionuclides were not analyzed. For carbonate-rich sediments like these, the atmosphere-borne radionuclide activities are usually extremely low and age dating is impossible. However, as Kongsi Island has little allochthonous input and the C_{org} concentration is low, it is likely that the CAR is also very low.

3.4. Biomass and carbon stocks

The aboveground tree biomass varied between 7.5 Mg ha^{-1} (E46) to 329 Mg ha^{-1} (B1), with the highest mean biomass measured in Berau (262.2 ± 65.3 Mg ha^{-1}), followed by Kongsi Island (161.4 ± 43.6 Mg ha^{-1}) and Segara Anakan Lagoon (33.7 ± 18.5 Mg ha^{-1} in the eastern and 21.7 ± 6.3 Mg ha^{-1} in the central lagoon, Table 5). Biomass values in the eastern lagoon are similar with the values reported by Nordhaus et al. (2018, this volume). However, the aboveground biomass in the central lagoon is higher in this study due to a higher DBH, which is likely as a result of a slight decrease of logging. A higher aboveground tree biomass resulted in a higher aboveground carbon stock in Berau (130.1 ± 32.1 Mg C ha^{-1}), followed by Kongsi Island (74.3 ± 20.2 Mg C ha^{-1}), and Segara Anakan Lagoon (15.8 ± 8.6 Mg C ha^{-1} in the eastern and 10.3 ± 3.0 Mg C ha^{-1} in the central lagoon). The mean sediment C_{org} stock was also highest in Berau (485 ± 197 Mg C ha^{-1}), but it was almost similar with the eastern area of Segara Anakan Lagoon (467 ± 118 Mg C ha^{-1}), while the sediment C_{org} stock in the central area was lower (161 ± 34 Mg C ha^{-1}). Kongsi Island had the lowest sediment C_{org} stock (37 ± 3 Mg C ha^{-1}) due to a low sediment depth of 40 cm and a low C_{org} content.

The total C_{org} stocks (aboveground and sediment) varied among stations, from the lowest of 95 Mg C ha^{-1} on Kongsi Island (K1) to the

Table 5
Mean values (± SD) of aboveground biomass and carbon stocks.

Location	Aboveground biomass	Aboveground C_{org} stock	Sediment C_{org} stock	Mean total C_{org} stock
	(Mg ha^{-1})	(Mg C ha^{-1})	(Mg C ha^{-1})	(Mg C ha^{-1})
SAL	28.4 ± 15.0	13.3 ± 6.9	288 ± 175	298 ± 181
- East	33.7 ± 18.5	15.8 ± 8.6	467 ± 118	483 ± 124
- Central	21.7 ± 6.3	10.3 ± 3.0	161 ± 34	167 ± 36
Berau	262.2 ± 65.3	130.1 ± 32.1	485 ± 197	615 ± 181
Kongsi Island	161.4 ± 43.6	74.3 ± 20.2	37 ± 3	112 ± 24

highest of 869 Mg C ha^{-1} in Berau (B2). The mean total C_{org} stock in the undegraded estuarine mangroves in Berau (615 ± 181 Mg C ha^{-1}) was twice as high as that measured in the degraded estuarine mangroves in the Segara Anakan Lagoon (298 ± 181 Mg C ha^{-1}). However, the mean total C_{org} stock in the eastern SAL was higher (483 ± 124 Mg C ha^{-1}) than that in the central SAL (167 ± 36 Mg C ha^{-1}). While marine mangroves on Kongsi Island had the lowest C_{org} stocks (112 ± 24 Mg C ha^{-1}).

4. Discussion

4.1. ^{210}Pb inventories

Expected inventories of $^{210}Pb_{xs}$ in sediments of the study region can be calculated from the atmospheric deposition of ^{210}Pb. While the authors are not aware of any estimates for Indonesia, literature values for north Australia, Torres Strait, and Malaysia can provide an indication. Brunskill et al. (2004) estimated deposition of ^{210}Pb in north Queensland based on rain collections and 15 soil profiles as 50 Bq·m^{-2} yr^{-1} and at Sassie Island in Torres Strait of 18–22 Bq·m^{-2} yr^{-1} based on three soil profiles. Bonnyman and Molina-Ramos (1971, cited in Brunskill et al., 2004) reported an average of 90 Bq·m^{-2} yr^{-1} deposition for Darwin. Gharibreza et al. (2013) derived an atmospheric ^{210}Pb flux of 90 Bq·m^{-2} yr^{-1} to Bera lake, Malaysia, based on sediment cores. From these published values we expect the maximum ^{210}Pb flux in our study area to be 100 Bq·m^{-2} yr^{-1}, therefore the upper limit of inventories in sediment cores is 3.2 kBq·m^{-2}, which can be compared to the experimentally determined radionuclide inventories. The observed values are reported in Table 4. They are significantly higher than expected in cores C24 and B2, which suggests an important additional contribution of $^{210}Pb_{xs}$ other than from the direct deposition, e.g. from the catchment area or through lateral transport and focusing.

4.2. Sources and composition of sedimentary organic matter

In the Segara Anakan Lagoon, differences between the central and the eastern areas occurred not only in mangrove communities (Hinrichs et al., 2009), but also in the composition of sedimentary organic matter. Variation of C_{org} and N contents, $\delta^{13}C_{org}$, and C/N ratio were observed between these two areas ($p < 0.05$). Based on the $\delta^{13}C_{org}$ (−29.5 to −23.9) and the C/N ratio (9–26.6), the sedimentary OM that accumulated in the central SAL is mainly allochthonous (Fig. 3), with 34–60% (median = 49%) derived from riverine sediment (Fig. 4). Conversely, sedimentary $\delta^{13}C_{org}$ (−29.4 to −25.8) and the C/N (18–79) values in the eastern SAL are fairly similar to those of mangrove root and leaf litter, which contributed about 40–55% (median = 48%) to sedimentary OM (Fig. 4), a similar portion as reported from many other mangrove ecosystems where 58% of sediment OM was mangrove-derived (Kristensen et al., 2008). Mangrove sediments in Berau displayed $\delta^{13}C_{org}$ (−28.4 to −26.9) and C/N (20.1–62.8) values similar to those of the eastern SAL ($p > 0.05$), and the 30–50% (median = 41%) mangrove root and leaf litter contributions indicate an important accumulation of autochthonous organic matter. However, due to overlapping values of $\delta^{13}C_{org}$ and C/N ratio between mangrove leaf litter and roots, the proportion of contribution from each of these endmembers was uncertain. Mangrove leaf litter and roots are important sources of organic matter. In some mangrove ecosystems, organic carbon content in sediment is determined more by the capacity of root production than by litter fall (Chen and Twilley, 1999). There, slow degradation of dead roots in combination with high rates of root production are the critical processes controlling organic carbon accumulation in the sediment (Middleton and McKee, 2001; Robertson and Alongi, 2016).

The hydro-geomorphics likely influenced the variations of sedimentary OM in the studied sites, as also reported from other studies (Kuramoto and Minagawa, 2001; Saintilan et al., 2013). Mangrove sediments growing in the river-dominated estuary in the central SAL, accumulated larger portions of allochthonous OM (mainly riverine sediment) than those in the tide-dominated estuaries in the eastern SAL and in Berau. Due to less dilution from river discharge, sediment mangroves in the eastern SAL and in Berau contained higher organic carbon content (7.7 ± 1.8% and 5.7 ± 3.7%, respectively) than the central SAL (2.4 ± 0.8%) which received high sediment inputs from the hinterland, with a large portion of mineral sediment diluting the C_{org} content.

In contrast to estuarine mangroves, sediment on Kongsi Island had a higher $\delta^{13}C_{org}$ (−25.9 to −22.1‰), which is closer to that of marine-derived organic matter, and the highest contribution comes from coastal POM (13–38%; Fig. 4). This carbonate setting is distinctly different from the estuarine systems, mainly because of the absence of river influence, and often being dependant upon in situ production of either mangrove peat or calcareous sediment (Woodroffe, 1992). In many cases, island mangroves accumulate a thick peat-muck layer overlying hard coral sand, and thus contain high sedimentary organic carbon, such as reported for the Yap and Palau islands, Micronesia, with around 14.2% and 18.4% of C_{org} content, respectively (Donato et al., 2011). Despite having similar characteristics with Yap and Palau islands where mangroves grow over former reef flats and coral sands fringing the island (Kauffman et al., 2011), the mangrove ecosystem on Kongsi Island has a lower sedimentary C_{org} content (0.8 ± 0.2%). This

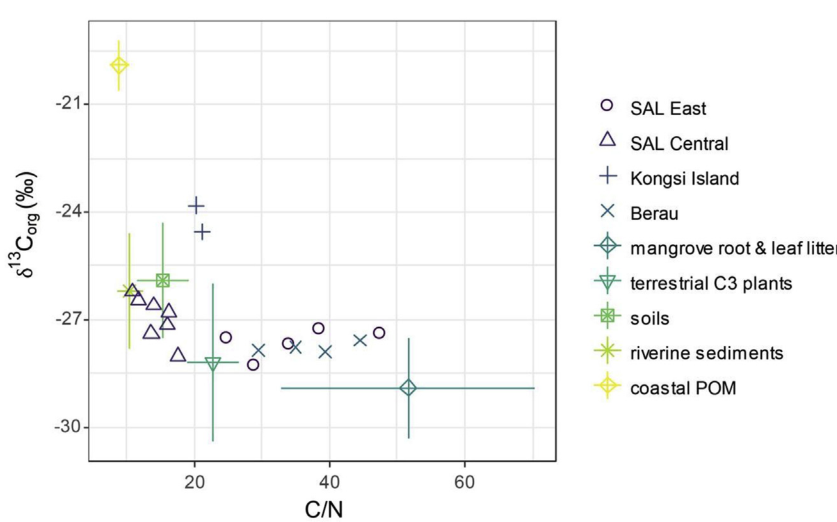

Fig. 3. Bi-plot of $\delta^{13}C_{org}$ and the C/N ratio of sediments from the study area and potential endmembers.

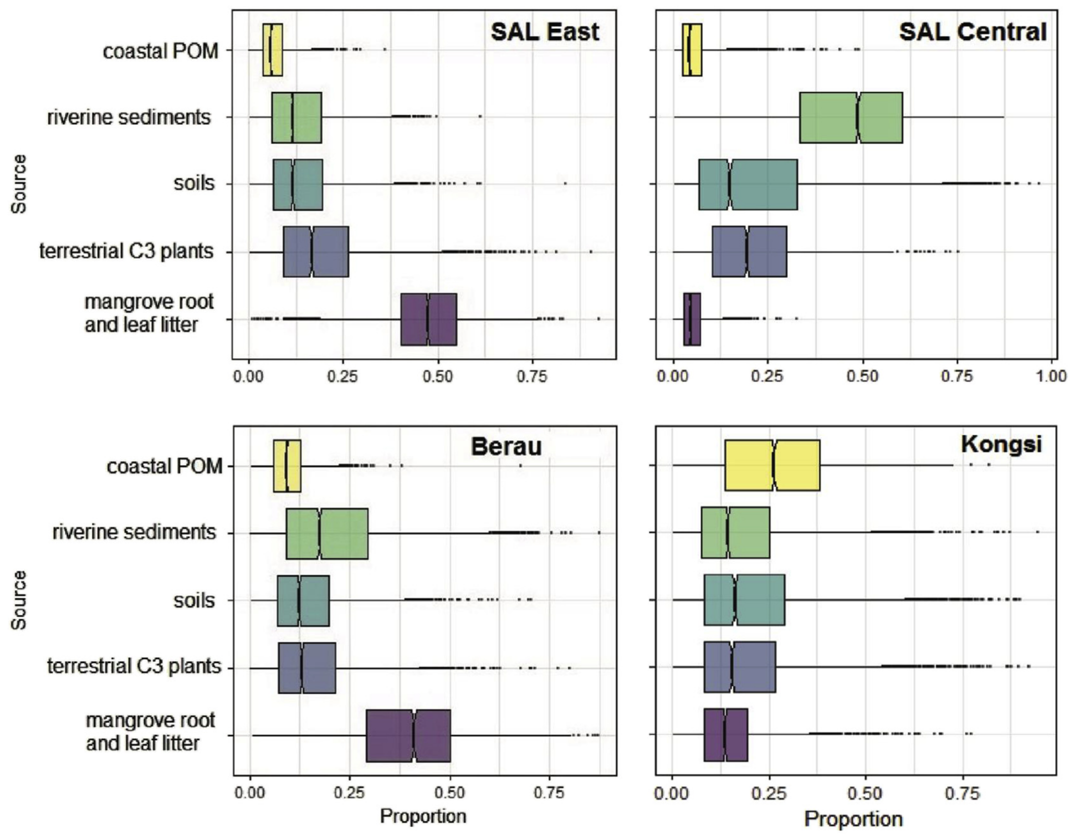

Fig. 4. Simmr credibility interval plot of the contribution of different endmembers to sedimentary organic matter (boxes enclose the 50% credibility interval; lines within boxes represent median values).

is probably because mangroves on Kongsi Island grow in the low intertidal zone that is frequently flushed by tides, which prevents the accumulation of autochthonous organic matter. Tides might have also delivered organic matter from sea water, and a large amount of eroded coral rubble that diluted the autochthonous organic matter, as indicated by a very high calcium carbonate content of the sediment (94.6 ± 1.0%).

4.3. Downcore variation of organic matter composition

Variation of organic carbon in the sediment is the result of changes in deposition from multiple sources and the decomposition of organic matter by microbes (Bouillon et al., 2008; Kuramoto and Minagawa, 2001). The downcore enrichment of $^{13}C_{org}$ ($p < 0.001$) coupled with a constant C/N ratio ($p = 0.13$) in the central SAL indicates a shift in the organic matter source, because decomposition of organic matter usually does not cause a significant enrichment of $^{13}C_{org}$ (Saintilan et al., 2013). It seems there was a shift in OM accumulation from a predominance of riverine sediment ($\delta^{13}C_{org}$ −26.2 ± 1.6‰, C/N 10.5 ± 1.9) and hinterland soils ($\delta^{13}C_{org}$ −25.9 ± 1.6‰, C/N 15.4 ± 3.9; Kuramoto and Minagawa, 2001; Yuwono et al., 2007; Weiss et al., 2016) in the bottom layer, to more C3 vegetation ($\delta^{13}C_{org}$ −28.2 ± 2.2‰, C/N 22.8 ± 3.8; Kuramoto and Minagawa, 2001) in the upper layer (Fig. 5). Moreover, the gradual decrease of C_{org} content and C_{org} density downcore ($p < 0.001$) reflects the dilution with mineral matter which is generally high in riverine suspended matter and soils (Yuwono et al., 2007). In the eastern SAL, the low $\delta^{13}C_{org}$ and high C/N ratio fall in the range of mangrove leaf litter ($\delta^{13}C_{org}$ −31 to −28‰, C/N 28–84; Herbon and Nordhaus, 2013; Nordhaus et al., 2017), and mangrove roots ($\delta^{13}C_{org}$ −29 to −28‰, C/N 28–60 of decomposed roots; Huxham et al., 2010; Weiss et al., 2016). Their increase with depth ($p < 0.001$), in combination with a downcore increase of C_{org} content and density indicates the predominance of autochthonous mangrove OM in the sediments. The somewhat lower concentrations at the surface are probably caused by an admixture of allochthonous sediment input by the tides. In Berau, downcore profiles of C_{org} content, C_{org} density, and the C/N ratio did not show variations ($p = 0.67$, 0.93, 0.62, respectively) and $\delta^{13}C_{org}$ increased only slightly with depth ($p < 0.001$). Values were in the same range as in the eastern SAL, and indicate a predominance of autochthonous mangrove OM throughout the core. Downcore variations at Kongsi Island are negligible.

4.4. Variation of organic carbon stocks

A variation of C_{org} stocks in different mangrove ecosystems was observed in this study, where the majority of C_{org} is stored in the sediment (from 79% in Berau up to 96% in the eastern SAL), which is in accordance with other studies (Donato et al., 2011; Kauffman et al., 2011; Adame et al., 2013; Murdiyarso et al., 2015). An exception was observed on Kongsi Island, where only 33% of the total C_{org} stock is allocated in the belowground pool because of dilution with eroded carbonate rubble which makes up 95% of the sediment.

4.4.1. The impact of ecosystem degradation on carbon storage

The aboveground C_{org} stock was higher in the undisturbed mangrove ecosystems in Berau (130.1 ± 32.1 Mg C ha^{-1}) and Kongsi Island (74.3 ± 20.2 Mg C ha^{-1}) than in the degraded mangrove ecosystem in the Segara Anakan Lagoon (15.8 ± 8.6 Mg C ha^{-1} in the eastern and 10.3 ± 3.0 Mg C ha^{-1} in the central lagoon, (Fig. 6)). The mangrove forest in SAL is dominated by a small-stature vegetation, where the highest mean DBH was only 6.30 ± 3.57 cm (from species *S. caseolaris*), while DBH was up to 50.2 ± 22.5 m (from species *S. alba*) in Berau (Kusumaningtyas, 2017). According to a previous study (Hinrichs et al., 2009), most of the large mangrove trees in SAL had

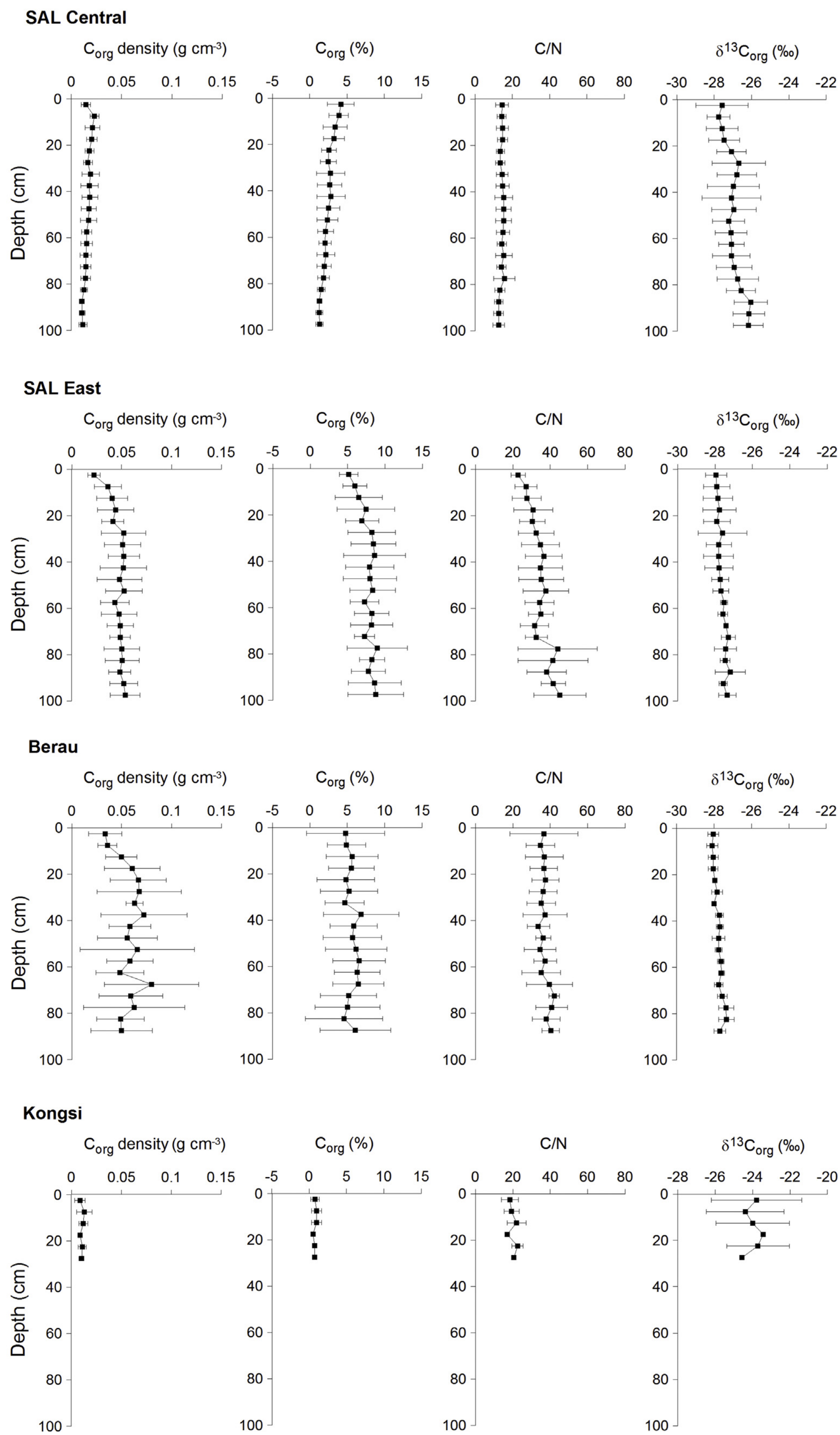

Fig. 5. Downcore variations of sediment properties at the studied sites (error bars indicate the standard deviation).

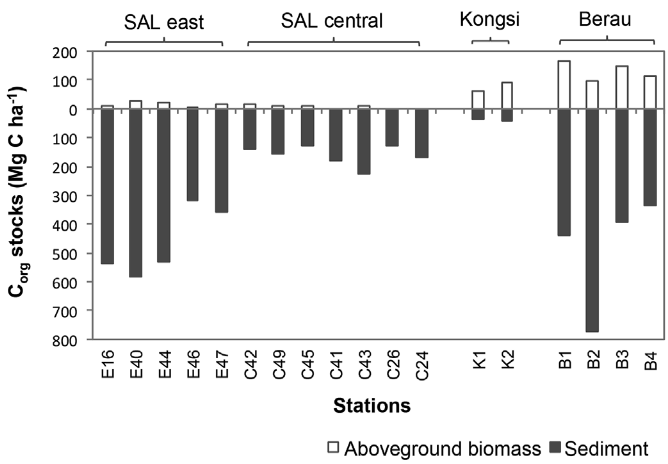

Fig. 6. Organic carbon stocks (aboveground biomass and sediment including belowground biomass) at all stations.

already been cut. Even during our data collection, at some stations in the central area, many cut trees were found. As a consequence, the aboveground C_{org} stocks are very low in SAL.

The mangrove habitat in SAL has undergone transformation due to temporal dynamics of riverine sediment input and deforestation, which caused the decline of mangrove tree density and the overall species number and diversity, particularly in the central area (Yuwono et al., 2007; Hinrichs et al., 2009; Lukas, 2017). In the past, some mangrove species such as *A. alba, A. corniculatum, S. caseolaris, Rhizophora* and *Bruguiera* were found in higher numbers in the central SAL, but the changing environmental conditions caused a shift from mangrove-dominated to understorey-dominated communities such as *Derris* and *Acanthus*. The abundance of *Acanthus*, which characterizes degraded mangrove areas in Java (Whitten et al., 2000; Hinrichs et al., 2009), was attributed to uncontrolled deforestation, high freshwater discharge, and high sedimentation as a result of extensive erosion in the hinterland due to land conversion for agriculture and settlements, deforestation for timber production, and volcanic eruptions (Yuwono et al., 2007; Hinrichs et al., 2009; Lukas, 2017; Nordhaus et al. this volume). Excess sediment input can reduce seedling numbers and bury aerial roots, thus inhibiting mangrove growth (Ellison, 1999; Sidik et al., 2016), and being aggravated with deforestation practices, these disturbances can prevent mangrove forests to reach a mature state.

Previous studies (Sun, 2011; Wang et al., 2013) found organic carbon content and density in the upper layers (down to 100 cm) increasing along with biomass growth, as primary production increased and input of dead roots and leaf litter also increased. In our study, sediment C_{org} stock in the upper meter layer in the eastern SAL (467 ± 118 Mg C Ha^{-1}) was similar to that in Berau (485 ± 197 Mg C Ha^{-1}), and much higher than that on Kongsi Island (37 ± 3 Mg C Ha^{-1}), despite a lower aboveground biomass. This is probably due to a combination of two factors. The relatively high tree density in the eastern SAL (Hinrichs et al., 2009), despite an absence of large trees, probably reflects a moderately high productivity that provided a large supply of mangrove litter and dead roots. High vegetation density also can inhibit resuspension by water motion and trap particles in the forest floor (Alongi, 2012). Moreover, the very low allochthonous input does not dilute the autochthonously produced OM. By contrast, the low sediment C_{org} stock in the central SAL is probably the result (i) of a lower tree density and low primary production due to an uncontrolled deforestation, and (ii) of a dilution with allochthonous mineral sediment input from the Citanduy River.

4.4.2. Carbon stocks in contrasting environmental settings

While carbon stocks also vary geographically, there are major differences between estuarine and marine settings, because of the different relative importance of allochthonous input by rivers vs. autochthonous production. The mean total C_{org} stocks found in the estuarine mangroves in Berau and Segara Anakan are higher than those in marine mangroves on Kongsi Island. This is in accordance with the pattern reported by Murdiyarso et al. (2009) who found a higher mean total C_{org} stock in the river-delta mangroves in Tanjung Puting, Central Kalimantan (1220 Mg C ha^{-1}) than in the oceanic mangroves in Bunaken, North Sulawesi (939 Mg C ha^{-1}). Donato et al. (2011) also found a higher C_{org} stock in estuarine mangroves (alluvial delta) than in oceanic mangroves (1074 Mg C ha^{-1} and 990 Mg C ha^{-1}, respectively) in the SE Asia region. Conversely, Weiss et al. (2016) reported a higher sediment C_{org} stock within the topmost meter of oceanic mangroves on the Togian Islands, Sulawesi (570 Mg C ha^{-1}) than in the estuarine mangroves in the Berau Estuary (310 Mg C ha^{-1}).

A major factor in explaining the large geographical variation of C_{org} stocks is the simple fact that the length of obtained sediment cores can vary largely. Depending on the coring device used and the within-system natural variability, it is possible that not the full sediment record is covered by the core, hence C_{org} stock calculations may have large uncertainties or even be underestimates. For example, in an Indonesia-wide study, sediment cores from 8 mangrove ecosystems differed between 46 cm and 300 cm in length even in one system, the respective carbon stocks varied between 408 and 2208 Mg C ha^{-1} (supplementary information in Murdiyarso et al., 2015). Estuarine mangrove forests may have a higher C_{org} stock due to a longer sediment record compared to most oceanic mangroves (Donato et al., 2011). This is mainly because the estuarine mangroves receive large allochthonous inputs from river discharge, which is to a large extent mineral sediment diluting the carbon content. However, depending on the proportion of mineral sediment, this dilution may also result in lower carbon stocks. In order to highlight geographical variations, we compare carbon stocks standardized to 1 m sediment depth. In cases where sediment cores have a maximum depth < 1 m, C_{org} stocks were extrapolated to 1 m depth. We grouped carbon stocks into estuarine and marine mangroves (Fig. 7). Marine/oceanic mangroves have no river influence, and include island mangroves, intertidal fringe mangroves, as well as mangrove forests growing in a karstic or carbonate landscape. Estuarine mangroves were categorized based on the existence of rivers, and include riverine and deltaic mangrove forests.

The overall total carbon stock (aboveground biomass and sediment including belowground biomass within 1 m depth) is higher in marine mangroves (median: 535 Mg C ha^{-1}, mean: 465 ± 193 Mg C ha^{-1}) than that in estuarine mangroves (median: 299 Mg C ha^{-1}, mean: 402 ± 242 Mg C ha^{-1}, Fig. 7). Even among the estuarine mangroves alone, variation of C_{org} stocks is high. The mean total C_{org} stock in Berau (615 ± 181 Mg C ha^{-1}) is lower than in an undisturbed, mixed-stature mangrove forest in Sembilang, than in the undisturbed, tall-stature mangrove forests in Timika (Murdiyarso et al., 2015), and than in the Encrucijada Biosphere Reserve, Mexico (Adame et al., 2015). However, C_{org} stocks in Berau and the eastern SAL (483 ± 124 Mg C ha^{-1}) are higher than those of the rest. It indicates that not all mangrove ecosystems have the same carbon storage capacity and that local variations of C_{org} stocks likely mainly depend on the differences in environmental settings and conditions (Woodroffe, 1992). For instance, among all estuarine mangrove ecosystems described above, lower C_{org} stocks are mostly found in river-dominated settings, such as in the Mui Ca Mau National Park in the Mekong Delta, in the Ganges-Brahmaputra Delta, in the Indian Sundarbans, and in the central SAL, which are likely due to high river inputs of mineral sediment that diluted the organic matter. The large difference in C_{org} stocks we found between central and eastern SAL demonstrates the large variability which can occur within one ecosystem. It is mainly a result of the differences in the dominant hydrodynamic processes, landforms and vegetation conditions (Hinrichs et al., 2009; Holtermann et al., 2009; Jennerjahn et al., 2009). In a global-scale approach and using an ecogeomorphology framework, a recent study relates carbon storage in mangrove soils to distinct

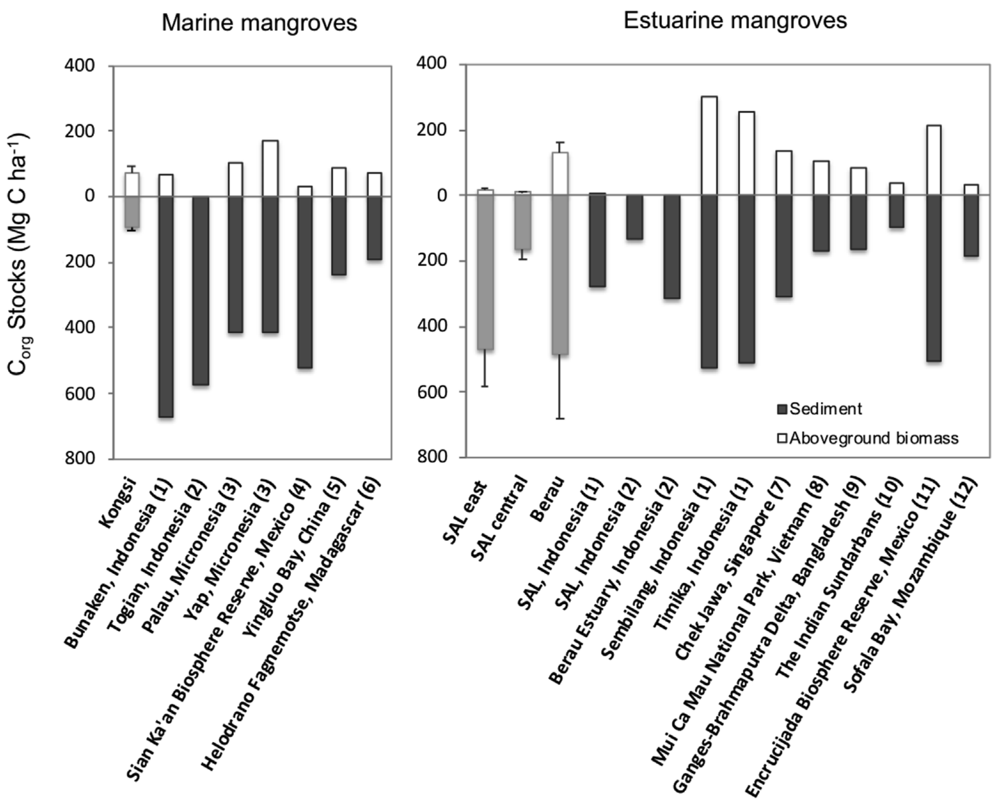

Fig. 7. Mean total C_{org} stocks (aboveground biomass and sediment including belowground biomass to 1 m depth) in marine and estuarine mangroves from several sites. Data source: 1 – Murdiyarso et al. (2015); 2 – Weiss et al. (2016); 3 – Kauffman et al. (2011); 4 – Adame et al. (2013); 5 – Wang et al. (2013); 6 – Benson et al. (2017); 7 – Phang et al. (2015); 8 – Tue et al. (2014); 9 – Donato et al. (2011); 10 – Ray et al. (2011); 11 – Adame et al. (2015); 12 – Sitoe et al. (2014). Boxes in light grey denote sites in this study.

coastal environmental settings. Similar to our results, it finds lower carbon densities in river delta, estuarine and lagoon settings with a substantial allochthonous inorganic sediment input than in other settings (Rovai et al., 2018).

Carbon stocks are also highly variable among marine mangrove forests, in which, Kongsi Island has the lowest C_{org} stock (Fig. 7). It implies that not all marine mangroves accumulate high sediment organic carbon, despite little or no dilution from river discharge. Local factors such as tidal amplitude, wave action, landform and elevation are the important drivers controlling organic carbon distribution and deposition in the intertidal mangroves. The restricted accumulation of organic carbon can be partly related to rapid water circulation that washes off autochthonous organic matter, high input from the ocean such as coral rubble that dilutes the organic matter, and a low residence time of water that increases exposure time to oxygen and promotes decomposition (Bouillon et al., 2008; Ranjan et al., 2011). These typical overwash mangrove ecosystems are usually found in carbonate reef environments (Woodroffe et al., 2016), such as on Kongsi Island. With its very low sedimentary C_{org} content and stock it appears to be an extreme example, but it highlights that the variability of carbon stocks for oceanic mangroves is larger than reported so far.

The standardization to 1 m sediment depth allows for a better comparison of C_{org} stocks among sites and hence a better assessment of the factors responsible for any observed variability. However, it does not provide the total C_{org} stock of a mangrove ecosystem. Moreover, sediment cores obtained for carbon stock assessments are usually not longer than 3 m although the total sediment record may be longer which adds more uncertainty to carbon stock estimates. In mangrove ecosystems with high allochthonous (mineral sediment) input, the sediment record may be much longer and hence the carbon stock much higher. In turn, if in such a case only a 3 m core is assessed, the dilution with mineral sediment will result in an underestimate of the total carbon stock of a mangrove ecosystem. In the case of the Segara Anakan Lagoon, for example, carbon stocks vary by a factor of three between two sites within one ecosystem (Fig. 7). While there is little allochthonous sediment input in SAL East and the carbon stock high, there is high allochthonous input from the Citanduy River in SAL Central which dilutes sedimentary organic matter there and results in a low carbon stock.

These variations are of particular importance for the calculation of the climate change mitigation potential of mangrove ecosystems (e.g. Donato et al., 2011; Kauffman et al., 2014; Murdiyarso et al., 2015). The climate change mitigation potential builds on keeping the high stocks of carbon. In contrast, degradation and deforestation of mangrove forests results in the decomposition of organic matter and the release of CO_2, hence a sink for atmospheric CO_2 is ultimately turned into a source. However, while these calculations allow to get an idea on the potential release of CO_2, they do not allow to assess how much CO_2 is actually accumulating in the form of organic carbon in mangrove ecosystems.

4.5. Carbon accumulation rates in the global context

In order to assess the present day sink function of mangrove forests for atmospheric CO_2 it is likely more useful to measure the current carbon accumulation rate (CAR) in mangrove sediments. In our study, the CAR of all dated cores (C24, E40, B2) is higher than the global average of 174 g C m^{-2} yr^{-1} (Alongi, 2012), in Berau (core B2) it is even an order of magnitude higher and among the highest rates ever measured (Fig. 8). While OM proportions in our endmember mixing model (Fig. 3) indicate a predominantly autochthonous origin of sedimentary organic matter, the high sedimentation and carbon accumulation rates and a C_{org} concentration of around 5% (Fig. 5) suggest high allochthonous input mainly of mineral sediment. The high CAR in Berau is therefore probably a product of high primary production and high allochthonous input. Primary production usually increases with stand age, and so does carbon burial in sediment (Alongi, 2014; Marchand, 2017). The high sedimentation rate measured in Berau (18 mm yr^{-1}) is likely related to high river floods, during which the mean river discharge can be up to 2000 m^3 s^{-1} (Hoekstra et al., 2007).

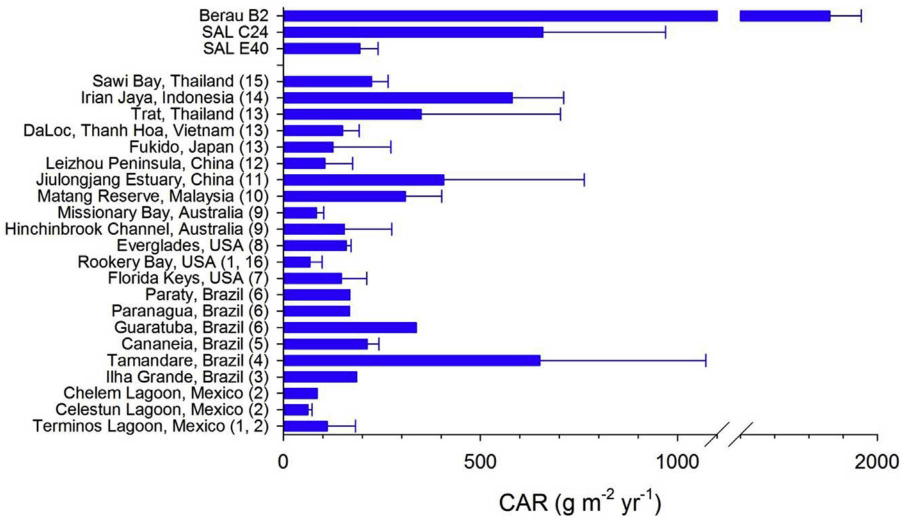

Fig. 8. Carbon accumulation rates from various sites. Data sources: 1 – Lynch (1989); 2 – Gonneea et al. (2004); 3 – Sanders et al. (2008); 4 – Sanders et al. (2010a); 5 – Sanders et al. (2010b); 6 – Sanders et al. (2010c); 7 – Callaway et al. (1997); 8 – Smoak et al. (2013); 9 – Brunskill et al. (2002); 10 – Alongi et al. (2004); 11 – Alongi et al. (2005); 12 – Yang et al. (2014); 13 – Tateda et al. (2005); 14 – Brunskill et al. (2004); 15 – Alongi et al. (2001); 16 – Cahoon and Lynch, unpublished data in Chmura et al. (2003).

Occasionally, strong currents and waves influenced by the Indonesian Throughflow (ITF) may cause resuspension of sediment and prevent its settlement. However, wave effects in the northern part of Berau are generally limited due to the breakwater effects of the delta front barrier reef and its shallow depth (Hoekstra et al., 2007), which may promote the settling of particulate organic matter in Berau.

In some cases the rate of sediment delivery may be a more important driver of CAR than primary production (Alongi et al., 2001), in particular in impacted areas, such as in the Jiulongjang estuary, China, which receives high amounts of sewage and has a massive accretion rate of 46.3 mm yr^{-1} (Alongi, 2005). In a highly impacted mangrove ecosystem in Cubatão, Brazil, the high CAR of 1023 g C m^{-2} yr^{-1} was to a large extent attributed to the eutrophication of coastal waters (Sanders et al., 2014, Fig. 8). Interestingly, the CAR distribution pattern in the Segara Anakan Lagoon is opposite to that of the C_{org} stocks. While the latter is higher in SAL East, the CAR is much higher in the central than in the eastern lagoon. The high sedimentation rate (36 ± 22 mm yr^{-1}) and CAR in the central SAL is most likely a result of high river input due to erosion in the agriculture-dominated hinterland (Yuwono et al., 2007; Lukas, 2017) as also illustrated by the high $^{210}Pb_{xs}$ inventory. Sedimentary OM is diluted by high mineral sediment input leading to the low C_{org} stock, as indicated by a C_{org} concentration of 2–4%, and it consists of a mixture of autochthonous and allochthonous OM, in which mangrove OM appears to be a minor contribution only (Figs. 3 and 4). In contrast, in SAL East little river influence, hence little allochthonous input, is responsible for a lower, but still significant accumulation rate of OM that is mainly of mangrove origin (Fig. 4).

On a global scale, the CAR in Berau and in the central SAL is at the upper end of the range and even in the eastern SAL it is higher than the global average. High rates of 581 ± 130 g C m^{-2} yr^{-1} were also measured in Irian Jaya (now Papua), Indonesia, in the Ajkwa River estuary. There, the mangrove forest receives high inputs of allochthonous sediment from the mountainous hinterland and it has a macrotidal exchange with the Arafura Sea (Brunskill et al., 2004). Similarly, a CAR of up to 949 g C m^{-2} yr^{-1} was measured at the margin of a mangrove forest in Tamandaré, Brazil, which receives allochthonous sediment input from a small river and has a mesotidal exchange with the Atlantic Ocean (Sanders et al., 2010a). In contrast, very low carbon accumulation rates of 67 ± 31 g C m^{-2} yr^{-1} were obtained in Rookery Bay, USA. It has an annual average tidal range of 0.6 m and a very low supply of allochthonous sediment by Henderson Creek which has a discharge of 0.7 $m^3 s^{-1}$ only (Lynch et al., 1989). The low CAR of 55–70 g C m^{-2} yr^{-1} in mangrove forests in Celestun Lagoon, Mexico, is also related to low allochthonous inputs (Lynch et al., 1989). The lagoon is located in a karstic landscape and therefore has almost no surface runoff and a maximum tidal range of 1.5 m (Herrera-Silveira and Morales-Ojeda, 2010). It appears that besides productivity, the environmental setting is a major driver of carbon accumulation in mangrove sediments (Woodroffe et al., 2016). Our study sites in Berau and the central SAL are river- and tide-dominated settings with high allochthonous inputs and hence high CARs, while SAL East and Kongsi have low allochthonous inputs, hence low CARs.

Our study, in line with other studies, demonstrates that the river- and tide-dominated mangrove settings are quantitatively most relevant in terms of carbon storage even despite the dilution with high amounts of mineral sediment. An average of global budgets estimates mangrove carbon storage to be on the order of 22 ± 6 Tg yr^{-1} (Jennerjahn et al., 2017), based on an area of 138,000 km^2 (Giri et al., 2011). Assuming that Indonesia's contribution to global mangrove carbon storage is equivalent to its portion of mangrove area of 22.6% (Giri et al., 2011), its total carbon accumulation would be at minimum 5 Tg yr^{-1}. However, as Indonesia is located in the zone of maximum natural weathering and erosion and hence high river fluxes of suspended sediments (Milliman and Farnsworth, 2011), it could be even higher.

5. Conclusion

Blue carbon storage is presently considered one of the most important natural sinks for annual anthropogenic greenhouse gas emissions. With respect to quantifying the recent sink function of mangrove ecosystems for carbon, it is likely more important to quantify current carbon accumulation rates rather than estimating carbon stocks. Stock assessments allow to calculate the potential of CO_2 being released upon degradation and deforestation, but they do not allow to estimate present-day carbon storage. While stock assessments are useful and numerous respective studies have been conducted in the past years, they may be misleading in cases where dilution with mineral sediment masks the real accumulation potential as illustrated by our example from the Segara Anakan Lagoon. There, SAL East has a much higher carbon stock than SAL Central, but the latter has a threefold higher CAR, hence presently stores carbon in a much higher rate than SAL East does. Quantifying carbon accumulation in mangrove sediments is therefore a useful tool in valuing ecosystem services and it is of particular importance for PES (payments for environmental services) and REDD+ (Reducing Emissions from Deforestation and Forest Degradation and the role of conservation, sustainable management of forests and enhancement of forest carbon stocks in developing countries) schemes.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecss.2018.12.007. The data set for this study is published in PANGAEA (Kusumaningtyas et al., 2018), https://doi.pangaea.de/10.1594/PANGAEA.896852.

References

Adame, M.F., Kauffman, J.B., Medina, I., Gamboa, J.N., Torres, O., Caamal, J.P., Reza, M., Herrera-Silveira, J.A., 2013. Carbon stocks of tropical coastal wetlands within the karstic landscape of the Mexican Caribbean. PLoS One 8 (2).
Adame, M.F., Santini, N.S., Tovilla, C., Vázquez-Lule, A., Castro, L., Guevara, M., 2015. Carbon stocks and soil sequestration rates of tropical riverine wetlands. Biogeosciences 12, 3805–3818.
Alongi, D.M., Wattayakorn, G., Pfitzner, J., Tirendi, F., Zagorskis, I., Brunskill, G., Davidson, A., Clough, B., 2001. Organic carbon accumulation and metabolic pathways in sediments of mangrove forests in southern Thailand. Mar. Geol. 179, 85–103.
Alongi, D.M., 2002. Present state and future of the world's mangrove forests. Environ. Conserv. 29, 331–349.
Alongi, D.M., Sasekumar, A., Chong, V.C., Pfitzner, J., Trott, L.A., Tirendi, F., Dixon, P., Brunskill, G.J., 2004. Sediment accumulation and organic material flux in a managed mangrove ecosystem: estimates of land-ocean-atmosphere exchange in peninsular Malaysia. Mar. Geol. 208, 383–402.
Alongi, D.M., Pfitzner, J., Trott, L.A., Tirendi, F., Dixon, P., Klumpp, D.W., 2005. Rapid sediment accumulation and microbial mineralization in forests of the mangrove Kandelia candel in the Jiulongjiang Estuary, China. Estuarine. Coast. Shelf Sci. 63, 605–618.
Alongi, D.M., 2012. Carbon sequestration in mangrove forests. Carbon Manag. 3, 313–322.
Alongi, D.M., 2014. Carbon cycling and storage in mangrove forests. Annu. Rev. Mar. Sci. 6, 195–219.
Amira, S., 2008. Pendugaan biomass jenis *Rhizophora apiculata* di hutan mangrove Batu Ampar, Kabupaten Kubu Raya, Kalimantan Barat. Institut Pertanian Bogor, pp. 1–76.
Appleby, P.G., Oldfield, F., 1983. The assessment of ^{210}Pb data from sites with varying sediment accumulation rates. Hydrobiologia 103, 29–35.
Ardli, E.R., Wolff, M., 2009. Land use and land cover change affecting habitat distribution in the Segara Anakan lagoon, Java, Indonesia. Reg. Environ. Change 9, 235–243.
Bengen, D.G., 2003. Teknik Pengambilan Contoh Dan Analisis Data Biofisik Sumberdaya Pesisir - Sinopsis. Pusat Kajian Sumberdaya Pesisir dan Lautan.
Benson, L., Glass, L., Jones, T.G., Ravaoarinorotsihoarana, L., Rakotomahazo, C., 2017. Mangrove carbon stocks and ecosystem cover dynamics in southwest Madagascar and the implications for local management. Forests 8, 1–21.
Bouillon, S., Rao, a V.V.S., Koedam, N., Dehairs, F., 2003. Sources of organic carbon in mangrove sediments: variability. Hydrobiologia 495, 33–39.
Bouillon, S., Borges, A.V., Castañeda-Moya, E., Diele, K., Dittmar, T., Duke, N.C., Kristensen, E., Lee, S.Y., Marchand, C., Middelburg, J.J., Rivera-Monroy, V.H., Smith, T.J., Twilley, R.R., 2008. Mangrove production and carbon sinks: a revision of global budget estimates. Global Biogeochem. Cycles 22, 1–12.
Brunskill, G.J., Zagorskis, I., Pfitzner, J., 2002. Carbon burial rates in sediments and a carbon mass balance for the Herbert River region of the Great Barrier Reef continental shelf, North Queensland, Australia. Estuar. Coast Shelf Sci. 54, 677–700.
Brunskill, G.J., Zagorskis, I., Pfitzner, J., Ellison, J., 2004. Sediment and trace element depositional history from the Ajkwa River estuarine mangroves of Irian Jaya (west Papua), Indonesia. Cont. Shelf Res. 24, 2535–2551.
Callaway, J.C., DeLaune, R.D., Patrick Jr., W.H., 1997. Sediment accretion rates from four coastal wetlands along the Gulf of Mexico. J. Coast Res. 13, 181–191.
Chen, R., Twilley, R.R., 1999. A simulation model of organic matter and nutrient accumulation in mangrove wetland soils. Biogeochemistry 44, 93–118.
Chmura, G.L., Anisfeld, S.C., Cahoon, D.R., Lynch, J.C., 2003. Global carbon sequestration in tidal, saline wetland soils. Global Biogeochem. Cycles 17. https://doi.org/10.1029/2002GB001917.
Clough, B.F., Scott, K., 1989. Allometric relationships for estimating above-ground biomass in six mangrove species. For. Ecol. Manag. 27, 117–127.
Damar, A., 2003. Effects of Enrichment on Nutrient Dynamics, Phytoplankton Dynamics and Productivity in Indonesian Tropical Waters: A Comparison Between Jakarta Bay, Lampung Bay and Semangka Bay. Math. Fak. der Christian-Albrechts-Universität zu Kiel 249 pp.
Donato, D.C., Kauffman, J.B., Murdiyarso, D., Kurnianto, S., Stidham, M., Kanninen, M., 2011. Mangroves among the most carbon-rich forests in the tropics. Nat. Geosci. 4, 293–297.
Duarte, C.M., Middelburg, J.J., Caraco, N., 2004. Major role of marine vegetation on the oceanic carbon cycle. Biogeosciences 2 (1), 1–8.
Ellison, J.C., 1999. Impacts of sediment burial on mangroves. Mar. Pollut. Bull. 37, 420–426.
Fromard, F., Puig, H., Mougin, E., Marty, G., Betoulle, J.L., Cadamuro, L., 1998. Structure, above-ground biomass and dynamics of mangrove ecosystems: new data from French Guiana. Oecologia 115, 39–53.
Fry, B., 2006. Stable Isotope Ecology. Springer, New York 308 pp.
Gharibreza, M., Raj, J.K., Yusoff, I., Othman, Z., Tahir, W.Z.W.M., Ashraf, M.A., 2013. Sedimentation rates in Bera lake (peninsular Malaysia) using ^{210}Pb and ^{137}Cs radioisotopes. Geosci. J. 17 (2), 211–220.
Giri, C., Ochieng, E., Tieszen, L.L., Zhu, Z., Singh, A., Loveland, T., Masek, J., Duke, N., 2011. Status and distribution of mangrove forests of the world using earth observation satellite data. Global Ecol. Biogeogr. 20, 154–159.
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. Estuar. Coast Shelf Sci. 61, 211–227.
Grellier, S., Janeau, J., Nhon, D.H., Cuc, N.T.K., Quynh, L.T.P., Thao, P.T.T., Nhu-Trang, T.T., Marchand, C., 2017. Changes in soil characteristics and C dynamics after mangrove clearing (Vietnam). Sci. Total Environ. 593–594.
Gordon, A.L., 2005. Oceanography of Indonesian seas. Oceanography 8 (14), 14–27.
Herbon, C.M., Nordhaus, I., 2013. Experimental determination of stable carbon and nitrogen isotope fractionation between mangrove leaves and crabs. Mar. Ecol. Prog. Ser. 490, 91–105.
Herrera-Silveira, J.A., Morales-Ojeda, S.M., 2010. Subtropical karstic coastal lagoon assessment, Southeast Mexico: the Yucatan peninsula case. In: Kennish, M.J., Paerl, H.E. (Eds.), Coastal Lagoons - Critical Habitats of Environmental Change. CRC Press, Boca Raton, pp. 307–333.
Hinrichs, S., Nordhaus, I., Geist, S.J., 2009. Status, diversity and distribution patterns of mangrove vegetation in the Segara Anakan lagoon, Java, Indonesia. Reg. Environ. Change 9, 275–289.
Hoekstra, P., Hoitink, T., Buschman, F., Tarya, A., Van den Bergh, G., 2007. From river basin to barrier reef: pathways of coastal sediments. In: Coastal Sediments '07 - Proceedings of 6th International Symposium on Coastal Engineering and Science of Coastal Sediment Processes. American Society of Civil Engineers, New Orleans, Louisiana, United States, pp. 1647–1659.
Holtermann, P., Burchard, H., Jennerjahn, T.C., 2009. Hydrodynamics of the Segara Anakan lagoon. In: In: Jennerjahn, T.C., Yuwono, E. (Eds.), Segara Anakan, Java, Indonesia, a Mangrove-fringed Coastal Lagoon Affected by Human Activities, Special Issue, Regional Environmental Change, vol. 9. pp. 259–274.
Huxham, M., Langat, J., Tamooh, F., Kennedy, H., Mencuccini, M., Skov, M.W., Kairo, J., 2010. Decomposition of mangrove roots: effects of location, nutrients, species identity and mix in a Kenyan forest. Estuar. Coast. Shelf Sci. 88, 135–142.
Jennerjahn, T.C., Ittekkot, V., 2002. Relevance of mangroves for the production and deposition of organic matter along tropical continental margins. Naturwissenschaften 89, 23–30.
Jennerjahn, T.C., Ittekkot, V., Klöpper, S., Adi, S., Purwo Nugroho, S., Sudiana, N., Yusmal, A., Prihartanto, Gaye-Haake, B., 2004. Biogeochemistry of a tropical river affected by human activities in its catchment: Brantas River estuary and coastal waters of Madura Strait, Java, Indonesia. Estuar. Coast Shelf Sci. 60, 503–514.
Jennerjahn, T.C., Yuwono, E., 2009. Editorial. In: In: Jennerjahn, T.C., Yuwono, E. (Eds.), Segara Anakan, Java, Indonesia, a Mangrove-fringed Coastal Lagoon Affected by Human Activities, Special Issue, Regional Environmental Change, vol. 9. pp. 231–233.
Jennerjahn, T.C., Nasir, B., Pohlenga, I., 2009. Spatio-temporal variation of dissolved inorganic nutrients in the Segara Anakan lagoon, Java, Indonesia. In: In: Jennerjahn, T.C., Yuwono, E. (Eds.), Segara Anakan, Java, Indonesia, a Mangrove-fringed Coastal Lagoon Affected by Human Activities, Special Issue, Regional Environmental Change, vol. 9. pp. 259–274.
Jennerjahn, T.C., Gilman, E., Krauss, K.W., Lacerda, L.D., Nordhaus, I., Wolanski, E., 2017. Chapter 7: mangrove ecosystems under climate change. In: Rivera-Monroy, V., Lee, S.Y., Kristensen, E., Twilley, R.R. (Eds.), Mangrove Ecosystems: a Global Biogeographic Perspective – Structure, Function and Services. Springer Publishing Company, New York, pp. 211–244.
Kauffman, J.B., Cole, T.G., 2010. Micronesian mangrove forest structure and tree responses to a severe typhoon. Wetlands 30, 1077–1084.
Kauffman, J.B., Heider, C., Cole, T.G., Dwire, K.A., Donato, D.C., 2011. Ecosystem carbon stocks of micronesian mangrove forests. Wetlands 31, 343–352.
Kauffman, J.B., Heider, C., Norfolk, J., Payton, F., 2014. Carbon stocks of intact mangroves and carbon emissions arising from their conversion in the Dominican Republic. Ecol. Appl. 24, 518–527.
Khan, N.S., Vane, C.H., Horton, B.P., 2015. Chapter 20 Stable Carbon Isotope and C/ N Geochemistry of Coastal Wetland Sediments as a Sea-Level Indicator. Handbook of Sea Level Research. pp. 295–311.
Komiyama, A., Poungparn, S., Kato, S., 2005. Common allometric equations for estimating the tree weight of mangroves. J. Trop. Ecol. 21, 471–477.
Kristensen, E., 2000. Organic matter diagenesis at the oxic/anoxic interface in coastal marine sediments, with emphasis on the role of burrowing animals. Hydrobiologia 426, 1–24.
Kristensen, E., Bouillon, S., Dittmar, T., Marchand, C., 2008. Organic carbon dynamics in mangrove ecosystems: a review. Aquat. Bot. 89, 201–219.
Kuramoto, T., Minagawa, M., 2001. Stable carbon and nitrogen isotopic characterization of organic matter in a mangrove ecosystem on the Southwestern coast of Thailand. J. Oceanogr. 57, 421–431.
Kusumaningtyas, M.A., 2017. Spatial Variation of Organic Carbon Stocks and Sources in

Indonesian Mangrove Ecosystems. MSc Thesis. University of Bremen 56 pp.

Kusumaningtyas, M.A., Hutahaean, A.A., Fischer, H.W., Pérez-Mayo, M., Ransby, D., Jennerjahn, T.C., 2018. In: Carbon, Nitrogen and Stable Carbon Isotopes, and Radionuclides in Sediment Cores from Segara Anakan Lagoon, Berau and Kongsi Island, Indonesia, 2013 and 2016, PANGAEA. https://doi.pangaea.de/10.1594/PANGAEA.896852.

Lukas, M.C., 2017. Widening the scope: linking coastal sedimentation with watershed dynamics in Java, Indonesia. Reg. Environ. Change 17, 901–914.

Lynch, J.C., Meriwether, J.R., McKee, B.A., Vera-Herrera, F., Twilley, R.R., 1989. Recent accretion in mangrove ecosystems based on ^{137}Cs and ^{210}Pb. Estuaries 12, 284–299.

Marchand, C., 2017. Soil carbon stocks and burial rates along a mangrove forest chronosequence (French Guiana). For. Ecol. Manag. 384, 92–99.

Meyers, P.A., 1994. Preservation of elemental and isotopic source identification of sedimentary organic matter. Chem. Geol. 114, 289–302.

Middleton, B.A., McKee, K.L., 2001. Degradation of mangrove tissues and implications for peat formation in Belizean island forests. J. Ecol. 89, 818–828.

Milliman, J.D., Farnsworth, K.L., 2011. River Discharge to the Coastal Ocean – a Global Synthesis. Cambridge University Press, Cambridge.

Murdiyarso, D., Donato, D., Kauffman, J.B., Kurnianto, S., Stidham, M., Kanninen, M., 2009. Carbon Storage in Mangrove and Peatland Ecosystems: a Preliminary Account from Plots in Indonesia. CIFOR 35 pp.

Murdiyarso, D., Purbopuspito, J., Kauffman, J.B., Warren, M.W., Sasmito, S.D., Donato, D.C., Manuri, S., Krisnawati, H., Taberima, S., Kurnianto, S., 2015. The potential of Indonesian mangrove forests for global climate change mitigation. Nat. Clim. Change 5, 1089–1092.

Nellemann, C., Corcoran, E., Duarte, C.M., Valdés, L., De Young, C., Fonseca, L., Grimsditch, G., 2009. Blue carbon: the role of healthy ocean in binding carbon. In: A Rapid Response Assessment. United Nations Environment Programme, GRID-Arendal.

Noor, Y.R., Khazali, M., Suryadiputra, I.N.N., 1999. Panduan Pengenalan Mangrove di Indonesia. PHKA/Wetland International-Indonesia Programme, Bogor.

Nordhaus, I., Salewski, T., Jennerjahn, T.C., 2017. Interspecific variations in mangrove leaf litter decomposition are related to labile nitrogenous compounds. Estuar. Coast Shelf Sci. 192, 137–148.

Nordhaus, I., Toben, M., Fauziyah, A., 2018. Impact of deforestation on mangrove tree diversity, biomass and community dynamics in the Segara Anakan lagoon, Indonesia: a ten-year perspective. Estuar. Coast. Shelf Sci.

Parnell, A.C., Inger, R., Bearhop, S., Jackson, A.L., 2010. Source partitioning using stable isotopes: coping with too much variation. PLoS One 5 (3).

Pendleton, L., Donato, D.C., Murray, B.C., Crooks, S., Jenkins, W.A., Sifleet, S., Craft, C., Fourqurean, J.W., Kauffman, J.B., Marbà, N., Megonigal, P., Pidgeon, E., Herr, D., Gordon, D., Baldera, A., 2012. Estimating global "blue carbon" emissions from conversion and degradation of vegetated coastal ecosystems. PLoS One 7.

Pérez, A., Machado, W., Gutierrez, D., Stokes, D., Sanders, L., Smoak, J.M., Santos, I., Sanders, C.J., 2017. Changes in organic carbon accumulation driven by mangrove expansion and deforestation in a New Zealand estuary. Estuar. Coast Shelf Sci. 192, 108–116.

Phang, V.X.H., Chou, L.M., Friess, D.A., 2015. Ecosystem carbon stocks across a tropical intertidal habitat mosaic of mangrove forest, seagrass meadow, mudflat and sandbar. Earth Surf. Process. Landforms 40, 1387–1400.

Pittauerová, D., Hettwig, B., Fischer, H.W., 2011. Pb-210 sediment chronology: focused on supported lead. Radioprotection 46 (6), 277–282.

Pittauerová, D., Kirchner, G., Garbe-Schönberg, D., Herut, B., Nishri, A., Fischer, H.W., 2014. Radionuclides and recent sedimentation and mixing rates in northern Gulf of Eilat/Aqaba, Red Sea. J. Mar. Syst. 139, 1–8.

Ranjan, R.K., Routh, J., Ramanathan, A.L., Klump, J.V., 2011. Elemental and stable isotope records of organic matter input and its fate in the Pichavaram mangrove-estuarine sediments (Tamil Nadu, India). Mar. Chem. 126, 163–172.

Ray, R., Ganguly, D., Chowdhury, C., Dey, M., Das, S., Dutta, M.K., Mandal, S.K., Majumder, N., De, T.K., Mukhopadhyay, S.K., Jana, T.K., 2011. Carbon sequestration and annual increase of carbon stock in a mangrove forest. Atmos. Environ. 45, 5016–5024.

R Core Team, 2017. R: a Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria. http://www.R-project.org/ Accessed Dec 2017.

Robertson, A.I., Alongi, D.M., 2016. Massive turnover rates of fine root detrital carbon in tropical Australian mangroves. Oecologia 180, 841–851.

Rovai, A.S., Twilley, R.R., Castañeda-Moya, E., Riul, P., Cifuentes-Jara, M., Manrow-Villalobos, M., Horta, P.A., Simonassi, J.C., Fonseca, A.L., Pagliosa, P.R., 2018. Global controls on carbon storage in mangrove soils. Nat. Clim. Change 8, 534–538.

Saintilan, N., Rogers, K., Mazumder, D., Woodroffe, C., 2013. Allochthonous and autochthonous contributions to carbon accumulation and carbon store in southeastern Australian coastal wetlands. Estuar. Coast Shelf Sci. 128, 84–92.

Salim, H.L., Ahmad, 2013. Karakteristik pantai gugusan pulau Pari. Region 5 (1), 1–11.

Sanchez-Cabeza, J.A., Ruiz-Fernández, A.C., 2012. ^{210}Pb sediment radiochronology: an integrated formulation and classification of dating models. Geochem. Cosmochim. Acta 82, 183–200.

Sanders, C.J., Smoak, J.M., Sathy Naidu, A., Patchineelam, S.R., 2008. Recent sediment accumulation in a mangrove forest and its relevance to local sea-level rise (Ilha Grande, Brazil). J. Coast Res. 24, 533–536.

Sanders, C.J., Smoak, J.M., Naidu, A.S., Sanders, L.M., Patchineelam, S.R., 2010a. Organic carbon burial in a mangrove forest, margin and intertidal mud flat. Estuar. Coast Shelf Sci. 90, 168–172.

Sanders, C.J., Smoak, J.M., Sathy Naidu, A., Araripe, D.R., Sanders, L.M., Patchineelam, S.R., 2010b. Mangrove forest sedimentation and its reference to sea level rise, Cananeia, Brazil. Environ. Earth Sci. 60, 1291–1301.

Sanders, C.J., Smoak, J.M., Sanders, L.M., Sathy Naidu, A., Patchineelam, S.R., 2010c. Organic carbon accumulation in Brazilian mangal sediments. J. S. Am. Earth Sci. 30, 189–192.

Sanders, C.J., Eyre, B.D., Santos, I.R., Machado, W., Luiz-silva, W., Smoak, J.M., Breithaupt, J.L., Kettere, M.E., Sanders, L., Marotta, H., Silva-Filho, E., 2014. Elevated rates of organic carbon, nitrogen, and phosphorus accumulation in a highly impacted mangrove wetland. Geophys. Res. Lett. 41, 2475–2480.

Sarma, V.V.S.S., Krishna, M.S., Prasad, V.R., Kumar, B.S.K., Naidu, S.A., Rao, G.D., Viswanadham, R., Sridevi, T., Kumar, P.P., Reddy, N.P.C., 2014. Distribution and sources of particulate organic matter in the Indian monsoonal estuaries during monsoon. J. Geophy. Res. Biogeosci. 119, 2095–2111.

Sidik, F., Neil, D., Lovelock, C.E., 2016. Effect of high sedimentation rates on surface sediment dynamics and mangrove growth in the Porong River, Indonesia. Mar. Pollut. Bull. 107, 355–363.

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

Smith, B.N., Epstein, S., 1971. Two categories of 13C/12C ratios for higher plants. Plant Physiol. 47, 380–384.

Smoak, J.M., Breithaupt, J.L., Smith III, T.J., Sanders, C.J., 2013. Sediment accretion and organic carbon burial relative to sea-level rise and storm events in two mangrove forests in Everglades National Park. Catena 104, 58–66.

Sun, L., 2011. Study on Carbon Storage of Subtropical Broad-leaved Forest Ecosystem in the Pearl River Delta. Sun Yat-Sen University.

Tarlan, M.A., 2008. Biomass estimation of nyirih (*Xylocarpus granatum* Koenig. 1784). In: Primary Mangrove Forest in Batu Ampar, West Kalimantan. Institut Pertanian Bogor, Indonesia.

Tateda, Y., Nhan, D.D., Wattayakorn, G., Toriumi, H., 2005. Preliminary evaluation of organic carbon sedimentation rates in Asian mangrove coastal ecosystems estimated by ^{210}Pb chronology. Radioprotection 40, S527–S532.

Thom, B.G., 1982. Mangrove ecology: a geomorphological perspective. In: Clough, B.F. (Ed.), Mangrove Ecosystems in Australia: Structure, Function and Management. Australia National University Press, Canberra, pp. 3–17.

Tomascik, T., Mah, A.J., Nontji, A., Moosa, M.K., 1997. The Ecology of the Indonesian Seas VIII part II Periplus, Singapore.

Tue, N.T., Dung, L.V., Nhuan, M.T., Omori, K., 2014. Carbon storage of a tropical mangrove forest in Mui Ca Mau National Park, Vietnam. Catena 121.

Twilley, R.R., Chen, R.H., Hargis, T., 1992. Carbon sinks in mangroves and their implications to carbon budget of tropical coastal ecosystems. In: Natural Sinks of CO_2. Springer Netherlands, Dordrecht, pp. 265–288.

Tyson, R.V., 1995. Sedimentary Organic Matter: Organic Facies and Palynofacies. Chapman & Hall, London.

Valiela, I., Bowen, J.L., York, J.K., 2001. Mangrove forest: one of the most threatened major tropical environments. Bioscience 51, 807–815.

Wang, G., Guan, D., Peart, M.R., Chen, Y., Peng, Y., 2013. Ecosystem carbon stocks of mangrove forest in Yingluo Bay, Guangdong Province of south China. For. Ecol. Manag. 310, 539–546.

Watanabe, K., Kuwae, T., 2015. How organic carbon derived from multiple sources contributes to carbon sequestration processes in a shallow coastal system? Global Change Biol. 21, 2612–2623.

Weiss, C., Weiss, J., Boy, J., Iskandar, I., Mikutta, R., Guggenberger, G., 2016. Soil organic carbon stocks in estuarine and marine mangrove ecosystems are driven by nutrient colimitation of P and N. Ecol. Evol. 6, 5043–5056.

Wiryawan, B., Khazali, M., Knight, M. (Eds.), 2005. Menuju Kawasan Konservasi Laut Berau, Kalimantan Timur: Status Sumberdaya Pesisir dan Proses Pengembangannya. Program Bersama Kelautan Berau TNC-WWF-Mitra Pesisir/CRMP II USAID, Jakarta, pp. 128.

Whitten, T., Soeriaatmadja, R.E., Afiff, S.A., 2000. The Ecology of Java and Bali. The Ecology of Indonesien Series, vol. II. Periplus Editions (HK) Ltd., pp. 387–412.

Woodroffe, C.D., 1992. Mangrove sediments and geomorphology. In: Robertson, A.I., Alongi, D.M. (Eds.), Tropical Mangrove Ecosystems. American Geophysical Union, Washington, DC, pp. 7–41.

Woodroffe, C.D., Rogers, K., McKee, K.L., Lovelock, C.E., Mendelssohn, I. a., Saintilan, N., 2016. Mangrove sedimentation and response to relative sea-level rise. Annu. Rev. Mar. Sci. 8, 243–266.

World Agroforestry Center, 2017. Wood density. http://www.dbworldagroforestry.org.

Yang, J., Gao, J., Liu, B., Zhang, W., 2014. Sediment deposits and organic carbon sequestration along mangrove coasts of the Leizhou Peninsula, southern China. Estuarine. Coast. Shelf Sci. 136, 3–10.

Yuwono, E., Jennerjahn, T.C., Nordhaus, I., Riyanto, E.A., Sastranegara, M.H., Pribadi, R., 2007. Ecological Status of Segara Anakan , Indonesia : a mangrove-fringed lagoon affected by human activities. Asian J. Water Environ. Pollut. 4, 61–70.