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ORIGINAL PAPER

The Sources of Organic Matter in Seagrass Sediments and Their Contribution to Carbon Stocks in the Spermonde Islands, Indonesia

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Abstract
Seagrass ecosystems have a potential role in climate change mitigation due to their ability to store high amount of carbon, particularly in the sediment. Studying the factors and mechanisms responsible for this storing capacity is essential to understand seagrass carbon sink function. Therefore, in this study, we identified the sources of organic carbon (C_{org}) in seagrass sediments and the implication to C_{org} stocks from four islands in the Spermonde Islands that located at different zones. We used the Bayesian stable isotope mixing model to estimate the proportional contribution of different sources to sediment carbon. Seagrass meadows that located in adjacent to high anthropogenic activities (deforestation and aquacultures) with direct exposure to wave actions, such as on the Bauluang Island, accumulated organic carbon that derived from multiple sources, where phytoplankton contributed the highest, while on the other three islands that are relatively protected from wave actions, the highest contribution (~75%) was from autochthonous production (seagrass-derived). Sediment C_{org} stocks vary spatially, ranging from 11.9 to 32.1 Mg C ha^{-1} (based on the obtained depth of 20–55 cm), or 40.5 to 83.5 Mg C ha^{-1} if extrapolated to 1 m depth. The variability of sediment properties and C_{org} stocks in this study is not solely determined by the geographical differences (inshore, nearshore and offshore islands), but also influenced by other local factors such as hydrodynamics that control the distribution of carbon sources, anthropogenic pressures and species composition. These factors should be taken into account when developing coastal management strategies, as efforts are being undertaken to include coastal ecosystems (including seagrass ecosystems) on the National Green House Gasses Reduction Strategy.

Keywords Seagrass · C_{org} stocks · Carbon sources · Spermonde Islands · Stable isotope

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1 Introduction

Seagrass meadows are one of the most important habitats in the coastal waters along with mangrove ecosystems and coral reefs. They form dense beds that cover a very wide area, particularly found in the shallow waters (Green and Short 2003). Despite account for less than 0.2% of the global ocean, seagrass ecosystems are highly productive and provide important services that support the overall functions of coastal ecosystems (Duarte and Chiscano 1999; Fourqurean et al. 2012a). They perform a wide spectrum of biological and physical functions, providing a feeding and nursery ground for various fishes and biota, including some charismatic and endangered animals such as dugongs, manatees and green sea turtles (Hemminga and Duarte 2000; Hutomo and Moosa 2005; Hogarth 2007).

One of the important functions of seagrass for climate change mitigation is their role as a natural carbon sink due to their ability to sequester and store high amount of carbon within a millennium timescale (Duarte et al. 2005; Kennedy et al. 2010; Fourqurean et al. 2012a). Globally, seagrass ecosystems can store up to 19.8 Pg carbon (Fourqurean et al. 2012a), which is comparable to that of mangrove ecosystems that store up to 20 Pg carbon (Donato et al. 2011). A considerable amount of organic carbon is stored at the belowground pool/sediment, with the rate of carbon burial up to 186 g C m^{-2} $year^{-1}$ (Duarte et al. 2005). This rate is much higher compared to that of terrestrial forests (Mcleod et al. 2011). The organic carbon that accumulates seagrass sediment derived from various sources (Kennedy et al. 2010). In some meadows, autochthonous organic matter (OM) such as seagrass litter (leaves and roots) and epiphytes may dominate on carbon burial, while in some other meadows, allochthonous OM (such as terrestrial plants, phytoplankton and seston) may dominate over autochthonous OM on carbon burial, particularly found in the areas located in adjacent to mangrove ecosystems, estuaries or in the enclosed bays (Kennedy et al. 2004, 2010; Dubois et al. 2012; Miyajima et al. 2015). These organic carbon sources differ in their persistence in the sediment stock (Holmer et al. 2004). Seagrass roots, for instance, are considered as an important autochthonous organic matter due to their high turn over rate coupled with the low decomposition rate. This is partly because seagrass roots generally contain a lower nutrient concentration than leaves, thus being less consumed and remain intact in the sediment (Kennedy and Björk 2009). In contrast, algal-derived organic matter is more labile and readily utilized by heterotrophic bacteria (Ghosh and Leff 2013). Given the important contribution of seagrass ecosystems in climate change mitigation, identification of organic carbon sources is therefore essential for evaluating the effectiveness of seagrass carbon sink.

The Indonesian seagrass ecosystems are one of the largest in the world (Green and Short 2003), where 15 seagrass species are reported existing in its waters (Hernawan et al. 2017). Critically, within the last decades, this ecosystem is continuously declining due to disturbances mainly from land conversion and eutrophication (Rahmawati 2011; Nadiarti et al. 2012). These disturbances can cause the release of stored carbon to the atmosphere and thus change seagrass role from being carbon sink to carbon source (Pendleton et al. 2012). Research about seagrass carbon sink capacity in Indonesia is still in its infancy. Based on some limited studies, the amount of seagrass carbon stocks from different areas in Indonesia are reported to vary between 0.2 and 2.3 Mg C ha^{-1} for biomass and up to 100 Mg C ha^{-1} for sediment depending on the obtained depth of sediment (Rustam et al. 2014; Supriadi et al. 2014; Graha et al. 2016; Indriani and Yona 2017; Irawan 2017; Rustam et al. 2017). The variability of seagrass carbon stocks is determined by various factors such as geomorphology (meadows landscape), hydrodynamics (tidal, wave energy and water depth) and environmental changes (e.g., seasonal dynamics), which affect the distribution of organic matter and biogeochemical processes (Mateo et al. 2006; Kennedy et al. 2010; Lavery et al. 2013; Ricart et al. 2015). Hence, the lack of information regarding the mechanisms responsible for the variability of seagrass carbon storage may lead to the uncertainties in seagrass carbon sink capacity. Study of it, therefore, would be most valuable to understand carbon sink capacity of seagrass ecosystems. Here, we identified the sources of sediment organic carbon and analyzed their contribution to organic carbon stocks in seagrass ecosystems from the Spermonde Islands, which cover areas of inshore, nearshore and offshore islands. To our knowledge, this study is among the first investigation of organic carbon sources in seagrass sediment to be reported from the Indonesian seagrass ecosystem.

1.1 Field Setting

The Spermonde Islands sit on the Spermonde Shelf situated on the west coast of South Sulawesi, Indonesia. The islands are coral reef complexes located in the Makassar Strait with a north–south trend direction following the shoreline of South Sulawesi (Imran et al. 2013). They lie off the coast from the city of Makassar, a highly urbanized and industrialized area with a total population of 1.7 million people (Teichberg et al. 2018).

The regional oceanography of the Spermonde Islands is significantly influenced by the ITF (the Indonesian Throughflow) which flows warm nutrient-rich mass water of the Pacific Ocean to the Indian Ocean through the Makassar Strait and the bidirectional wind system of the monsoons (west and east). During the northwest monsoons (December to March), the strong current of the ITF flows to the south through the shallow platform of the Spermonde Islands and is deflected eastward to the Banda Sea along the southwest coast of Sulawesi (Jompa 1996). During the southwest monsoon (June to August), the pattern is reversed releasing the weak current of the ITF through the Spermonde Island and is diverted to the west direction (Moll 1984).

The Spermonde Islands contain more than a hundred small coral islands, where most of the islands are populated, and seagrass meadows occupy most of the reef flat area in each island (Ambo-Rappe 2014). The seagrass species found in the Spermonde Islands are, in estimated order of abundance (Rustam et al. 2017): *Enhalus acoroides, Thalassia hemprichii, Halophila decipiens, Halophila ovalis, Cymodocea rotundata, Halodule uninervis, Halodule pinifolia* and *Syringodium isoetifolium*.

2 Methodology

2.1 Sampling Design

Field surveys were conducted at four islands in the Spermonde Islands including the Bauluang Island, the Barranglompo Island, the Sarappokeke Island and the Kapoposang Island in October 7–18, 2015 (during rainy season). Seagrasses in these islands grow in a carbonate-rich setting. Study sites (Fig. 1) were selected purposely to ensure a spatially representative record of seagrass sediment carbon distribution which characterize three different zones including middle inner zone (the Bauluang and Barranglompo Islands), middle outer zone (the Sarappokeke Island) and outer zone (the Kapoposang Island). The zonation is based on the distance to the mainland (Moll 1984; Hoeksema 1990, 2012).

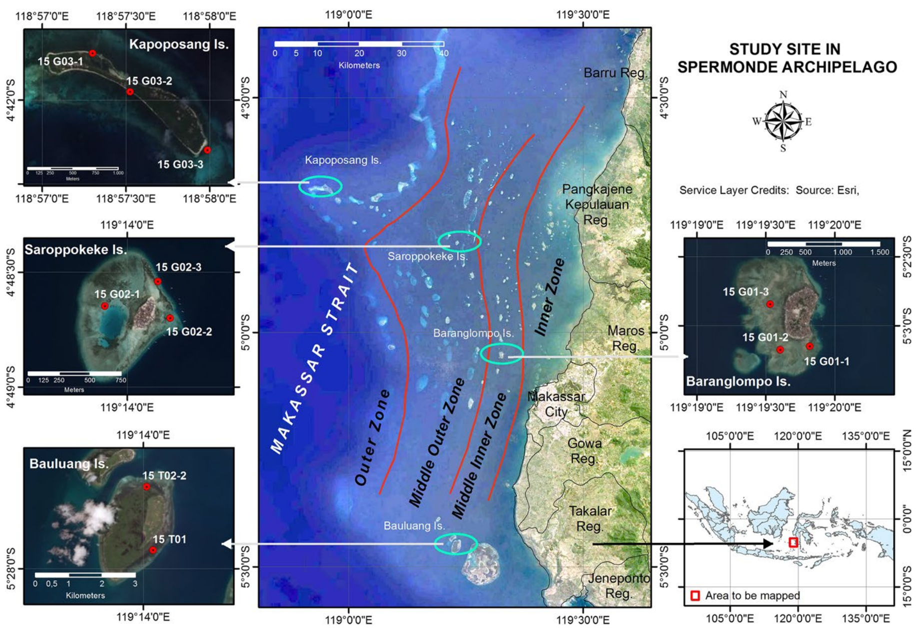

Fig. 1 Study site in the Spermonde Islands showing the zonation of the Spermonde Shelf and the sites selection of sediment sampling (red dot)

Sediments were obtained by an AMS gouge auger core. A total of 11 sediment cores were collected from seagrass meadows on the Bauluang Island (2 cores), the Barranglompo Island (3 cores), the Sarappokeke Island (3 cores) and the Kapoposang Island (3 cores), with core penetration ranging from 20 to 55 cm. At each core, a 5-cm-interval sediment from the base to the top of the core was sampled and stored in the sample container (cool box) with labels for further analysis.

2.2 Analytical Method

2.2.1 Laboratory Analysis

All sediment samples were subsequently analyzed for total carbon (C) content, organic carbon (C_{org}) content, total nitrogen (N) content, as well as stable isotope compositions ($\delta^{13}C_{org}$ and $\delta^{15}N$). The analysis was conducted at the Leibniz-Zentrum für Marine Tropenforschung Laboratory, Bremen, Germany. All samples were grinded to fine powder and then flash-combusted in a CN analyzer (Eurovector EA3000 Elemental Analyzer) to obtain the total C content, total N content and C_{org} content. For C_{org} content measurement, carbonate was first removed by acidification with hydrochloric acid. The stable isotope compositions were measured using the Finnigan Deltaplus mass spectrometer coupled to a Carlo Erba Flash EA1112 Elemental Analyzer. The data were expressed in a conventional delta (δ) notation, where the isotopic ratio of $^{15}N/^{14}N$ was expressed relative to Air and the isotopic ratio of $^{13}C/^{12}C$ was expressed relative to the international VPDB standard as defined below:

$$\delta(‰) = \left[\left(\mathrm{Ratio}_{\mathrm{sample}} - \mathrm{Ratio}_{\mathrm{standards}}\right)/\left(\mathrm{Ratio}_{\mathrm{standards}}\right)\right] \times 1000$$

The accuracy of the instrument was checked by calculating the standards which resulted in standard deviations as follows: C = 0.037%, δ^{13}Corg = 0.069 ‰, δ^{15}N = 0.12 ‰.

2.2.2 The Bayesian Stable Isotope Mixing Model

Various organic matters have distinct isotopic composition. This natural isotopic variation occurs as a result of the different ways on how plants fix carbon during photosynthesis, which then divided plants into three main groups; C_3, C_4 and CAM plants (Smith and Epstein 1971; Fry 2006). Their individual contribution to sediment accumulation thus can be resolved through the measurement of their isotopic signatures, such as δ^{13}C and δ^{15}N (Hemminga and Mateo 1996; Gacia et al. 2002; Kennedy et al. 2004; Fry 2006). Some organic matter may have δ^{13}C signatures that overlap to each other, and may confound the interpretation. Therefore, in this study we combined $\delta^{13}C_{org}$ with C/N ratio to distinguish organic carbon in seagrass sediment.

To estimate the proportional contribution of different sources to seagrass sediment, we used the Bayesian Stable Isotope Mixing Model in R (simmr; Parnell and Inger 2016) that has been used elsewhere to estimate sources contribution in coastal ecosystems (Kusumaningtyas et al. 2019). The model uses the Markov chain Monte Carlo (MCMC) algorithm to determine the proportion of sources contribution while incorporating the uncertainties (e.g., isotope fractionation). We used four end members (organic matter that is incorporated in sediment) as potential sources, which are seagrass litter, mangrove detritus, terrestrial plants and coastal particulate organic matter (POM). The samples of seagrass leaves and POM were taken during field sampling, while references for mangrove detritus and terrestrial plants signatures were taken from the region-relevant literature. The reference for mangrove detritus (leaf litter and root) is from Segara Anakan, Indonesia (Herbon and Nordhaus 2013; Nordhaus et al. 2017), while reference for terrestrial plants is from Trang, Thailand (Kuramoto and Minagawa 2001).

2.2.3 Sediment Organic Carbon Stocks

Seagrass carbon stock refers to the amount of carbon stored in seagrass ecosystems, mainly in living biomass and sediment, but to a lesser extent also in dead wood and litter. The sediment organic carbon stock was calculated by multiplying sediment carbon density with sediment thickness (per 5-cm depth interval). The organic carbon (C_{org}) density was first determined by multiplying the sediment bulk density with organic carbon content at a specific depth. The sediment 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:

$$C_{org}\mathrm{stock}\,(\mathrm{Mg\,C\,ha^{-2}}) = C_{org}\mathrm{density}\left(\mathrm{g\,cm^{-3}}\right) * \mathrm{sediment\,thickness\,or\,depth\,interval\,(cm)}$$

The total sediment C_{org} stock from one core was determined by summing up the amount of C_{org} stock at all depth intervals from the obtained sample. Sediment C_{org} stocks were also extrapolated to 1 m depth to allow for an accurate and equal comparison to other studies.

2.2.4 Statistical Analysis

Difference of a single variable (C density, C_{org}, C/N, $\delta^{13}C_{org}$, δ^{15}N) by location, as well as by depth, was analyzed by using a one-way ANOVA. Prior to statistical analysis, the normality of data distribution was checked using Shapiro–Wilk test. If the data are not normally distributed, then some variables were log-transformed to fit the linear model. The analysis was performed in R programming (R Core Team 2017).

3 Results

3.1 Seagrass Sediment Properties in the Spermonde Islands

The mean values of elemental CN contents, C/N ratio, stable isotope compositions and dry bulk density at the study sites are presented in Table 1. Seagrass sediment on the Bauluang Island that located in the middle inner zone has the highest C_{org} content and C/N ratio, but has the lowest $\delta^{13}C_{org}$, $\delta^{15}N$ and dry bulk density. Statistically, based on the mean values of all these parameters (CN contents, C/N ratio, stable isotope compositions and dry bulk density), the Bauluang Island shares similarity of those parameters with the Barranglompo Island ($p=0.724$), the Sarappokeke Island ($p=0.717$) and the Kapoposang Island ($p=0.803$); however, the latter three islands are different to each other (all $p<0.05$) in CN contents, C/N ratio, stable isotope compositions and dry bulk density.

3.2 Seagrass Carbon Stocks in the Spermonde Islands

Biomass carbon stocks from this study had been reported in the previous article by Rustam et al. (2017), with the highest biomass carbon stock measured on the Bauluang Island (1.89 ± 0.92 Mg C ha^{-1}), followed by the Barranglompo Island (1.55 ± 0.37 Mg C ha^{-1}), the Kapoposang Island (1.31 ± 0.45 Mg C ha^{-1}) and the Sarappokeke Island (0.77 ± 0.35 Mg C ha^{-1}). For sediment C_{org} stocks, the highest was measured on the Kapoposang Island (32.1 ± 13.4 Mg C ha^{-1}) and the lowest was measured on the Sarappokeke Island (11.9 ± 5.3 Mg C ha^{-1}) based on the obtained depth of 20–55 cm (Table 2). If extrapolated to 1 m the range is 40.5 to 83.5 Mg C ha^{-1}. The higher sediment C_{org} stock resulted in the highest total C_{org} stock (biomass and sediment) on the Kapoposang Island, followed by the Bauluang Island, the Barranglompo Island and the Sarappokeke Island.

3.3 Downcore Profiles of Seagrass Sediment Properties in the Spermonde Islands

On the Barranglompo Island, the patterns of C density, C_{org} content, C/N and $\delta^{13}C_{org}$ tend to be stable downcore ($p=0.08$, 0.88, 0.35, 0.23, respectively), except for $\delta^{15}N$ which slightly decreases with depth ($p<0.05$; Fig. 2). The Kapoposang Island displays similar patterns with those of the Barranglompo Island which tend to be stable downcore (all $p>0.05$). On the Bauluang Island, the pattern of C density, C_{org} content and C/N tends to increase downcore, while both $\delta^{13}C_{org}$ and $\delta^{15}N$ decrease with depth (all $p<0.05$). On the Sarappokeke Island, C density, $\delta^{13}C_{org}$ and $\delta^{15}N$ do not vary with depth ($p=0.10$, 0.87, 0.65, respectively), while C_{org} content and C/N decrease with depth ($p=0.0027$, 0.0026, respectively).

Table 1 Mean values of total carbon, organic carbon, total nitrogen, C/N atomic, $\delta^{13}C_{org}$, $\delta^{15}N$ and dry bulk density (BD) from seagrass sediments in the Spermonde Islands

Zone	Site	C_{total} (%)	C_{org} (%)	N_{total} (%)	C/N	$\delta^{13}C_{org}$ (‰)	$\delta^{15}N$ (‰)	BD (g cm^{-3})
Middle inner	Barranglompo	11.8 ± 0.1	0.35 ± 0.04	0.04 ± 0.01	10.6 ± 1.0	− 12.3 ± 0.8	2.51 ± 0.29	1.15 ± 0.13
	Bauluang	12.1 ± 0.2	0.94 ± 0.37	0.08 ± 0.02	13.9 ± 6.0	− 20.2 ± 4.5	0.93 ± 0.43	0.76 ± 0.02
Middle outer	Sarappokeke	11.9 ± 0.1	0.38 ± 0.06	0.05 ± 0.01	9.7 ± 0.9	− 12.4 ± 0.5	2.29 ± 0.22	1.14 ± 0.06
Outer	Kapoposang	12.2 ± 0.1	0.78 ± 0.08	0.09 ± 0.04	9.8 ± 0.7	− 12.7 ± 0.9	1.03 ± 0.31	1.09 ± 0.15

Table 2 Mean C_{org} stocks (biomass and sediments) from seagrass ecosystems in the Spermonde Islands

Site	Biomass C_{org} stocks ± SD(*) Mg C ha^{-1}	Sediment C_{org} stocks ± SD Mg C ha^{-1}	Total C_{org} stocks Mg C ha^{-1}
Barranglompo	1.55 ± 0.37	18.8 ± 4.1	20.40
Bauluang	1.89 ± 0.92	20.3 ± 3.3	22.24
Sarappokeke	0.77 ± 0.35	11.9 ± 5.3	12.67
Kapoposang	1.31 ± 0.45	32.1 ± 13.4	33.49

(*)Rustam et al. (2017)

4 Discussion

4.1 Stable Isotopes Composition and C/N Ratio of End Member

Seagrass biomass (leaves and roots) that were collected in this study have an average $\delta^{13}C_{org}$ value of −8.04 ± 1.70 ‰ and CN ratio of 40.44 ± 21.96. The highest $\delta^{13}C_{org}$ was measured from species *S. isoetifolium* (−3.58 ‰ for leaves and −3.41 ‰ for roots; Table 3). The heavier seagrass $\delta^{13}C$ values in the open ocean compared to those of terrestrial plants (−28.2 ± 2.2 ‰; Kuramoto and Minagawa 2001) or mangrove plants (−28.9 ± 1.4 ‰; Herbon and Nordhaus 2013; Nordhaus et al. 2017) are partly related to their ability to use HCO_3^- (0 ‰) than dissolved CO_2 (−9 ‰) as carbon source (Hemminga and Mateo 1996; Beer et al. 2002). The seagrass $\delta^{13}C_{org}$ values from our study fall within the range of natural $\delta^{13}C$ values of seagrasses worldwide, which reported between −3.0 and −23.8 ‰ by Hemminga and Mateo (1996) or −4.8 to −19.6 ‰ by Kennedy et al. (2010) based on the compilation data from 88 locations around the world.

The average $\delta^{13}C$ value and CN ratio of POM (n = 25) in this study are −23.5 ± 0.95 ‰ and 5.83 ± 3.42, respectively. In some waters, POM contains phytoplankton as a major component which has a low C/N ratio of 5–7 (Redfield et al. 1963; Cifuentes et al. 1988). Variation of $\delta^{13}C$ occurs between freshwater and marine phytoplanktons. Freshwater phytoplankton has a lower $\delta^{13}C$ (−30 to −25 ‰) due to the uptake of isotopically light dissolved CO_2, while marine phytoplankton has a higher $\delta^{13}C$ (−24 to −18 ‰) due to the fixation of heavier HCO_3^- (Raven et al. 1993; Meyers 1994). The higher $\delta^{13}C_{org}$ value of POM in this study indicates that marine phytoplankton was a major contributor to POM. The POM $\delta^{13}C_{org}$ and CN ratio in this study resemble to previous report from the Phang Nga Bay, southern Thailand of −24.1 ± 0.06 ‰ and 6.85 ± 0.21, respectively (Gillis et al. 2014), but are lower than those reported from the Madura Strait waters of −19.9 ± 0.7 ‰ and 9.0 ± 1.4, respectively (Jennerjahn et al. 2004).

4.2 The Sources of Organic Matter

Based on the bi-plot of $\delta^{13}C_{org}$ and C/N ratio (Fig. 3), we found that organic carbon on the Barranglompo, Sarappokeke and Kapoposang Islands has similar characteristics. Organic carbon that accumulates seagrass sediment on these three islands is predominantly seagrass-derived, which contributes around 75% to sedimentary organic carbon (Fig. 4), implying that a significant amount of seagrass primary productions are buried in the sediment. The proportional contribution of seagrass to sediment carbon on

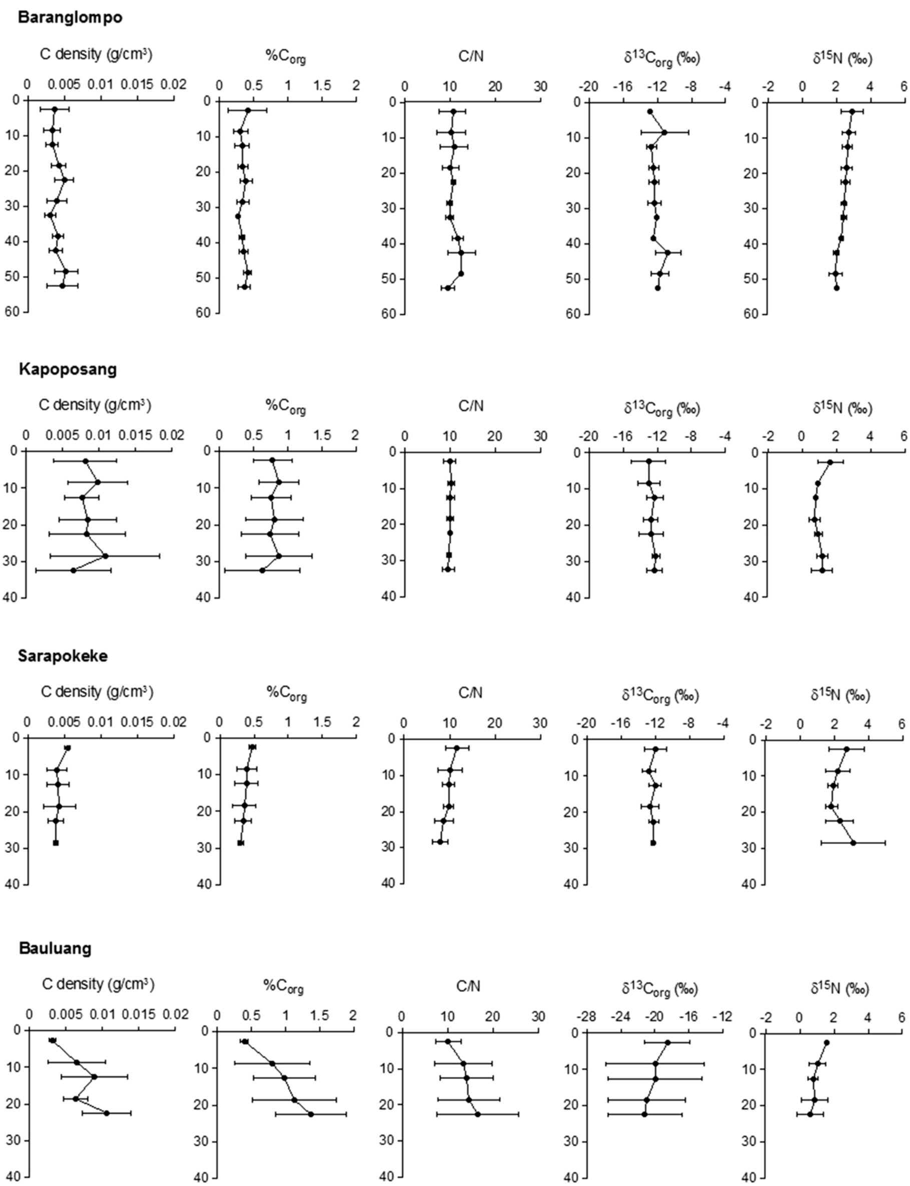

Fig. 2 Downcore profiles of seagrass sediment properties in the study sites

the Barranglompo Island is around 71–80% (median = 75%), on the Kapoposang Island is around 68–77% (median = 73%) and on the Sarappokeke Island is around 70–79% (median = 74%). Meanwhile, organic carbon that accumulates seagrass sediments on the Bauluang Island is predominantly derived from coastal POM, which contributes around 27–57% (median = 44%), while seagrass-derived OM contributes only 29%. The composition of organic carbon in seagrass sediments is the result of a combination of primary production or autochthonous production (seagrass detritus) and allochthonous inputs

Table 3 Stable isotope compositions ($\delta^{13}C_{org}$ and ^{15}N) of seagrasses from the study sites

Seagrass species	$\delta^{13}C_{org}$	$\delta^{15}N$
E. acoroides (*n* = 2)		
Leaves	− 6.89 ± 0.25	3.40 ± 0.39
Roots	− 6.54 ± 0.27	1.77 ± 0.58
T. hemprichii (*n* = 6)		
Leaves	− 7.86 ± 0.45	2.55 ± 0.99
Roots	− 7.87 ± 0.84	2.18 ± 0.87
H. uninervis (*n* = 2)		
Leaves	− 9.15 ± 0.99	3.44 ± 0.34
Roots	− 10.00 ± 0.99	2.13 ± 0.34
C. rotundata (*n* = 4)		
Leaves	− 9.02 ± 0.86	1.88 ± 1.49
Roots	− 9.32 ± 1.44	1.20 ± 1.03
H. decipiens (*n* = 1)		
Leaves	− 7.06	7.26
Roots	− 7.03	2.12
S. isoetifolium (*n* = 1)		
Leaves	− 3.58	1.83
Roots	− 3.41	1.37
H. ovalis (*n* = 1)		
Leaves	− 9.41	5.28

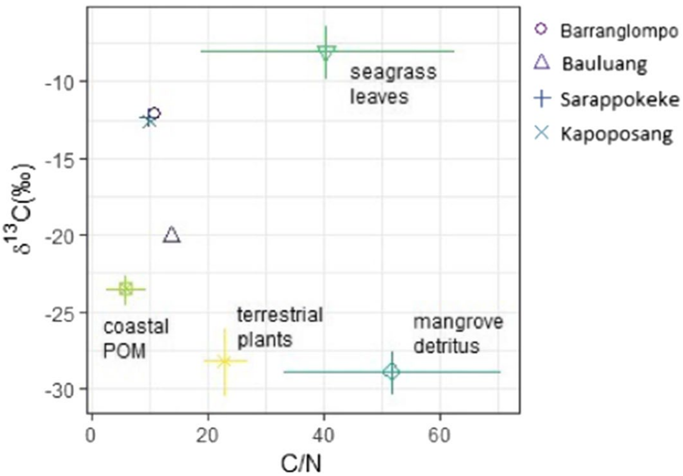

Fig. 3 Biplot of $\delta^{13}C_{org}$ and CN ratio

(terrestrial- and marine-derived OM). It was reported that around 50% of the organic carbon stored in the top 10 cm of seagrass sediments is derived from seagrass biomass (Kennedy et al. 2010). However, variation occurs spatially, depending on the hydro-geomorphological settings and local conditions (e.g., the distance relative to the land,

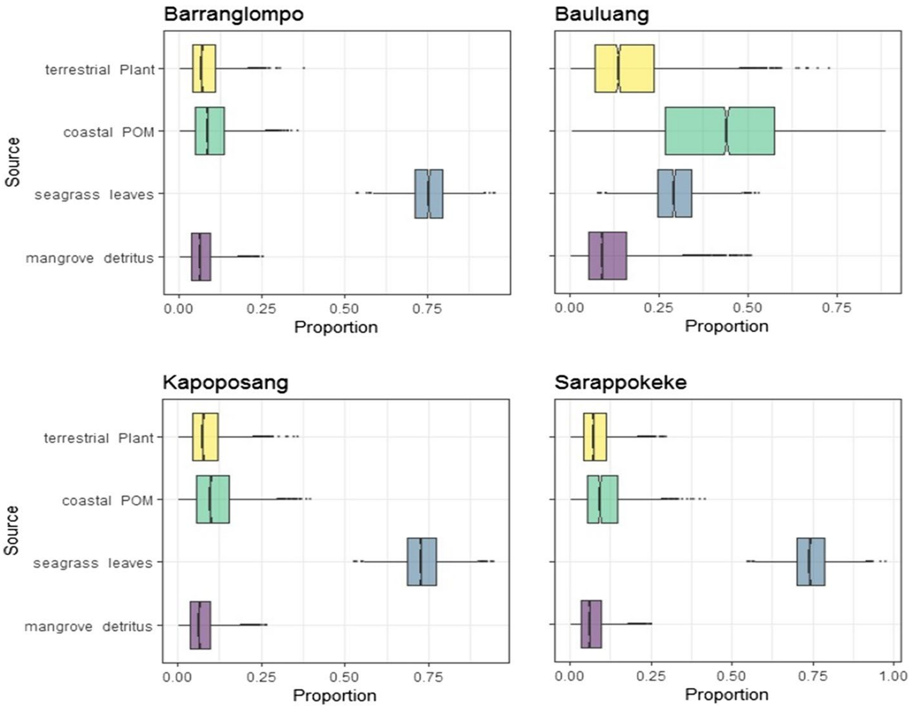

Fig. 4 The simmr plot of the contribution of different end members to seagrass sediment organic carbon (boxes enclose the 50% credibility interval; lines within boxes represent median values)

seagrass meadows, water depth, waves), which control the distribution and accumulation of organic matter (Mateo et al. 2006; Kennedy et al. 2010; Ricart et al. 2015).

On the Barranglompo Island, the Kapoposang Island and the Sarappokeke Island, the downcore patterns of sediment properties mostly do not vary with depth ($p > 0.05$). Early degradation of organic matter usually does not significantly change $\delta^{13}C_{org}$ (Meyers 1994; Kennedy et al. 2010). Slight decrease of $\delta^{15}N$ was observed on the Barranglompo and the Bauluang Islands. Fractionation due to discrimination of heavier isotope (^{15}N) relative to lighter isotope (^{14}N) during decomposition of organic matter by microbes usually causes an increase of $\delta^{15}N$ with depth (Nadelhoffer and Fry 1988). However, inverse pattern of $\delta^{15}N$ isotope downcore observed here indicates that $\delta^{15}N$ isotope values have large potential for variation due to decomposition (Greiner et al. 2016). Organic carbon content on the Sarappokeke Island tends to decrease with depth, while C_{org} content on the Bauluang Island increases. The vertical profile of carbon accumulation mostly shows the decrease in organic matter with depth, because carbon diagenesis usually causes a gradual loss of first labile carbon (Lavery et al. 2013) and an enrichment in N relative to C; thus, C/N profile is expected to decrease with depth. However, the inverse patterns may occur, depending on the species of seagrass and the habitat setting they occur (Lavery et al. 2013).

Although seagrass coverage areas are similar at all sites (Bauluang = 41.75 ± 2.25%; Barranglompo = 48.06 ± 6.74%; Sarappokeke = 50.56 ± 4.82%; Kapoposang = 44.06 ± 4.85%; Rustam et al. 2017), based on the simmr plot of organic matter contribution to sediment organic carbon (Fig. 4), a smaller fraction of seagrass detritus is accumulated on the

Bauluang Island compared to those on the other islands. This might occur because seagrass litter was washed off due to wave action, as the Bauluang Island is exposed directly to open ocean without barrier from surrounding islands, unlike the other three islands. In the Bauluang Island, the highest contribution of organic matter to seagrass sediment was from phytoplankton (Fig. 4), which might indicate that phytoplanktons are abundant in the water. The Bauluang Island is situated next to the Tanakeke Island, where massive land conversion occurs. Conversion from mangroves to aquacultures (shrimp ponds), settlement and charcoal industry on the Tanakeke Island had caused approximately 32.25% mangrove loss during the last 20 years (Akbar et al. 2014; Moore 2018). Coastal seagrass beds that receive terrigenous sediment input usually have a considerably higher biomass of phytoplankton, epiphytic algae and macroalgae, if compared to seagrasses growing in carbonate-rich sediments (Erftemeijer 1994).

The surrounding surface water of the Bauluang Island is eutrophic due to high nutrient contents that might have been released from anthropogenic activities (nitrate concentrations exceed the threshold determined by the Indonesian Ministry of Environment Decree No 51 year 2004, which are ranged between 0.1 and 0.4 mg l^{-1}, unpublished data). Nutrients known to directly increase plant productivity and biomass thus contribute to carbon sequestration in seagrass sediments. However, it was reported that plant biomass accumulation in seagrass beds in the Everglades National Park in Florida Bay was not sufficient to affect sediment carbon at the short timescale (Armitage and Fourqurean 2016). The high nutrient inputs, however, might trigger the growth of phytoplankton (Erftemeijer 1994) and thus dominate carbon accumulation in seagrass sediment in our study sites. Similar finding was reported in seagrass meadows that located in the impacted water due to intensive human pressures (Mazarrasa et al. 2017). They studied the effect of coastal anthropogenic pressures on the variability of carbon sources in seagrass carbon sinks during the last 150 years in the top meter sediment and found higher contribution of seston (40–80%) than seagrass (*P. oceanica*) in the impacted than in the most pristine areas. Sediments in seagrass beds located in an impacted water in Xincun Bay, an aquaculture area in China, were also reported to contain mostly marine-originated organic matter, with an average $\delta^{13}C$ value of − 15.44 ‰ (Liu et al. 2016).

4.3 The Contribution of Various Organic Matter to Sediment C_{org} Stocks

Sediment C_{org} stock of seagrass is determined by various factors such as geomorphology (meadows landscape), hydrodynamics (tidal and wave energy), environmental changes (e.g., seasonal dynamics, anthropogenic activities), sediment depth and the sources of organic matter (Mateo et al. 2006; Kennedy et al. 2010; Fourqurean et al. 2012a; Ricart et al. 2015). Here, we evaluate the contribution of various organic carbons to sediment C_{org} stocks, as various sources of organic matter differ in their persistence in the sediment (Holmer et al. 2004).

The Kapoposang Island has the highest sediment C_{org} stocks among other islands (Fig. 5) with 73% contribution to sediment carbon derived from seagrass litter. The meadow is dominated by larger species of *E. acoroid*es and *T. hemprichii* (Rustam et al. 2017) that have higher belowground to aboveground biomass ratio than smaller species (Duarte and Chiscano 1999). Seagrass rhizomes typically decompose slowly, and it was even reported that no decomposition could be detected for the seagrass rhizome detritus of *E. acoroides* after 48 days of experiment (Holmer and Olsen 2002). The highest sedimentary C_{org} stocks also were found in meadows composed of the largest seagrass species (*E.*

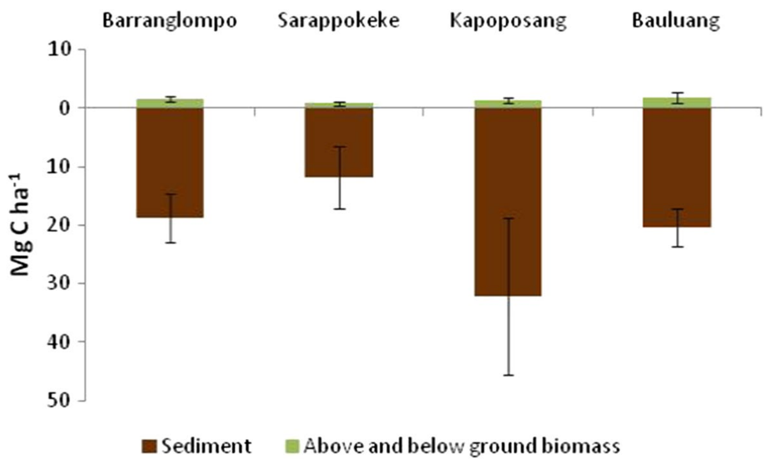

Fig. 5 The mean total C_{org} stocks (sediment and biomass) of seagrasses at the study sites. Error bars display variability of C_{org} stocks among stations at each location

acoroides and *T. ciliatum*) than the meadows composed of smaller species in the Western Indian Ocean (Gullstrom et al. 2018). Domination of smaller size seagrasses of *H. uninervis* and *C. rotundata* on the Sarappokeke Island (Rustam et al. 2017) likely resulted to a low sediment C_{org} stock in this area (Fig. 5).

The Bauluang Island has also a considerable amount of sediment C_{org} stocks, with the highest contribution to sediment carbon from phytoplankton (44%). Usually, sestonic matter, particularly phytoplankton, is much more labile than seagrass tissues (Enriquez et al. 1993), thus is more susceptible to microbial decomposition and is prone to release back to the ocean–atmosphere CO_2 pool. The considerable amount of sediment C_{org} stocks on the Bauluang Island is likely due to the additional contribution of terrestrial vegetations, such as mangrove and general terrestrial plants (Fig. 4) that might have been transported from the Tanakeke Island, where massive land conversion occurs. Mangroves and other terrestrial plants are potential carbon source, partly because they contain lignin, the most refractory compound occurs only in woody plants (Emerson and Hedges 2003), that is harder to decompose than phytoplankton.

4.4 Seagrass Carbon Stocks

The mean sediment C_{org} stock in this study is estimated to be 20.8 ± 8.4 Mg C ha^{-1} (based on the depth of 20–55 cm), with the highest measured on the Kapoposang Island (32.1 Mg C ha^{-1}), followed by the Bauluang Island (20.3 Mg C ha^{-1}), the Barranglompo Island (18.8 Mg C ha^{-1}) and the Sarappokeke Island (11.9 Mg C ha^{-1}). If the values are extrapolated to 1 m depth, the mean sediment C_{org} stock is estimated to be 59.3 ± 21.5 Mg C ha^{-1}, with the highest also measured on the Kapoposang Island (83.5 Mg C ha^{-1}), followed by the Bauluang Island (71.1 Mg C ha^{-1}), the Barranglompo Island (41.8 Mg C ha^{-1}) and the Sarappokeke Island (40.5 Mg C ha^{-1}). Standardization into 1 m depth allows for accurate accounting of sediment C_{org} stocks (Fourqurean et al. 2012a), as well as for equal comparison to other studies. The mean sediment C_{org} stock in this study is lower than those reported from other studies (Fig. 6), such as in the Sungai Pulai estuary, Malaysia, which is impacted by anthropogenic activities (61 Mg C ha^{-1}; Rozaimi et al. 2017), in Chek Jawa,

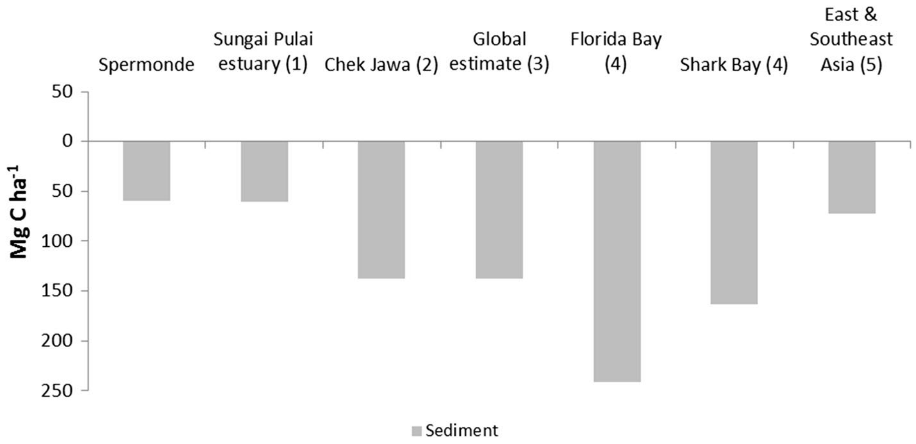

Fig. 6 The mean seagrass sediment C_{org} stocks (to 1 m depth) from various sites. *Data sources*: 1—Rozaimi et al. (2017), 2—Phang et al. (2015), 3—Fourqurean et al. (2012a), 4—Fourqurean et al. (2012b), 5—Miyajima et al. (2015)

Singapore, located 5 km away from the Johor estuary that receive large sediment load (138 ± 8.6 Mg C ha^{-1}; Phang et al. 2015), in the Florida Bay and Shark Bay (163.0 and 241.3, respectively; Fourqurean et al. 2012b), in the tropical seagrass meadows in East and Southeast Asia (72.4 Mg C ha^{-1}; Miyajima et al. 2015), and compared to the global C_{org} storage in seagrass sediments estimated by Fourqurean et al. (2012a), using a conservative estimate of 137.9 Mg C ha^{-1} (based on both data with full vertical profile of 1 m and the extrapolated data). In general, seagrass beds growing in carbonate-rich environment, such as in the Spermonde Islands, contain low organic carbon (Erftemeijer 1994).

Our results are in accordance with other studies (Duarte et al. 2005; Kennedy et al. 2010; Fourqurean et al. 2012a) that seagrass meadows are not only able to store their primary production in sediments, but also can trap material organic from adjacent ecosystems and thus have the capacity as a potential carbon sink. However, the effectiveness of carbon stored in sediment depends on the sources of organic matter and other physical factors that control the distribution of organic matter and biochemical processes. The meadows that are located in adjacent to mangrove forests or in the impacted areas, like on the Bauluang Island, have sediments that contain organic carbon derived from multiple sources. While seagrass meadows that are relatively protected in reef flats, their sediment organic carbons are mostly seagrass-derived.

5 Conclusion

The composition of seagrass sediment properties in this study is determined not only by geographical differences (zonation based on the distance from mainland and water depth), but also influenced by hydrodynamics (wave actions) that control the distribution of carbon sources. Other factors such as anthropogenic pressures can also influence the composition of sediment properties (e.g., organic carbon content) and thus affect its C_{org} stocks, as shown from the Bauluang Island. Although the Bauluang Island is located at the same zone with the Barranglompo Island, the sediment organic carbon compositions are different. A combination of land conversion and aquaculture practices that occur in the neighbor island (the Tanakeke Island), in addition to wave action exposure, likely influences the composition of sediment organic matter on the Bauluang Island, where phytoplankton contributed the highest, followed by seagrasses, terrestrial plants and mangroves. The other three islands, the Barranglompo, the Sarappokeke and the Kapoposang Islands, despite located at the different zones, have similar sediment organic carbon composition, where seagrasses contributed higher than the other organic matter. This is partly because these islands are relatively protected from direct wave actions that potentially flushing off the autochthonous organic matter. Although the proportional contribution of seagrass-derived organic matter is similar in these islands, sediment C_{org} stocks vary spatially. Differences in species domination likely determine those variations. From this study, we found that seagrasses are a potential carbon sink; however, their capacity to sequester and store carbon is determined by various local factors and should be taken into account when developing coastal management strategy to mitigate climate change, as efforts are being undertaken to include coastal ecosystems (including seagrass ecosystems) in the National Green House Gasses Reduction Strategy.

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