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Changes in Seagrass Community Structure in Response to Sediment Load and Excess Nutrients, and its implication to Carbon Stocks in the Berau Marine Conservation Area

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ABSTRACT

As the urgency to reduce carbon emission increases, seagrass ecosystems have recently received attention due to their capacity to take up and store high amounts of carbon. Protection of this ecosystem is key to increase resilience to climate change. However, in some of the Marine Protected Areas (MPAs), seagrass ecosystems are still under threat. This study aims to investigate the current condition of seagrass ecosystems and compare it to the previous study before MPA was established in the Berau coastal water. SeagrassWatch method was used to measure seagrass community structure. Other proxies were also used to explain factors affecting seagrass condition such as total suspended solid (TSS) and sedimentary stable isotopes to identify the source of organic carbon. The percentage cover of seagrass in this study were categorized as not healthy (<29–59.9%), which was statistically related to TSS. The higher TSS resulted in the lower seagrass cover, as observed in the Rabu Rabu island located adjacent to mainland. Changes in seagrass composition were observed, including the emergence of larger species of *E. acoroides* and *T. hemprichii* in the islands located adjacent to mainland. The spatial and temporal changes of seagrass ecosystems observed in Berau MPA should be taken into consideration that conservation on seagrass ecosystems needs to be prioritized by improving the MPA function to avoid further loss of carbon from seagrass ecosystems.

Keywords: Berau, Derawan, conservation, carbon stocks, Marine Protected Area, seagrass ecosystems.

INTRODUCTION

Seagrass ecosystems are key components of coastal ecosystems that provide numerous ecosystem services, despite only covering 0.1% of the ocean floor [Spalding et al., 2003; Short et al., 2016]. Seagrasses protect coastlines from floods [Nordlund et al., 2017; Nordlund et al., 2018], provide food source for exotic biotas like dugong and sea turtles [Wirsing et al., 2007], and provide nursing areas for commercial fishes thus support fisheries and livelihoods [De la Torre Castro et al., 2014; Quiros et al, 2018; Miller 2022]. Seagrasses also serve as a regulator; they utilize CO_2 and store it in the form of biomass and in sediment. The capacity to store high amounts of organic carbon by coastal ecosystems is known as blue carbon [Nellemann et al., 2009; Howard et al., 2014; Macreadie et al., 2021]. As the urgency to reduce carbon emission increases, blue carbon ecosystems increasingly receive attention as a nature-based climate solution.

Protecting blue carbon ecosystems is the key to increasing resilience to climate change, especially for island countries. It has been estimated that between 0.02 to 0.65 gigatons of carbon dioxide equivalent ($GtCO_2e$)/year of green house gas emissions could be sequestered and stored by increasing the protection and restoration of blue carbon ecosystems, including the avoided emissions from continued degradation of these ecosystems [Northrop et al. 2021; Hoegh Guldberg et al. 2019]. The adoption of ecosystem-based conservation within the Marine Protected Areas (MPAs) management increases seagrass capacity in storing carbon, such as reported by Rahayu et al. [2023], that sedimentary seagrass carbon inside of Nusa Penida MPA, Indonesia, was higher than those in the outside of MPA. However, in many MPAs, seagrass ecosystems are still under threat, such as from land-use change, coastal construction, water pollution and tourism [Waycott et al., 2009; Quiros et al, 2017; Dahl et al., 2022].

Located in the center of Coral Triangle, Berau Water is blessed with high biodiversity that has an important value to support the development of tourism, research, education, and local livelihoods. The Berau Regency launched Regional Regulation No. 31 year 2005 about the establishment of Berau Marine Conservation Area that covers an area of 1,222,988 ha, which includes the Derawan Islands, which consists of 30 reef-islands with high diversity of coral and reef fish species, a large population of green turtles (*Chelonia mydas*), manta rays (*Manta* spp.) and extensive seagrass meadows [Hoeksema et al., 2004; De Voogd et al., 2009; van Katwijk et al., 2011]. Further in 2016, the Coastal and Small Islands Conservation Area (KKP3K) of the Derawan Islands and Surrounding Waters was established through the Decree of Minister of Marine Affairs and Fisheries No. 87/KEPMEN-KP/2016 that covers an area of 285,548.95 ha. Unfortunately, like many other coastal areas worldwide, Berau coastal waters are under pressure from human activities. Land-use changes into coal mining, oil palm plantations, as well as agriculture and aquaculture developments in the catchment area along the Berau River have led to increased loads of sediment, nutrients, and pollutants in the river discharge [Buschman et al., 2012; Dahl et al., 2022], that give impacts to the ecosystems in front of the Berau river to the Derawan Islands. Although the Berau Delta has the efficiency of trapping most of the suspended material, it will still be carried into the sea [Hoekstra et al., 2007].

In 2003, before the Berau MPA was established, a study carried out by van Katwijk et al. [2011] reported that seagrass cover and diversity in the Derawan Islands decrease spatially, from the farthest islands toward Berau Delta [van Katwijk et al., 2011]. In order to evaluate the condition of seagrass in this area, this study aims to investigate the current condition of seagrass ecosystems in the waters of the Berau and Derawan MPA that received multiple stressors, especially sedimentation and excess nutrient input from river run off. We took samples at the same locations with previous study by Van Katwijk et al. [2011] to see the changes in seagrass community structures (coverage and species composition) and the implication to carbon stocks. We used several approaches such as SeagrassWatch to assess seagrass cover and composition, remote sensing to investigate the potential threats to seagrasses from terrestrial, seawater quality measurement (especially total suspended solid and nutrients), and sedimentary stable isotopes to identify the source of organic carbon in seagrass sediment. This study will be useful to raise awareness and support the management of seagrass conservation in the Berau and Derawan MPA.

METHODOLOGY

Study site

Berau is one of the regencies of the East Kalimantan Province, Indonesia, which has a strategic location with an area of 36,962.37 km^2 or equivalent to 13.92% of the total area of East Kalimantan Province [Central Bureau of Statistics, 2022].

Geographically, Berau Regency is located in the tropics; the topography varies from highlands, hills, and lowlands to the coast, with abundant natural resources and high economic potential. Several mining commodities, such as coal and nickel, are the backbone of supporting the economic sector in the Berau Regency. Apart from mining, the agricultural, plantation, and fisheries sectors also play an essential role in supporting development in Berau Regency.

Derawan Islands is a part of the Berau Regency, lying in the Makassar Strait that was passed through by the Indonesian Throughflow (ITF) which carries water masses from the Pacific Ocean to the Indian Ocean [Gordon, 2005; Gordon et al., 2019]. The islands are located in the center of the coral triangle area, which was formed through a long geological process. These unique characteristics cause the biodiversity in the Derawan Islands to be high [Wiryawan et al., 2004]. Some of its offshore islands contain anchialine lakes, the rare and vulnerable ecosystems that house rare and endemic species [Tomascik et al., 1997; Becking et al., 2011]. Derawan Islands consists of several small reef-islands such as Maratua, Kakaban, Panjang, Derawan, Sangalaki, Samama, and several other small islands in the Sulawesi Sea. Derawan and Maratua islands are famous tourist destinations with beautiful scenery and underwater attractions, while Samama, Sangalaki, and Kakaban islands are well-known conservation areas with several protected animals in the region, such as green turtles, manta rays, stingless jellyfish, and other endangered species. Seagrass ecosystems can be found in the conservation area. The existence of seagrass ecosystems in the Berau MPA supports the existence of biota that use seagrasses as their food sources, such as turtles and dugongs, and biota that use seagrasses as nursery ground.

This study was conducted on several islands of the Derawan Islands within the Berau conservation area (Figure 1). The sampling stations were selected based on previous study by van Katwijk et al. [2011] in 2003 before the MPA was established to examine the change of seagrasses condition. The study area was separated into three main shelves based on salinity gradient and bathymetry [Tomascik et al., 1997; van Katwijk et al., 2011; Tarya et al., 2018); the the inner shelf (Rabu Rabu Island), the middle shelf (Panjang Island, Derawan Island, Samama Island, and Sangalaki Island), and the outer shelf (Maratua Island).

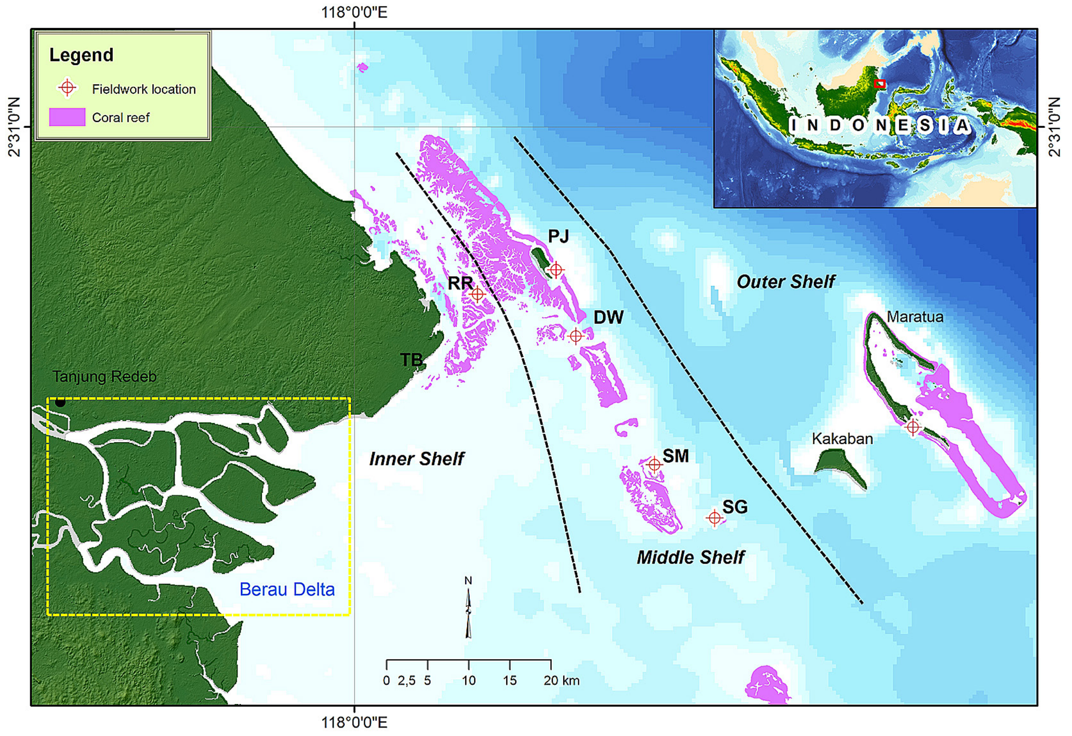

Figure 1. Map of the study area that shows three zones; the inner shelf, the middle shelf, and the outer shelf (TB – Tanjung Batu; RR – Rabu Rabu Island; PJ – Panjang Island; DW – Derawan Island; SM – Samama Island; SG – Sangalaki Island). The red dots are the sampling points for seagrass

Data collection

Data collection was conducted twice in March 2019 (representing wet season) and August 2019 (representing dry season), on six islands of the Derawan Islands (Rabu Rabu Island, Panjang Island, Derawan Island, Samama Island, Sangalaki Island, and Maratua Island).

Seagrass community structure

Seagrass data sampling was done using a purposive sampling method based on the presence of seagrass meadows, which can be observed by walking or by boat. A 50×50 cm^2 frame quadrant was thrown randomly into a seagrass meadow. Seagrass percentage cover was taken within each quadrant frame using a visual estimation method based on the *SeagrassWatch* standard guide [Mackenzie et al., 2003]. The larger seagrass species (such as *Enhalus acoroides*) encountered within the frame were counted from their shoots and then sampled, while the smaller seagrass species found within the frame were sampled using a pipe core size 0,0035 m^2 and then counted in the basecamp. The epiphyte cover on the surface of *E. acoroides* leaves were estimated first by measuring how much of an average seagrass leaf surface was covered, and how many of the leaves in the frame were covered [Mackenzie et al., 2003]. In the basecamp, biomass samples were cleaned to remove the attached epiphytes and other substrate materials. Each identified species was separated into aboveground (leaves and stems) and belowground parts (root and rhizome), weighed to obtain the wet weight, and then stored for further analysis.

Seagrass sediment

Seagrass sediments were also sampled in this study. In total, nine surface sediment samples were collected from Derawan Island (4), Rabu Rabu Island (1), Maratua Island (1), Samama Island (1), Sangalaki Island (1) and Panjang Island (1) using a modified syringe (volume 50 ml) for organic carbon analysis. The syringe was inserted into sediment near seagrass stand inside the quadrat. All extracted sediments were placed in plastic bags and secured in ice boxes for further analysis.

Water samples for total suspended solid (TSS) and nutrients

Water samples were taken for nutrients and TSS measurement. Water samples were collected along the Berau River to the coastal water. Surface water was collected using a 5 L Niskin sampler at 10–20 cm depth. For nutrient analysis, water samples were filtered through GF/F filter paper (diameter 25 mm and porosity 0.45 µm, Whatman), placed in acid-cleaned polyethylene bottles, and frozen at -20 °C. While the suspended solid trapped in filter papers were used for TSS analysis.

Analysis

Elemental and isotopic analysis of carbon and nitrogen

In the laboratory, biomass and sediment samples were dried at 60 °C until constant weight, weighed to obtain dry weight, ground to a fine powder, and analyzed for carbon and nitrogen concentration, and $\delta^{13}C$ and $\delta^{15}N$ isotope composition. The measurement of carbon-nitrogen concentration and $\delta^{13}C$ and $\delta^{15}N$ isotope composition was done at the Atmosphere and Ocean Research Institute (AORI), University of Tokyo, Japan. Sediment samples were treated following the procedure of Miyajima et al. [1998]. The samples were first acidified using 4 N HCl to remove the carbonate. A precombusted glass fiber filter (Whatman GF/F, 25 mm) was spotted with an acid-soluble fraction. The centrifuge pellets were used to determine the amount of acid-insoluble fractions of the samples. The concentrations and isotope ratios of organic carbon were determined simultaneously by an elemental analyzer-isotope ratio mass spectrometer (FLASH 2000/Conflo IV/DELTA V Advantage, ThermoFisher Scientific, Inc., Bremen, Germany). The measured isotope ratios were represented using conventional δ notation (in permil) with Vienna Peedee Belemnite as the reference material.

Seagrass biomass carbon stocks and community structure

Seagrass biomass ($g{\cdot}m^2$) was obtained from dry weight measurements, while biomass carbon stock ($g{\cdot}C{\cdot}m^{-2}$) was obtained by multiplying the dry weight with carbon content (% wt) of a specific species. The analysis of seagrass community structure consists of seagrass species composition, seagrass density, and percent cover to estimate the overall condition of seagrass ecosystems [English et al., 1997 Short et al., 2001, McKenzie et al., 2003].

Seagrass sediment carbon stocks and sources

Sediment carbon stock ($Mg·C·ha^{-1}$) was calculated by multiplying dry bulk density ($g·cm^3$) with organic carbon content (% wt) and sediment thickness (cm). Furthermore, the combination of $\delta^{13}Corg$ and $\delta^{15}N$ was used to identify the sources of organic matter in the seagrass surface sediment. The isotopic combination of the sediments and the potential sources of organic matter (mangrove, seagrass, terrestrial plants, plankton) was included in the Bayesian isotopic modeling package, the Stable Isotope Mixing Model in R (SIMMR), to estimate the proportional contribution of each source to seagrass sedimentary organic carbon [Parnell et al., 2010; Kusumaningtyas et al., 2018; Rahayu et al., 2019; 2023]. The isotopic signatures of the organic matter references were taken from the region-relevant literatures. A model was run through 1×103 iterations, and the results are presented using a boxplot which depicts the 50% credibility interval.

Nutrients and TSS analysis

Nutrients was analyzed for nitrate, ammonia, and orthophosphate using a method from APHA [2012], while TSS measurement was done using a gravimetric method following ASTM [1999] standard with a detection limit of 1 mg/L and uncertainty of ±12% [APHA, 2005; APHA, 2015]. The filter papers were oven dried and weighted to obtain the dry weight (final weight). The TSS value was obtained by calculating the difference between the final weight and the initial weight of the filters filled with samples and divided by the volume of the samples.

Land use change in the Berau coastal area

To assess whether land use change (LUC) in coastal areas cause an increase of TSS and nutrients in the estuary, we measured the percentage of land use change from flooded vegetation around the delta (e.g. mangrove ecosystems) to other forms within the last 5 years and linked it with TSS and nutrient values. The buffer area of LUC was spatially analyzed within 8 km radius from TSS and nutrient sampling points, as shown in the map below (Figure 2).

Statistical analysis

Pearson correlation was used to assess the correlation between LUC with TSS and nutrient in the estuary, and to assess the correlation between TSS in the coastal water with seagrass cover in the studied areas. Regression analysis was used to assess the strength of the relationships between variables. One-way Anova was also used to test the differences of TSS within salinity gradient (in different shelves).

RESULTS

Seagrass biomass carbon stocks and community structure

In total, there were eight seagrass species found in the study area, which are *Thalassia hemprichii*, *Halodule pinifolia*, *Halodule uninervis*, *Halophila ovalis*, *Syringodium isoetifolium*,

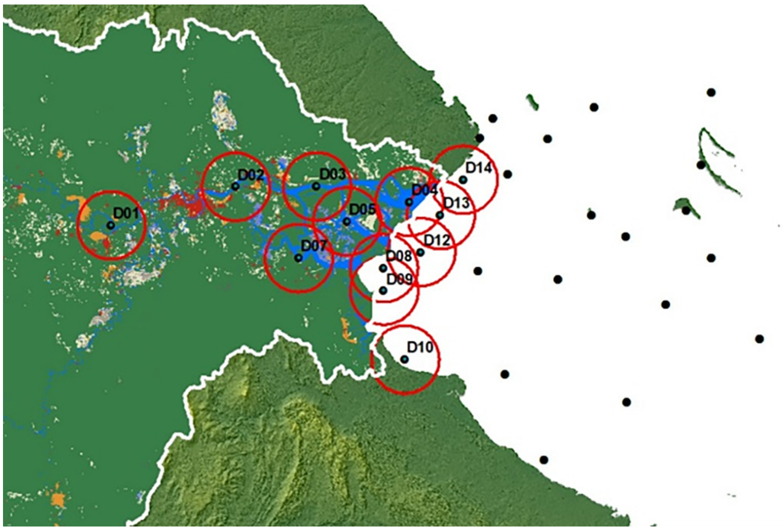

Figure 2. The buffering area for LUC analysis measured 8 km radius (red circles) from sampling points for TSS (black dots)

Cymodocea rotundata, *Cymodocea serrulata* and *Enhalus acoroides*. The mean seagrass cover ranged between 28% to 58% (Figure 3a). The highest mean cover (58%) was measured in Maratua Island (outer shelf), with 70% dominated by smaller species *Halodule pinifolia*. The second highest mean cover (52%) was found in Panjang Island (mid shelf) with 80% dominated by larger species of *Thalassia hemprichii*. The lowest mean cover (28%) was measured in Rabu Rabu Island (inner shelf), with 35% covered by larger species of *T. hemprichii* and *E. acoroides* (Figure 3b). Larger species (*T. hemprichii* and *E. acoroides*) were only found on islands close to the mainland, in Rabu-Rabu and Panjang Islands. While smaller species like *H. pinifolia* and *H. ovalis* were predominantly found in the inner and outer shelves. Only *H. ovalis* was found on all islands. The epiphyte percentage cover on seagrass leaf (*E. acoroides*) in Rabu Rabu island was measured between 30–40% (with the average of 33% ± 4.83%) and in Panjang island ranged between 30–90% (with the average of 63% ± 14%).

Seagrass biomass carbon stock was measured the highest in Rabu Rabu Island (4.35 Mg·C·ha^{-1}) due to the presence of both larger species of *T. hemprichii* and *E. acoroides*, although only a single whole individual of *E. acoroides* was found in Rabu Rabu Island. The lowest biomass carbon stocks were measured in Sangalaki and Maratua Islands due to the dominance of smaller species, despite having the highest shoot density (Table 1).

Surface sediment properties, carbon stock and sources

Surface sediment carbon content (Table 2) ranged between 2.04% and 2.88%, with the highest surface sediment carbon stock measured in Maratua Island (16.0 Mg·C·ha^{-1}). Rabu Rabu island has the highest $\delta^{15}N$ composition (3.95 ‰) with the lowest $\delta^{13}C$ composition (-19.16 ‰). While Maratua and Panjang islands has the highest $\delta^{13}C$ composition (-12.68 ‰ and -12.92 ‰, respectively), and the lowest $\delta^{15}N$ composition (2.56 ‰ and 2.40 ‰, respectively).

According to the SIMMR model (Figure 4), the sources of surface sediment organic carbon in Rabu Rabu island were 40%–50% from seagrass (autochthonous) and the rest were from other sources (allochthonous), such as mangroves and terrestrial plants that share a considerable contribution. Meanwhile on other

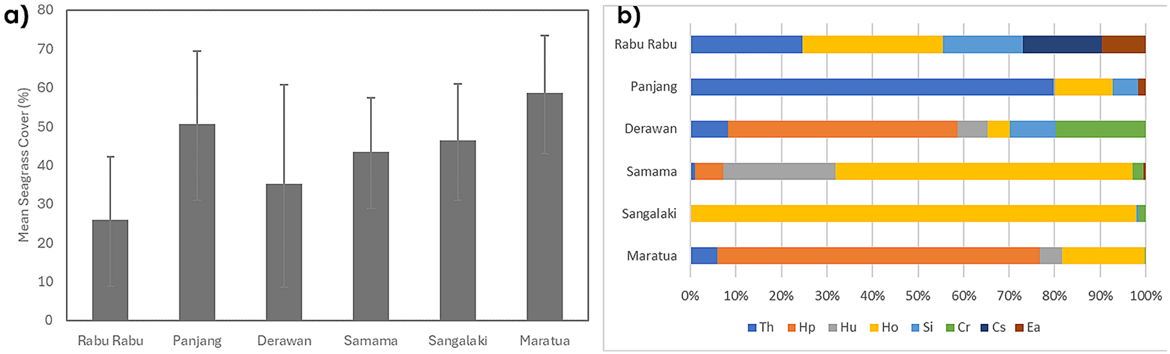

Figure 3. a) Mean seagrass cover (error bars indicate the standard deviation), and (b) Species composition and distribution in the study area (Th – *T. hemprichii*, Hp – *H. pinifolia,* Hu – *H. uninervis,* Ho – *H. ovalis,* Si – *S. isoetifolium,* Cr – *C. rotundata,* Cs – *C. serrulata*, Ea – *E. acoroides*)

Table 1. Seagrass biomass, biomass carbon stocks, and density in the study sites

Location	Biomass (g·m^{-2})	Biomass C stock (Mg·C·ha^{-1})	Species density (shoot m^{-2})
Rabu Rabu	1,320	4.35	10,814
Panjang	264	0.87	1,786
Derawan	618	2.04	3,976
Samama	88	0.29	1,143
Sangalaki	28	0.12	12,000
Maratua	34	0.11	16,190

Table 2. Seagrass surface sediment properties in the study sites

Station	Organic C (wt%)	N total (wt%)	C density ($g \cdot cm^{-3}$)	$\delta^{13}C$ (‰)	$\delta^{15}N$ (‰)	C_{org}/N ratio	C stock ($Mg \cdot C \cdot ha^{-1}$)
Rabu Rabu	2.88	0.27	0.04	-19.16	3.95	12.43	13.0
Panjang	2.30	0.28	0.02	-12.92	2.40	9.64	11.0
Derawan	2.26	0.27	0.03	-13.98	3.25	9.72	14.3
Samama	2.24	0.27	0.03	-13.40	3.61	9.56	8.9
Sangalaki	2.13	0.23	0.03	-13.53	3.13	10.62	5.1
Maratua	2.04	0.22	0.03	-12.68	2.56	10.96	16.0

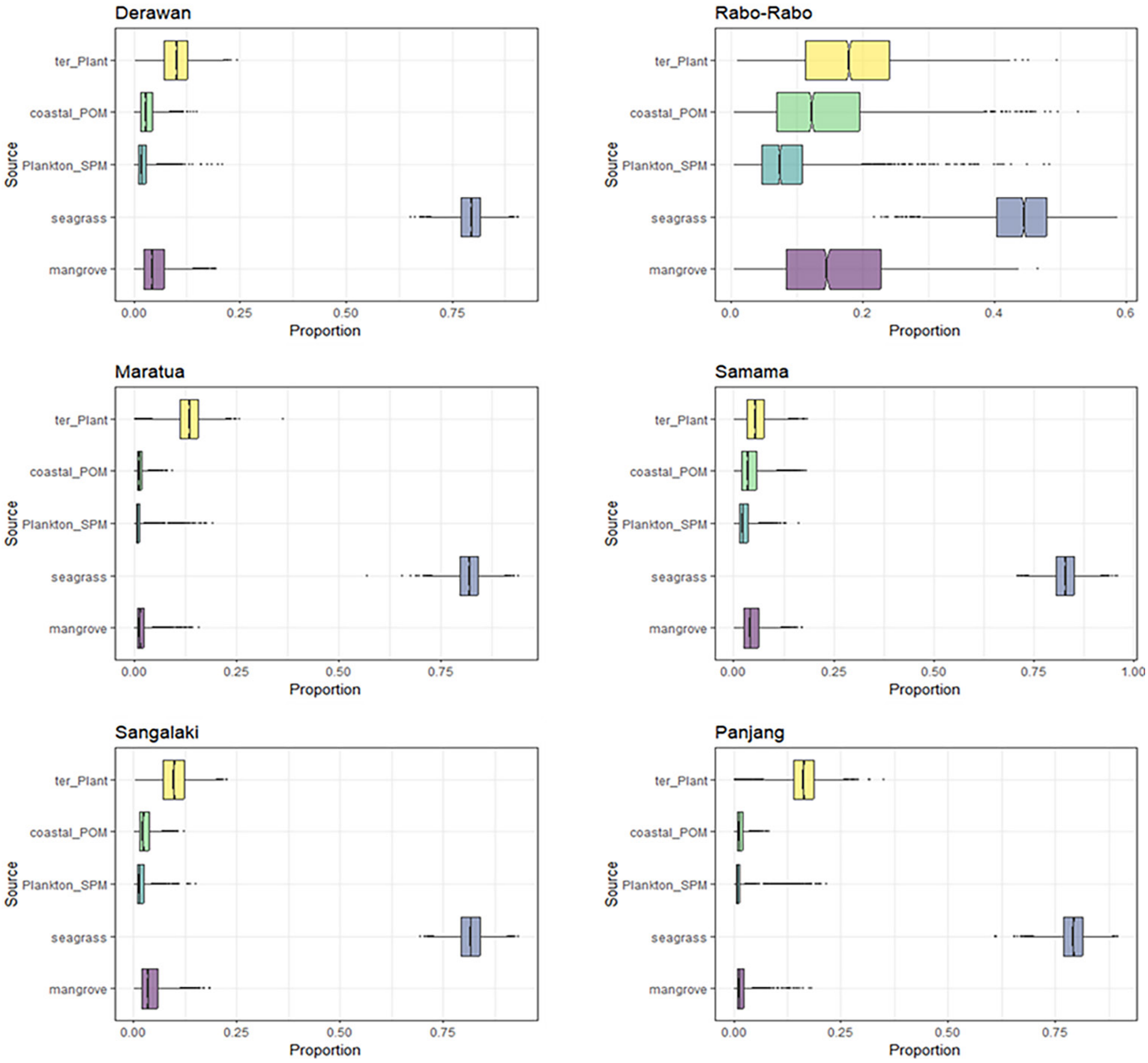

Figure 4. The simmr models showing the proportional contribution of various endmembers (terrestrial plant, coastal particulate organic matter, plankton/suspended particulate matter, seagrass and mangrove) to surface sediment organic matter in the study sites (lines within boxes represent median values)

islands (Derawan, Maratua, Samama, Sangalaki, and Panjang islands), the surface sediment carbon was predominantly derived autochthonously from seagrass, with a proportion of more than 75%.

Nutrients and total suspended solid

Nitrates were measured above the threshold for seagrasses at all sampling points (Table 3), however no correlation between nitrate and LUC

Table 3. Nutrients values (ammonia, nitrate and ortho phosphate) from surrounding water of the study sites

Location	Ammonia [mg/L]	Nitrate [mg/L]	Ortho phosphate [mg/L]
Berau River	0.08	0.10	0.045
Berau Delta	0.07	0.19	0.064
Berau Estuary	0.05	0.09	0.002
Tanjung Batu	0.05	0.10	0.002
Panjang Island	0.10	0.09	0.002
Derawan Island	0.02	0.10	0.002
Threshold for marine biota (seagrass)*	0.3	0.06	0.015

Note: * Government Regulation No. 22 year 2021.

was observed (Pearson Corr = 0.19, $r^2 = 0.04$). Although ortho phosphate was measured high in the river and delta, the values from estuary to Derawan water were below the threshold for seagrasses. Ammonias were all below the threshold for seagrasses.

The values of TSS vary between seasons ($p < 0.05$, F = 14.7). During wet season (March 2019), TSS in the inner to outer shelves were still below the threshold for seagrasses (20 mg/L), while during dry season (August 2019), the values were above the threshold. The mean TSS also vary spatially between shelves ($p < 0.05$, F = 6.56), which was decreasing from the river toward the outer shelf (Figure 5). Correlation was observed between mean TSS with LUC (Pearson corr = 0.77; $r^2 = 0.59$), and between mean TSS with seagrass cover (Pearson Corr = -0.58, $r^2 = 0.93$).

DISCUSSION

Seagrass cover, carbon stocks and sources

The percentage cover of seagrass in this study was categorized as poor (<29.9%) and not healthy (30–59.9%) according to the Degree of the Minister of State for Environment, Republic of Indonesia No. 200/2004. Similar results were also reported by Rahmawati et al. [2014] that the seagrass percent cover in Derawan Islands was poor (0–25% in Maratua island) to moderate (26–50% in Rabu Rabu Island). In this study, correlation was observed between mean TSS value and seagrass cover (Pearson Corr = -0.58, $r^2 = 0.93$). The negative correlation value indicated the opposite direction, which implied that the decrease of seagrass cover was related to the increase of TSS in the studied area. High TSS value in the estuary (especially during dry season where the values were above the threshold for seagrasses) could be attributed to land use change of flooded vegetation in the delta (Pearson corr = 0.77; $r^2 = 0.59$), as we observed some mangrove clearing in the delta. High TSS value has a consequence to seagrasses, as it increases turbidity that causes light reduction and affect photosynthesis [Burkholder et al., 2007]. However, other factors might have also contributed to the decrease of seagrass cover such as high nutrient inputs. In this study, nitrates from the estuary to Panjang and Derawan Islands were measured above the threshold for seagrasses. Excess nutrients in the water can inhibit seagrass growth and survival by stimulating algal growth that increases competition and cause light reduction, as well as affect plant physiology [Touchette and Burkholder, 2000]. Other potential threats to seagrasses in Berau and Derawan coastal waters may include overgrazing by sea turtles because this area has high abundance of sea turtles [Christianen et al., 2013], and tourism expansion [Yumi, 2018]. Derawan Islands are popular tourist areas. Homestays and other businesses had expanded since 2008 in Derawan Island [Yumi, 2018].

In this study, larger species like *E. acoroides* and *T. hemprichii* predominantly occupied Rabu-Rabu and Panjang islands, while smaller species like *H. pinifolia* and *H. ovalis* predominantly found in Derawan, Samama, Sangalaki and Maratua. Both species *E. acoroides* and *T. hemprichii* are the most abundant species found in Indonesian Waters that can grow in various substrates from terrigenous mud to coarse carbonate sediment in tidal area [Tomascik et al., 1997]. According to the SIMMR model, the surface sedimentary organic matter of seagrasses in Rabu Rabu island were a mixture of terrigenous, oceanic and seagrass origin, which was still favorable for larger seagrass species like *E. acoroides* and *T. hemprichii* to live. Species *E. acoroides* is known to be relatively insensitive to siltation and turbid water [Terrados et al., 1998]. As a consequence of the predominant presence of both larger

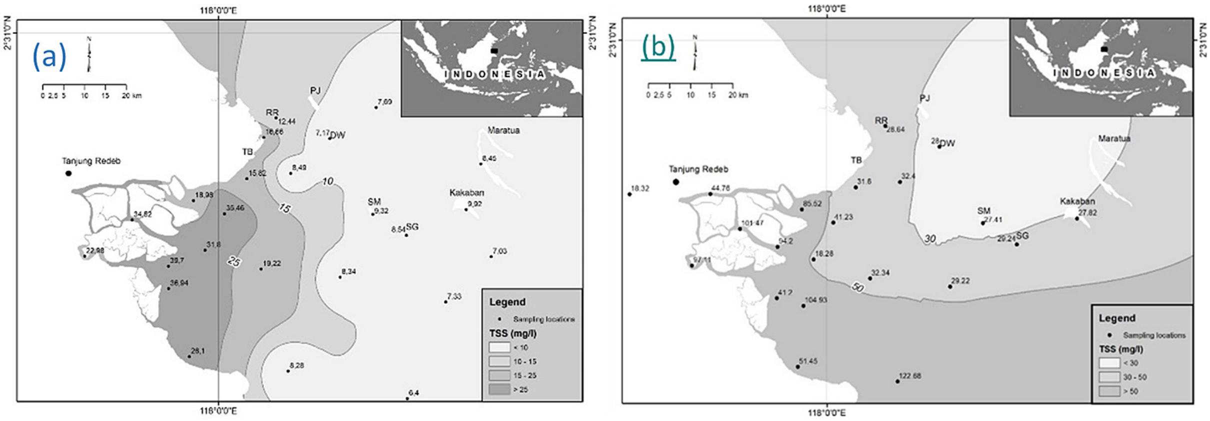

Figure 5. TSS distribution in Berau coastal waters during (a) wet season in March 2019, and (b) dry season in August 2019

species *E. acoroides* and *T. hemprichii* in Rabu Rabu Island, biomass carbon stock was measure higher in Rabu Rabu island (4.35 Mg·C·ha^{-1}) compared to those in other islands, despite having the lowest seagrass cover. The amount of biomass carbon stocks in this study were comparable to those of other areas such as reported from the Kepulauan Seribu National Park, Jakarta [Rustam et al., 2021], that ranged between 0.56–4.39 Mg·C·ha^{-1} (mean = 1.81 ± 0.32 Mg·C·ha^{-1}), and from the Tanjung Lesung, Banten, with mean biomass carbon stock of 1.32 Mg·C·ha^{-1} [Rustam et al., 2014]. Similar to our study, in the Kepulauan Seribu National Park, species *E. acoroides* and *T. hemprichii* were also found predominantly in the islands located adjacent to mainland. The environmental conditions there were still tolerable for larger species to grow but not suitable for other species (especially smaller and more vulnerable species) to live [Rustam et al., 2014].

According to the SIMMR model, the sources of surface sediment organic carbon in Rabu Rabu island were 40–50% from seagrass (autochthobous) and the rest were from other sources (allochthonous), such as mangroves and terrestrial plants that share a considerable contribution. Meanwhile on other islands, the sources of organic carbon were predominantly seagrass derived. This is in accordance with previous study that mangrove-derived carbon rapidly declines with distance, with no mangrove-derived material 3 km from the source [Huxham et al., 2018]. The proportion of allochthonous and autochthonous organic carbon in seagrass sediment can affects the quality of sedimentary carbon [Mazarrasa et al., 2017]. The relatively higher surface sediment carbon content measured in Rabu-Rabu island (2.88%) was likely due to contribution from allochthonous in addition to autochthonous organic matter. Although, the higher carbon content in Rabu Rabu island did not necessarily result in the higher carbon stocks, as in this study, the highest surface sediment carbon stock was measured in Maratua island. Surface sediment in shallow water is more dynamic due to influence from tides, waves, coastal current, fauna, and disturbance than in the deeper sediment [Hearn, 2009; Graves et al., 2022]. Therefore, a deeper sediment profile should be further assessed to understand seagrass carbon sink capacity in this area.

The changes of seagrass ecosystems in Berau MPA: A 15-year perspective

A previous study about the condition of seagrass ecosystems in Berau Coastal Waters had been conducted in 2003 [van Katjwik et al., 2011] before Berau MPA was established in 2005. The study highlighted the spatial decrease of seagrass cover and diversity toward river influence and used the information as an early warning indicator for river nutrient and sediment load in the near-pristine coastal water. Comparing the study to our findings, we found changes on seagrass ecosystems in Berau after 15 years. In 2003, seagrass *H. uninervis* was reported to be found in a fringing area of Tanjung Batu (TB in the map; Figure 1) [van Katjwik et al., 2011]. However, during our observations, no seagrass was found there. Moreover, van Katjwik et al. [2011] reported that only two species (*H. ovalis* and *T. hemprichii*) occupied Rabu-Rabu and Panjang Islands (inner and mid shelves), and *E. acoroides* was only found in a sheltered bay of Maratua (outer shelf), while in our study, larger-sized species like *E. acoroides* and *T. hemprichii* were predominantly found in Rabu Rabu and Panjang Islands, coexisted with other species like *H. ovalis*, *S. isoetifolium* and *C. serrulata*.

Seagrass loss due to poor water quality usually occurs slowly, starting with the loss of the smaller-sized and pioneer species like *H. ovalis* due to epiphytes cover, and continues with epiphyte cover in the larger-sized species, until the ecosystem is shifted to macroalgae, and subsequently with alga bloom [Green and Short, 2003; Cardoso et al., 2004; Burkholder et al., 2007; Kennish, 2009]. Epiphyte cover can prevent seagrass from obtaining sunlight for photosynthesis. In this study, *E. acoroides* leaves in Rabu Rabu and Panjang Islands were attached by epiphytes (30–90% coverage). The high abundance of epiphytes on seagrass leaves can be triggered by nutrient increase in the water [Prado et al., 2008].

The loss of the seagrass meadow in Tanjung Batu may strengthen the results of this study that the increase in sediment load and nutrients to coastal waters can give impact to seagrass ecosystems. Negative impacts of land use change in mainland have been reported on seagrass ecosystems in Thailand, where species diversity was lower in seagrass beds near the river mouth [Nakaoka et al., 2004], and in the Philippines, where land-based human activities determined seagrass condition [Quiros et al., 2017]. Seagrass cover in Berau water was decreasing towards the river (both in this study and in Van Katjwik et al., 2011), however, species number and diversity seemed to increase since 2003, from previously only two species found in Rabu Rabu and Panjang Islands, into 4–5 species found in those islands in 2019. In our study, species numbers were relatively similar on all islands, except for Sangalaki island. This could also indicate the positive impacts of protection inside the Berau MPA.

Conservation management are mostly focused on the protection inside the MPAs boundaries. However, seagrass threats can come from outside the MPAs [Quiros et al., 2017], and therefore, should also be taken into consideration. The low seagrass cover in this area is a warning that the coastal management should be improved, where the coastal development should implement the concept of sustainability, such as improving domestic waste management and implementing sustainable tourism in small islands. These practises require participation of various stakeholders, not only the MPAs officers, but also local communities and local governments (District and Province) in order to be effective and successful.

CONCLUSIONS

As reported in many areas, poor water quality can be a signal of seagrass degradation. In this study, seagrass ecosystems in Berau and Derawan MPA was categorized as poor (<29.9%) and not healthy (30–59.9%), which was likely due to receive multiple stressors, including an increase of sediment load, poor water quality, overgrazing and tourism expansion. We observed changes in seagrass composition after 15 years, where in current study, larger-sized and adaptive species like *E. acoroides* and *T. hemprichii* were predominantly found on islands located adjacent to mainland or river mouth (Rabu-Rabu and Panjang Islands). These species were found attached by epiphytes. This indicated that the environmental conditions there were may still tolerable for larger species to grow but not suitable for other species (especially smaller and more vulnerable species) to live. The changes on seagrass ecosystems observed in Berau coastal waters due to poor environmental conditions is a warning that conservation on seagrass ecosystems needs to be prioritized by improving the MPA function to avoid further loss of carbon from seagrass ecosystems.

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