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Connectivity of green-blue carbon ecosystems and its implication on sediment carbon sources and stocks in Berau Coastal Water, Indonesia

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ABSTRACT

Connectivity plays a fundamental role in ecological processes by facilitating the exchange of energy and materials in coastal environments. However, its influence on carbon dynamics within coastal ecosystems remains poorly understood. This study investigated the role of ecological connectivity in affecting sedimentary carbon sources and stocks across a range of interconnected coastal habitats in Berau Coastal Waters, Indonesia, ranging from the transition area to upland vegetation, estuarine mangroves, intertidal mudflats, seagrass meadows, and carbonate mangroves on offshore islands. Sediment samples were collected using a 1-meter-long semi-cylindrical hand auger and were analysed for elemental and isotopic compositions. A Bayesian isotopic mixing model was applied to estimate the relative contributions of different organic matter (OM) sources to sedimentary carbon. The transition area and mangrove ecosystems exhibited comparable average sediment carbon stocks (~202 Mg C ha^{-1}), higher than those in the intertidal mudflats (151 Mg C ha^{-1}), despite the absence of vegetation in the latter. The mangrove-derived OM contributed approximately 42–55% of the sedimentary carbon in the transition area, mangrove ecosystem, mudflat, followed by terrestrial plants-derived OM (26–35%). A declining trend in land-based OM was observed along the land-to-sea gradient, with contributions decreasing from ~37% to seagrass sediment at Rabu-Rabu Island to ~19% at Panjang Island. These findings suggest that both distance from source and hydrodynamic forces (e.g., tides and currents) play key roles in transporting OM across the coastal interface. The Berau coastal system thus functions not only as a carbon sink but also as a carbon transport pathway, linking green carbon from terrestrial sources to the blue carbon stored in marine sediments. Recognising and managing this ecological connectivity is essential for maintaining sediment carbon stocks and has important implications for climate change mitigation and carbon crediting frameworks, especially those requiring deductions for allochthonous carbon inputs.

Keywords: allochthonous, autochthonous, blue carbon, connectivity, carbon credits, organic matter, stable isotopes.

INTRODUCTION

Vegetated coastal ecosystems, commonly known as blue carbon ecosystems, such as mangroves, seagrasses, and salt marshes, provide important ecological services, including carbon sequestration (Costa and Macreadie, 2022). These ecosystems take up and store large amounts of carbon on a millennial timescale and therefore contribute to the strategies for mitigating climate change (Pendleton et al., 2012). Located in the intertidal area, blue carbon ecosystems are influenced by both land and ocean. This landscape connectivity enhances the exchange of energy and materials that affect carbon storage capacity, especially in sediments (Hortua et al., 2023). Connectivity is fundamental in the ecological process. It not only promotes the persistence and recovery of populations through the dispersal of marine life across populations and communities (Balbar and Metaxas, 2019) but also facilitates the natural processes that support material transfer across ecosystems and maintain ecosystem health. Studies reveal that habitat connectivity can be a key factor in blue carbon sequestration (Smale et al., 2018). In the places where seagrass meadows are located adjacent to mangrove ecosystems, a large proportion of carbon buried in seagrass is derived from mangroves (allochthonous derived), which suggests that carbon stocks can be enhanced by the proximity to adjacent ecosystems (Huxham et al., 2018).

Identifying the source of organic carbon (OC) is essential in understanding carbon cycling and sequestration in coastal ecosystems (Bouillon et al., 2008), particularly in the areas that exhibit ecosystem connectivity. The relative contributions of allochthonous and autochthonous OC in sediments can influence the overall quality of sedimentary carbon stocks (Watanabe and Kuwae, 2015; Mazarrasa et al., 2017). However, long-term organic matter (OM) burial is primarily governed by the quality (concentration) or lability of the OM rather than its origin (Hedger and Keil, 1995; Xia et al., 2023). Different types of OM vary in chemical composition and stability, thereby contributing differently to carbon sequestration (Saintilan et al., 2013). Organic matter additions can enhance sediment organic content only when they do not stimulate microbial mineralisation or lead to decomposition into CO_2 (Xia et al., 2023; Zhang et al., 2024). Ghosh and Leff (2013) investigated the bacterial preferences for different types of organic carbon—labile versus recalcitrant—and found that bacteria preferentially utilised readily available labile organic carbon sources.

Identifying the origin of organic carbon is also a critical component of the Measuring, Reporting, and Verification (MRV) framework in carbon projects. It helps prevent double-counting of carbon credits, as required by certification standards like VERRA's verified carbon standard (VCS) methodology for wetlands restoration (VM0033) and the Gold Standard methodology for mangrove management, which expects projects to generate carbon primarily by increasing autochthonous soil OC and deducting the contribution of allochthonous carbon from total carbon calculations (Needelman et al., 2018; Emmer et al., 2023). However, in the context of ecosystem carbon dynamics, allochthonous organic matter is essential in subsidizing the local carbon budget, and when the allochthonous OM is recalcitrant (e.g., lignin-rich plants), it provides a net gain in carbon sequestration potential due to its slow degradation (Bianchi et al., 2011; Cragg et al., 2020).

Most studies on sediment carbon sources and stocks often lack representation across the land-to-sea gradient, which is essential for understanding the role of landscape connectivity in carbon dynamics. This study aimed to identify sedimentary carbon sources and stocks across the coastal interface—from the transition zone between mangrove and upland vegetation, estuarine mangroves, intertidal mudflats, seagrasses on small islands, to carbonate mangroves on small islands—in the Berau Coastal Water, Indonesia, to better assess the blue carbon potential along the land-coast gradient. This site offers a comprehensive green-blue carbon ecosystem for examining the interconnections and effects on carbon sources and stocks. The study employed stable isotopes and the OC/N ratio to determine the sources of carbon contributing to sedimentary carbon stocks. Stable isotopes of carbon and nitrogen ($\delta^{13}C_{org}$ and $\delta^{15}N$) are commonly utilised to identify carbon sources in coastal sediment (Kennedy et al., 2010). Although stable isotopes have limitations due to substantial overlap in signatures among different organisms (Reef et al., 2017), they remain valuable tools for identifying organic matter sources, especially when combined with other proxies, such as the OC:N ratio (Kusumaningtyas et al., 2018).

METHODOLOGY

Study site

The study was conducted in Berau Coastal area, East Kalimantan, Indonesia (2°26'N – 1°43'N; 117°39'E – 118°36'E). This site demonstrates strong green-blue carbon ecosystem connectivity, with tropical rainforest vegetation in the uplands and mangrove ecosystems in the estuary. The mangrove forests in Berau represent the most extensive coverage in East Kalimantan, spanning 80,277 hectares (Wiryawan et al., 2005). Berau coastal area is influenced by rivers (Berau and Tabalar) and strong currents, forming an extensive intertidal mudflat seaward of the mangrove area. Mangroves, mudflats and seagrasses serve as a vital buffering zone for the Derawan Islands—coral islands the surrounding waters of which host some of the richest marine biodiversity on Earth (Wiryawan et al., 2004; Tomascik and Mah, 2013). This landscape exemplifies strong connectivity between land and sea ecosystems. However, the remaining primary mangrove forests there are facing various pressures, especially land conversion for shrimp farming (Sahri et al., 2013; Fasabbih et al., 2025). Recognising the importance of the mangrove ecosystem in sustaining marine biodiversity and supporting local fisheries, various stakeholders, including the local government, have initiated mangrove rehabilitation efforts in the area (Berau Regency, 2020).

Data sampling for this study was undertaken in September 2018, covering the areas of Karang Tigau, Tanjung Batu, Semanting, and Panjang Island (Figure 1). These areas represent stations with varying influence from the Berau River, ranging from less influenced (Karang Tigau) to more influenced (Tanjung Batu and Semanting), characteristic of estuarine settings. Meanwhile, the mangrove ecosystem on Panjang Island exhibits characteristics typical of marine/carbonate settings.

Sample collection

Sediments were taken in different zones: in the intertidal mudflats (A), in mangrove ecosystems (B), and in the transition zone between mangroves and upland vegetation (C). Sediment samples were extracted using a 1-m-long semi-cylindrical hand auger (with a diameter of 6.35 cm). One sediment core was collected per zone at each of the three study sites (Karang Tigau, Tanjung Batu, and Semanting), serving as spatial replicates for each zone. Samples were also taken from mangrove ecosystems in the Panjang Island, which represent marine settings. To understand the sequence values across the coastal interface, seagrass sediment carbon data in Rabu-Rabu and Panjang Islands were also used based on a study by Rustam et al. (2024). The sediment samples were divided into 5 cm intervals, stored in plastic bags, and secured in an icebox upon transfer to the laboratory. Samples of mangrove leaves from different species found at the study sites were also collected as a reference for organic matter.

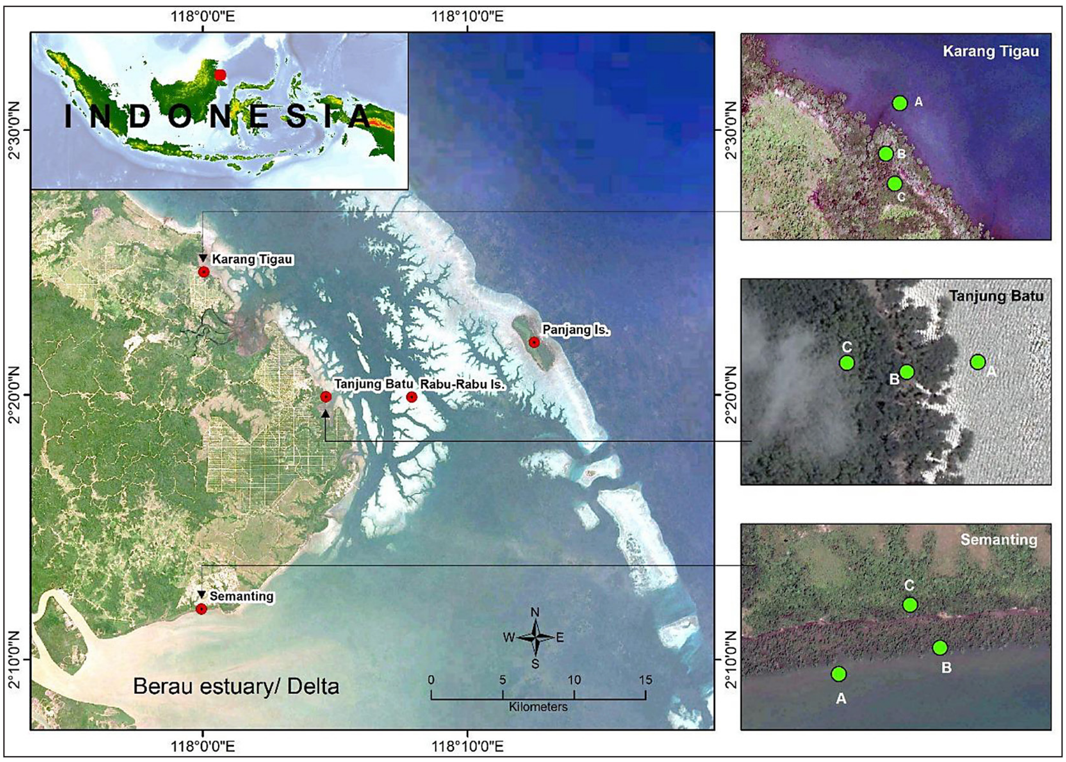

Figure 1. Location of the study. Station A is located in the intertidal mudflat, station B is located in the estuarine mangrove ecosystems, and station C is located in a transition zone to upland vegetation

Laboratory analysis

The sediment and mangrove leaf samples were oven-dried, weighed, and ground to a fine powder. A 4 N HCl was subsequently added to the sediment samples to eliminate inorganic components, particularly carbonates. Carbon and nitrogen contents, along with $\delta^{13}C_{org}$ and $\delta^{15}N$ isotope compositions, were simultaneously measured using a combined elemental analyser and isotope ratio mass spectrometer (ThermoFisher Scientific). Isotopic ratios were expressed in standard δ notation (‰), using Vienna Pee Dee Belemnite as the reference standard.

Carbon stock calculation

Sediment carbon stock was measured by multiplying the organic carbon content (% dry weight), sediment thickness (cm), and dry bulk density (g/cm^3) which was calculated by dividing the dry weight of the samples by their initial volume. The total sediment carbon stock was obtained by summing the carbon stocks throughout the 1-meter core. The measurements were converted to the standard unit commonly reported in carbon stock studies of Mg C ha^{-1}.

Stable isotope mixing model

To estimate the relative contributions of different OM sources to sediment carbon, the Bayesian isotopic mixing model package Stable Isotope Mixing Model in R (SIMMR) was used (Parnell and Inger, 2023; R Core Team, 2017). The model utilises the Markov Chain Monte Carlo (MCMC) algorithm to estimate source proportions within the observed mixtures (size of burn-in = 1000, amount of thinning = 10, number chains = 4, number of iterations = 10.000; Parnell et al., 2013). In the model, both $\delta^{13}C_{org}$ values and OC:N ratios of sediment samples (the mixtures) and the potential OM—mangrove leaves, seagrass leaves, terrestrial plants, and plankton— were incorporated as source references. The isotopic and elemental signatures of mangrove leaves were measured in this study ($\delta^{13}C_{org}$ = -30.4 ± 0.9 ‰; OC/N = 45.9 ± 13.7), while reference values for the other OM sources were obtained from regionally relevant literatures. Terrestrial plants were from Kuramoto and Minagawa (2001), oceanic plankton were from Gillis et al., (2014), and seagrass leaves were from Rahayu et al., (2019).

In the isospace plot or the plot of $\delta^{13}C_{org}$ (‰) and OC/N (Figure 2), most of the mixtures (sediment samples) lie inside the polygon. Generally, in the linear mixing model, if the mixtures are inside the polygon, then the sources are good predictors and the model can be run, while if the mixtures are lying outside of the polygon, the model cannot be run, because either the sources are missing, or the data are wrong. However, the Bayesian mixing model evaluates source distribution even when the model is unlikely to satisfy the point-in-polygon, as it incorporates uncertainties in the model (Parnell and Inger, 2023).

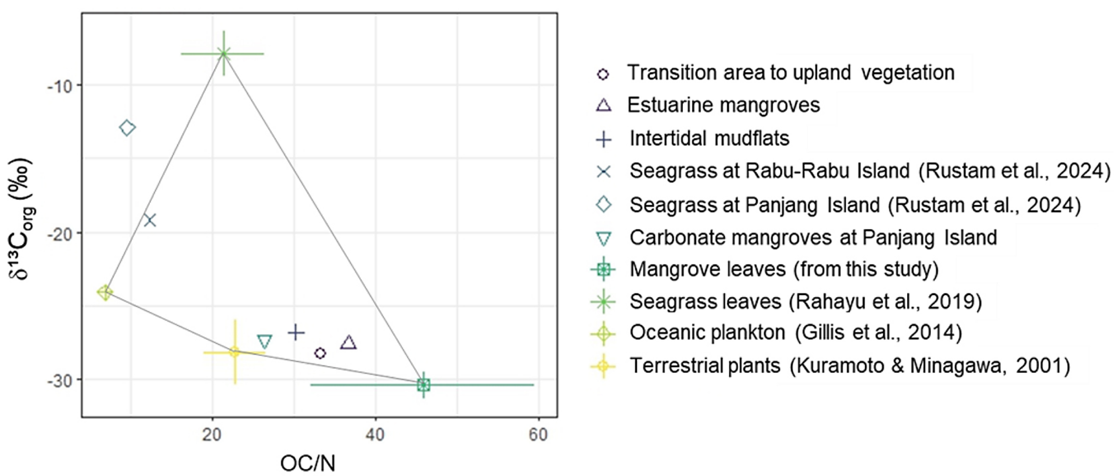

Figure 2. The $\delta^{13}C_{org}$ (‰) versus OC/N plot for both the sediment mixtures and various OM used as a reference source

Statistical analysis

To test for significant differences in each parameter across the coastal interface — the transition area to upland vegetation, the mangrove ecosystem, and the intertidal mudflat — a one-way ANOVA was performed.

RESULTS

Comparison of sedimentary carbon stocks

On average, sediment carbon stocks in the transition zone to upland vegetation (202.1 ± 90.8 Mg C ha^{-1}) did not differ from those in mangrove ecosystems, both in the estuarine setting and in the marine setting (202.5 ± 46.7 Mg C ha^{-1} and 203.7 Mg C ha^{-1}, respectively). However, those values are higher than those in the intertidal mudflat (151 ± 65.8 Mg C ha^{-1}; Table 1).

Trend of elemental and isotopic compositions across zones

The results of the One-Way ANOVA test indicate that there is a significant difference in OC content among the transition area, mangrove, and mudflat, $F(2, 33) = 12.46$, $p < 0.05$, with a decreasing pattern from the transition area toward the mudflat (Table 2). However, no difference in OC was observed between the mangroves in the estuarine setting and marine setting, $F(3, 12) = 3.04$, $p = 0.07$. No significant difference was also measured in $\delta^{13}C_{org}$ and $\delta^{15}N$ values ($p > 0.05$) among areas, although the value of $\delta^{13}C_{org}$ showed an increase from land toward seagrass meadows (Table 2). In contrast, the N content shows a significant difference among areas, $F(2,33) = 11.21$, $p < 0.05$.

DISCUSSION

Contribution of organic matters to sediment carbon stocks

Carbon stocks of mangrove ecosystems in this study (186.3–255.2 Mg C ha^{-1}; Table 1) are below the global mangrove sediment carbon stocks in top 1 m of 516.4 ± 19.8 Mg C ha^{-1} reported by Alongi (2022), and lower than those previously reported in the same area of 485 Mg C ha^{-1} (Kusumaningtyas et al., 2018) and 310 Mg C ha^{-1} (Weiss et al., 2016). However, the amounts are comparable with those reported from a global dataset of 282–250 Mg C ha^{-1} by

Table 1. Sediment carbon stock in three zones (transition to upland, mangrove, and intertidal mudflat) across three study sites, including a mangrove on a carbonate island. The reported mean and standard deviation (SD) values represent zone-level averages across the sites

Stations	Transition to upland (Mg C ha^{-1})	Mangroves (Mg C ha^{-1})	Intertidal mudflats (Mg C ha^{-1})
Estuarine setting			
Karang Tigau	303.2	255.2	217.3
Tanjung Batu	127.2	166.0	85.7
Semanting	176.0	186.3	150.1
Mean ± SD	202.1 ± 90.8	202.5 ± 46.7	151.0 ± 65.8
Marine/carbonate setting			
Panjang Island	-	203.7	-

Table 2. Elemental and isotopic compositions (mean values ± SD) of sediment organic matter in the study sites (n = number of core)

Parameters	Transition to upland (n=3)	Estuarine mangrove (n=3)	Intertidal mudflat (n=3)	Seagrass Rabu-Rabu (*)	Seagrass Panjang Island (*)	Mangrove Panjang Island (n=1)
$\delta^{13}C_{org}$ (‰)	-28.2 ± 0.4	-27.5 ± 0.3	-26.9 ± 0.3	-19.2	-12.9	-26.9 ± 0.4
$\delta^{15}N$ (‰)	1.20 ± 1.98	2.81 ± 3.17	2.31 ± 0.90	3.95	2.40	4.50 ± 0.33
OC (%)	6.4 ± 4.3	2.3 ± 0.6	1.3 ± 0.5	2.9	2.3	3.9 ± 1.4
N (%)	0.22 ± 0.14	0.07 ± 0.02	0.05 ± 0.02	0.27	0.28	0.16 ± 0.04
OC/N (atomic)	33.4 ± 5.4	36.7 ± 4.7	30.3 ± 4.9	12.4	9.6	26.5 ± 5.5

Note: (*) surface sediment (Rustam et al., 2024).

Zhang et al. (2024). The lower mangrove sediment carbon stock observed in this study is likely due to the reduced carbon content resulting from dilution by riverine inputs. Inorganic minerals, particularly suspended matter delivered by the river, can dilute the concentration of OC in sediments, especially in the areas influenced by turbid river discharge, as noted in previous studies (Suello et al., 2022; Soria-Reinoso et al., 2022). The mangrove sediment OC content observed in this study (2.3–3.9% dry weight) is comparable to that reported in seagrass sediments (2.3–2.9% dry weight (DW); Rustam et al., 2024), which are also often subject to dilution from carbonate sources (Mazarrasa et al., 2015). The OC content observed is considerably low, as previous studies have reported values as high as 15–19% DW in West Papua (Sasmito et al., 2019). On the basis of the proximity to the Berau River, the highest carbon stocks (transition, mangrove, and mudflat areas) were observed in Karang Tigau (the site farthest from direct river influence) followed by Panjang Island, suggesting that reduced dilution by river-derived inorganic carbon contributes to higher sediment carbon stocks.

From a land–sea gradient perspective, the transition area and the mangrove ecosystem exhibit similar mean carbon stocks (Figure 3). However, they differ in OC content, with sediments in the transition area showing higher OC levels compared to those in the mangrove and mudflat zones (Figure 4). Despite the higher OC content, the values in the transition area decrease with depth, which likely results in a comparable total carbon stock across these areas. This vertical decline in OC is commonly observed in terrestrial forest soils, where OC content generally decreases with depth due to increased bacterial mineralisation (Dorji et al., 2014). In contrast, OC content in estuarine mangroves slightly increases with depth, while in mudflats it tends to remain relatively constant. Similar patterns have been reported in other mangrove ecosystems (Suello et al., 2022), often attributed to tidal influences that create anaerobic conditions and inhibit microbial decomposition in the sediment (Brodersen et al., 2019). In addition, organic matter decomposition are influenced by sediment texture (Guo et al., 2024). Finer sediments (e.g., silt and clay) are generally more effective at retaining organic material than coarser, sandy sediments. This pattern is evident in the coarse sandy sediments of mangroves on Panjang Island, where OC content tends to decrease with depth, in contrast to the finer sediments of estuarine mangroves (Figure 4). However, although sediments from the transition area also exhibit a downcore decline in OC despite their finer texture, this may be influenced by other factors, such as redox conditions and microbial activity (Canfield, 1994; Dorji et al., 2014).

The average carbon stocks in vegetated areas (the transition zone and mangrove ecosystems) are higher than those in the intertidal mudflats. However, despite the absence of vegetation, intertidal mudflats still contain substantial carbon stocks, ranging from 150 to 217 Mg C ha^{-1}. These values are comparably higher than the global average for top-meter intertidal mudflats, which is 83.6 Mg C ha^{-1} (Chen and Lee, 2022). They also exceed the values reported from mudflats in Chek Jawa, Singapore (124–143 Mg C ha^{-1}; Phang et al., 2015) and Bintuni Bay, Indonesia (62 ± 10

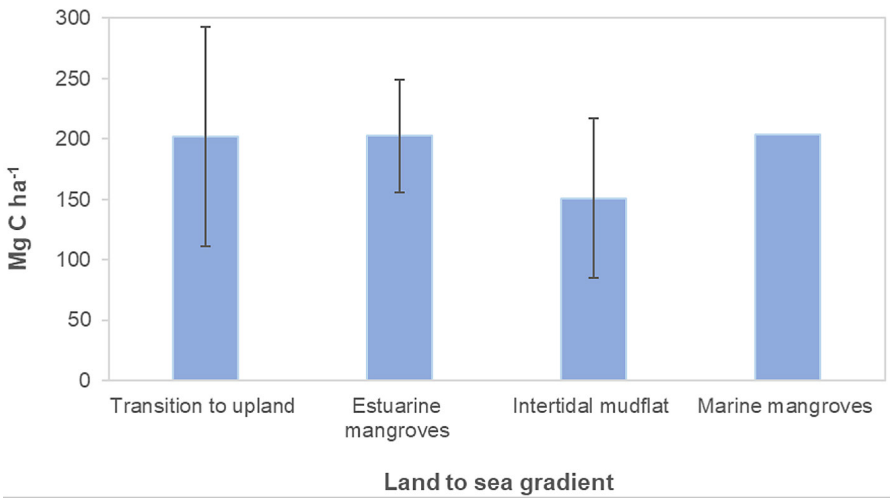

Figure 3. Variation in sediment carbon stocks along the land to sea gradient

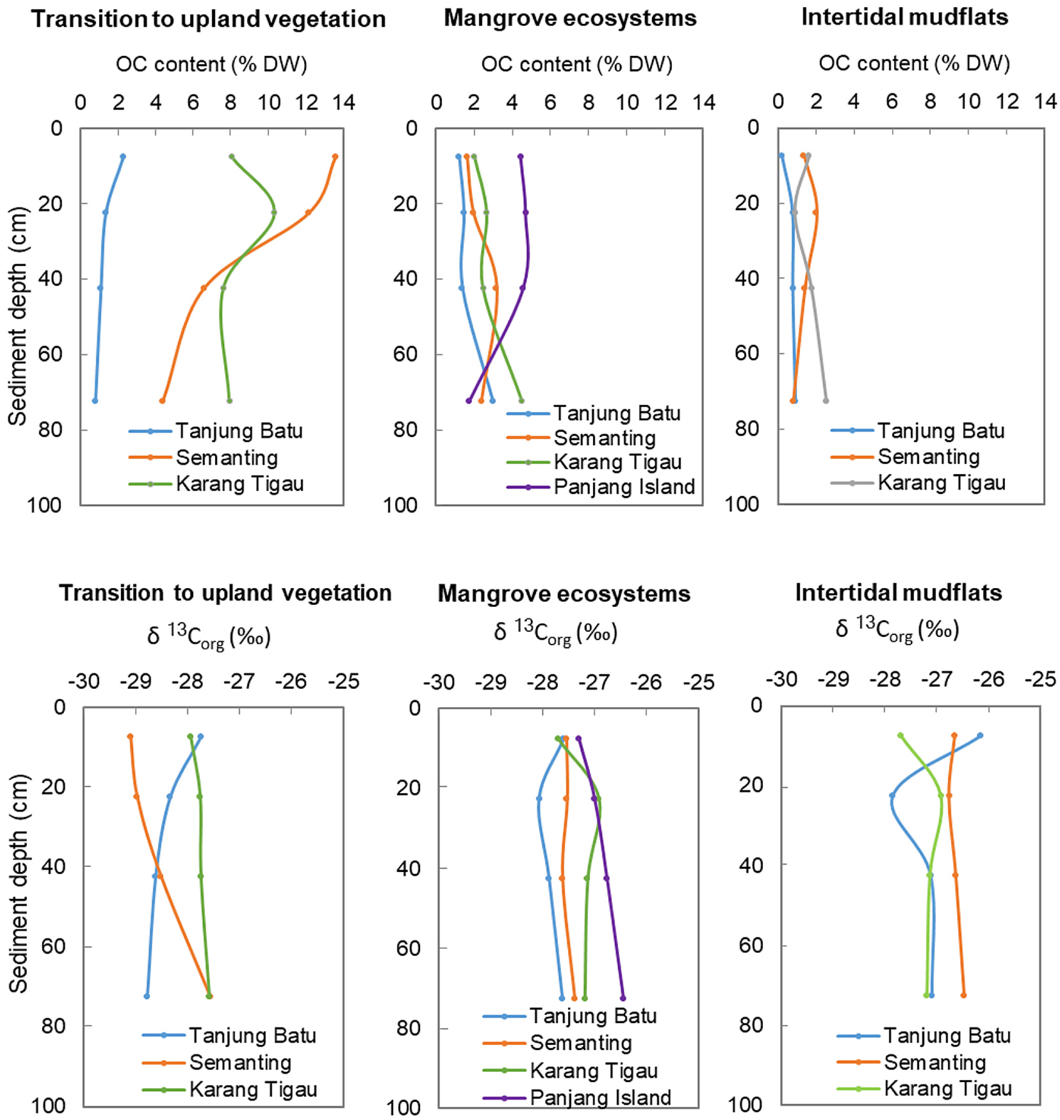

Figure 4. Downcore profile of OC content (% DW) and $\delta^{13}C_{org}$ (‰) in the transition area to upland vegetation, mangrove ecosystems, and intertidal mudflats in Berau

Mg C ha^{-1}; Sasmito et al, 2020). The primary sources of carbon in the intertidal mudflat are mangroves (~42%) and terrestrial plants (~35%; Figure 5), contributing to the relatively high carbon stocks. Similar source patterns have been observed in Bintuni Bay, where sedimentary carbon is also predominantly derived from mangroves and upland vegetation (Sasmito et al., 2020). These finding suggest that the intertidal mudflats in Berau appear to function as important carbon reservoirs and transport pathways, facilitating the transfer of carbon from terrestrial sources to adjacent marine ecosystems, consistent with patterns reported from other regions (Chen and Lee, 2022). In contrast, oceanic plankton contributed less to the mudflat (~13%) than to the mangrove ecosystems (~15%). Although both systems are influenced by tidal activity and receive labile organic matter such as plankton, mudflats likely experience more rapid decomposition and direct consumption of fresh plankton by filter-feeding organisms (Griffen et al., 2004), due to their open hydrology and lack of vegetation. Moreover, respiration rates in unvegetated mudflats have been reported to increase during summer (Lin et al., 2021), aligning with elevated daytime temperatures during field data sampling, which likely accelerate the decomposition of organic matter in these environments.

According to the stable isotope mixing model, mangrove-derived OM) contributed over 50% to sediment carbon in the transition area and in the mangrove ecosystem (Figure 5), followed by terrestrial plants, which contributes approximately

26–29%. On a global scale, autochthonous organic matter originating from mangroves accounts for approximately 49–62% of OC in the top meter of sediment (Zhang et al., 2024). The relatively high contribution from mangrove and terrestrial plants likely influenced the substantial carbon stocks observed in the study area. Mangrove litter is an important source of organic matter accumulating coastal sediments (Jennerjahn and Ittekkot 2002). This is partly due to the high productivity of mangroves and the greater resistance of their plant material to microbial decomposition compared to more labile sources, such as phytoplankton (Enriquez et al., 1993; Holmer and Olsen, 2002), allowing the material to persist longer in the sediment. During the dry season, mangrove litter production in Berau was estimated at approximately 15.45 metric tons per hectare annually, which is moderately higher than the litter production reported in other regions of Indonesia (Yuniarti et al., 2016) and is expected to increase during the rainy season (Soeroyo, 2003; Sukardjo et al 2013). While about 50% of OC is buried within the mangrove ecosystems, the remaining portion is transported to adjacent ecosystems. This suggests that mangroves in Berau play a vital role in the regional carbon budget by supplying a significant amount of organic matter both autochthonously and allochthonously to surrounding areas.

The distribution of land-based OM originating from terrestrial and mangrove plants on the Berau mainland shows a decreasing pattern from the transition area toward the seagrass meadow at Panjang Island (Figure 5). According to Rustam et al. (2024), terrestrial-derived particulate matter has been transported as far as Rabu-Rabu Island, influencing seagrass cover in the area. Despite potential ecological impacts, this allochthonous input also contributes significantly to carbon burial in seagrass sediments, accounting for approximately 37% at Rabu-Rabu Island and 19% at Panjang Island. The lateral decline in OM contribution highlights the role of distance as key factor influencing carbon burial in adjacent seagrass ecosystems. In tidal estuary systems like Berau, hydrodynamic forces such as tides, waves, and currents play a crucial role in transporting particulate organic matter from riverine to coastal zones (Takasu et al., 2020). For instance, Gillis et al. (2014) found that wave exposure can reduce the trapping efficiency of mangrove roots, thereby increasing the export of organic matter to surrounding areas. Furthermore, hydrodynamic modelling has demonstrated that tidal pumping is a major driver of material transport from terrestrial sources to coastal areas within the tidally influenced regions of the Berau Delta (Tarya et al., 2023). Tides and currents rework the organic-rich material delivered by rivers, with some fraction is deposited in intertidal mudflats and the rest is resuspended and transported further offshore, eventually reaching the seagrass ecosystems around Rabu-Rabu and Panjang Islands.

This study highlighted the crucial role of ecosystem connectivity in facilitating carbon

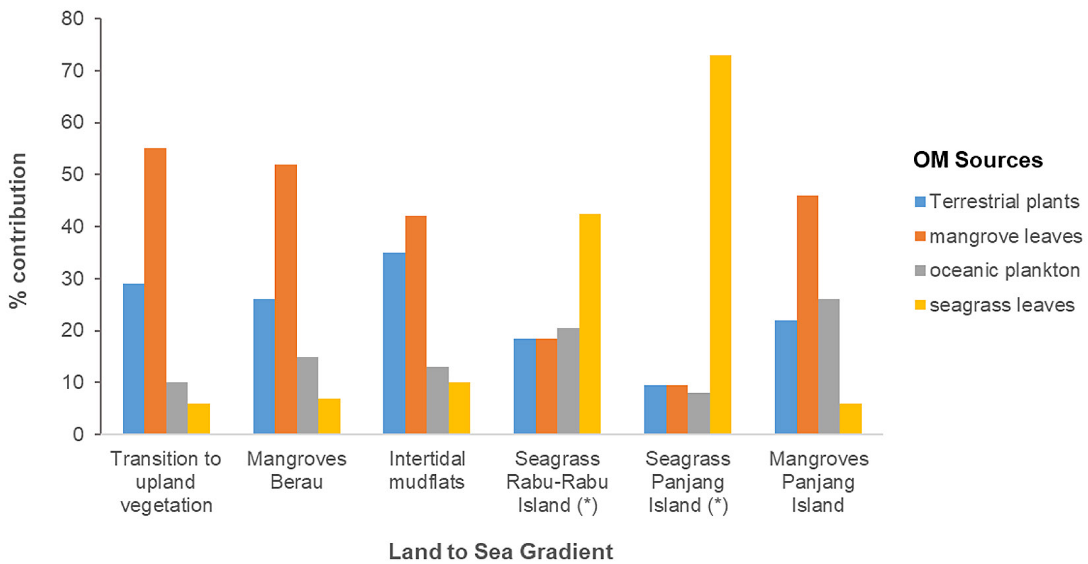

Figure 5. Comparison of percent contribution (median values) of OM along the land-to-sea gradient based on the stable isotope mixing model; (*) Rustam et al., 2024

storage and transfer across coastal ecosystems. The Indonesian government, through the Ministry of Marine Affairs and Fisheries (KKP), has expressed a strong commitment to strengthening blue carbon management synergies in coastal and small-island areas as part of its climate change mitigation and adaptation strategy in the marine sector. Strategic actions include integrating blue carbon ecosystems into marine spatial planning, supported by the regulations aimed at protecting and enhancing carbon stocks (KKP, 2023). In this study, Rabu-Rabu and Panjang Islands, both part of the Derawan Marine Protected Area (MPA), receive organic matter from the mangrove ecosystems in Berau. This highlights the importance of ecological connectivity in enhancing blue carbon stocks within the MPA. Strengthening coastal management strategies that reinforce the linkages between green and blue carbon ecosystems could potentially increase carbon sequestration both within and beyond the protected areas.

Implication to carbon credits

In carbon credit methodologies, such as the VCS for Wetland Restoration and Conservation (VERRA, 2023), connectivity is considered one of the key criteria. Projects with hydrological connectivity must ensure that their design does not lead to unintended greenhouse gas (GHG) emissions caused by ecological leakage—a scenario in which restoration in one area leads to increased emissions in adjacent areas (Emmer et al., 2023). This reflects a growing recognition that connectivity in coastal ecosystems plays a critical role in carbon transport and distribution, particularly in the systems with high inputs of allochthonous OM.

Despite the importance of connectivity, many carbon credit methodologies still require the deduction of allochthonous organic carbon (OC) when calculating eligible carbon credits (VERRA, 2023; Gold Standard, 2024). Some schemes, such as the Methodology for Sustainable Management of Mangroves (Gold Standard, 2024), allow the inclusion of allochthonous OC if additionality can be demonstrated that this carbon would have otherwise been released into the atmosphere without the implementation of the project (Houston et al., 2024). In contrast, others, like Australian BlueCAM methodology, do not require any deduction of organic carbon (Lovelock, 2022). However, there is still no standardized scientific method for calculating allochthonous OC in blue carbon projects (Houston et al., 2024), leading to inconsistencies and uncertainty across schemes. While the current guidelines under the VCS (VERRA, 2023) permit estimation of allochthonous OC using field measurements, modelling, or peer-reviewed literatures, they lack methodological clarity. This study provided field-based evidence from a highly connected coastal system, which may help inform and support future efforts to quantify and account for allochthonous OC in carbon credit assessments.

CONCLUSIONS

This study highlighted the critical role of land–sea connectivity in affecting sediment carbon stocks and the distribution of OM across interconnected coastal ecosystems in the Berau region. Clear spatial patterns observed along the land–sea gradient, where the highest carbon stocks were measured in vegetated areas (the transition zone and mangrove ecosystems) approximately 202 Mg C ha^{-1}. Intertidal mudflats, despite being unvegetated, also exhibited relatively high carbon stocks (~151 Mg C ha^{-1}), exceeding global averages for similar environments. These values are largely driven by the dominant contributions of mangrove-derived OM (~42–55%) and terrestrial plant sources (~26–35%), with decreasing contributions observed toward seagrass meadows at Rabu-Rabu and Panjang Islands (~37% and ~19%, respectively). Hydrodynamic processes, such as tides, waves, and current, facilitate the movement of land-based OM into adjacent marine systems. This lateral carbon flux demonstrates that the Berau coastal system functions not only as a carbon sink but also as a carbon transport pathway, linking green carbon from terrestrial sources to blue carbon stored in marine sediments. Understanding the origin of sedimentary organic carbon is essential for accurately estimating coastal carbon budgets and informing blue carbon conservation and policy. In particular, the identification of allochthonous carbon inputs is increasingly relevant for carbon crediting mechanisms, which often require the exclusion of allochthonous carbon sources when calculating eligible credits. Therefore, identifying OM sources and quantifying their contributions is critical for ensuring the scientific integrity and financial credibility of blue carbon projects. Maintaining and enhancing land–sea connectivity is fundamental to supporting long-term carbon storage across coastal ecosystems. Accordingly, conservation strategies and marine spatial planning efforts should account for these ecological linkages to maximise carbon sequestration potential.

Acknowledgements

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