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Assessment of soil fraction, carbon storage capacity, and rate of carbon uptake from three coastal ecosystems: Mangroves, seagrass, and mudflats in Benoa Bay, Indonesia

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Abstract. *Dharmayasa IGNP, Sugiana IP, Putri PYA, Boonyasana K. 2024. Assessment of soil fraction, carbon storage capacity, and rate of carbon uptake from three coastal ecosystems: Mangroves, seagrass, and mudflats in Benoa Bay, Indonesia. Biodiversitas 25: 2541-2549.* Coastal habitats, known as blue carbon ecosystems, are highly productive at absorbing and storing carbon. Most carbon is stored as soil organic carbon, and its quantity can vary depending on various factors, including the presence of plants such as mangroves and seagrass, and environmental conditions, including soil fraction. This study quantifies soil carbon stored and its burial rate in three primary coastal ecosystems: mangroves, seagrasses, and mudflats. The ashing method (loss on ignition) is used to quantify carbon content, which is then converted into soil carbon storage and burial rate. Gravimetry and the settling time method are used to determine the soil fraction. We also measure the soil and water properties directly during the sampling time. This study revealed significant soil carbon stock and burial rate variations across different ecosystems. The order of ecosystems with the most extensive carbon stock and burial rate is as follows: mangrove (69-145 tC ha^{-1} and 1.6-3.4 tCha^{-1}yr^{-1})>seagrass (63-75 tC ha^{-1} and 1.5-1.7 tCha^{-1}yr^{-1})>mudflat (49-61 tC ha^{-1} and 1.2-1.4 tCha^{-1}yr^{-1}). Mangroves with natural growth have a higher carbon storage capacity than rehabilitated ones. Soil carbon content is highly correlated with the soil and water pH, Dissolved Oxygen (DO), water content, bulk density, and soil type. The findings demonstrate that carbon absorption capability varies among coastal habitats, with vegetated environments exhibiting higher carbon storage levels. Converting land, particularly mudflats, into seagrass beds or mangrove forests may maximize the efficiency of coastal ecosystems as carbon sinks. However, it should be noted that these findings are only estimates, and the precise measurement numbers may differ due to seasonal circumstances or reclamation activities, which might cause oscillations in sedimentation rates. These variations, in turn, could affect the levels of carbon stored and the speed at which it is buried.

Keywords: Gravimetry, loss on ignition, mangrove, mudflat, seagrass, settling time method

INTRODUCTION

The occurrence of global warming has become a substantial issue that is being discussed on a worldwide scale. An indication of global warming is the increase in the Earth's atmosphere's average temperature, which results from rising carbon dioxide (CO_2) levels. The concentration of CO_2 has risen to 409.9 parts per million (ppm) since the pre-industrial era in 1750 (IPCC 2021). Human activities, including the combustion of fossil fuels, the release of pollutants from transportation, and deforestation, are the main contributors to the increasing concentrations of CO_2 in the atmosphere. The occurrence of global warming has resulted in substantial modifications in worldwide climatic patterns, mostly rainfall patterns and speed up polar ice melting, and this, along with thermal expansion, has caused an increase in seawater levels (Khan 2019; Dharmayasa et al. 2022; Dervash et al. 2023). Many strategies have been implemented to tackle the escalating issue of elevated carbon dioxide emissions in the Earth's atmosphere. One of these initiatives is to enhance the capacity of productive wetlands to absorb and retain carbon by strategically afforesting trees, particularly in coastal habitats (Moomaw et al. 2018; Serrano et al. 2019). This approach is being implemented to conserve and restore ecosystems, specifically mangrove forests, seagrass, and other wetlands, which have a significant capacity to capture and store carbon (Twilley et al. 2017).

Coastal ecosystems are complex and dynamic since both land and sea conditions influence them. Indonesia's most often observed coastal ecosystems are mangrove, seagrass, and mudflat environments. The total area of mangrove forests in Indonesia is 19.5% of the total world mangrove area (Bunting et al. 2018), and the seagrass beds occupy 875,967-1,847,341 hectares (Martha 2017; Sui et al. 2020). These mangroves are called blue-carbon ecosystems because they can absorb and store more carbon than terrestrial ecosystems, except wetland ecosystems. Specifically, mangrove forests can absorb three times the amount of CO_2 compared to terrestrial forests (Alongi 2014). Studies conducted by Kusumaningtyas et al. (2019) showed that mangrove forests in Indonesia have effectively sequestered a quantity of CO_2 up to 1722±183 g C m^{-2} yr^{-1} from a total area of 875,967 hectares (Wahyudi et al. 2020). According to Arifanti et al. (2022), there are ongoing attempts to improve the management and conservation of ecosystems in Indonesia to maximize their capacity to absorb and retain carbon dioxide.

Mangroves and seagrass store most of their carbon in the soil as organic carbon. Around 80% of the overall carbon stored in the mangrove ecosystem is found in the soil, while the remaining portion exists as biomass (Murdiyarso et al. 2015; Kauffman and Bhomia 2017). However, this distribution can be altered by the soil type variations (Xiong et al. 2018). Typically, soil fractions with a finer texture, like clay and loam, have a greater carbon content than sandy soil (Matus 2021; Amorim et al. 2023). Seagrass beds are primarily characterized by sandier soil, while muddy soil is commonly seen in mangrove ecosystems (Hogarth 2015). In such circumstances, variations in carbon levels may occur in both ecosystems, even if they are close to each other.

Several studies have been undertaken to evaluate the amount of carbon stored in the soil of coastal ecosystems. The soil carbon stocks in similar areas have been assessed in research by Dewanti et al. (2020), Sugiana et al. (2023), Sugiana et al. (2024), Ainindya et al. (2024). However, these investigations were restricted to the mangrove ecosystem. Rahadiarta et al. (2019) and Parnata et al. (2020) conducted research on carbon stock in seagrass vegetation. However, measurements of seagrass soil and the mudflat in Benoa Bay have yet to be carried out. This will likely contribute to carbon storage capacity since coastal ecosystems may have different soil fractions (where soil fraction is the relative proportions of sand, silt, and clay). Hence, exploring the relationship of soil fraction to ecosystem type could provide valuable insights as it has seldom been examined in previous research.

This study aims to quantify the carbon storage capacity and rate of carbon uptake in the soil of coastal ecosystems (mangroves, seagrass, and mudflat) and provide data on the extent of the difference in carbon storage between different ecosystems. This study substantially contributes by collecting carbon budget data from three coastal ecosystems in Indonesia. Our findings provide significant scientific benefits and should contribute to preserving and administrating wetland ecosystems in Indonesia.

MATERIALS AND METHODS

Study site

This research site is in Benoa Bay, Bali, Indonesia, with coordinates 8°42'50.46"S-8°47'49.92"S and 115°10'9.42"E-115°15'13.19"E. This bay is a semi-open water body with two mouths flowing directly into the open sea. Mangrove forest dominates the coastal area of Benoa Bay, covering an area of 1,373.5 hectares, whereas seagrass beds are mostly found at the mouth and outside the bay area (Figure 1). The dominant species in the mangrove forest are *Rhizophora* spp. and *Sonneratia alba* Sm., with a moderate health condition and varying tree density (Sugiana et al. 2022). Meanwhile, the seagrass meadows predominantly consist of the large seagrass species *Thalassia hemprichii* (Ehrenb. ex Solms) Asch. and *Cymodocea rotundata* Asch. & Schweinf. We established sampling points with 6 points in the mangrove region (3 from rehabilitated areas and 3 natural growth areas) and 3 points in the seagrass meadow area. We also selected a reference point in areas without mangrove or seagrass vegetation (mudflat). The data collection distribution points are shown in Figure 1.

Soil sample and water properties measurement

Soil samples were obtained using a soil auger with a 5 cm diameter at 0-100 cm depth. We took 3 samples at each point with a distance between repetitions of approximately 5 meters. After homogenizing the soil, we collected and stored 200 g of the soil in plastic containers. Therefore, 100 g of soil was dried at 70°C to determine the water content percentage until reaching a consistent weight, which took approximately 48 hours. Additionally, we dried another 100 g of soil at 105°C to measure the bulk density value by comparing the dry weight of the soil and auger volume. The dried soil samples were reused for grain size analysis (10 g) and Soil Organic Carbon (SOC) measurement (3 g). We used the dry sieve method (gravel: 2 mm, sand: 1.1 mm-75 µm) and the settling time method for silt and clay categorization for soil grain size analysis. We used the Loss On Ignition (LOI) method for SOC, and the samples were burned at a temperature of 550°C (Chen et al. 2014).

Since the data collection was conducted during low tide, water samples were mostly found at 30-70 cm from the soil surface (except for seagrass plots, which were found at a depth of 10-30 cm). We measured several parameters, including temperature, pH, and salinity, using the Multimeter COM-600 Water Quality Tester, and the dissolved oxygen (DO) was measured using a Lutron DO-5519 meter. Water quality was measured after soil sampling by waiting for the water to stabilize (±15 minutes).

Soil carbon stock and burial rate calculation

The carbon burial rate in soil within the coastal ecosystem is derived using a comprehensive calculation that considers the values of bulk density, percentage of organic carbon, and soil accretion rate.

$$SCB = BD \times C_{org} \times SAR$$

Meanwhile, soil carbon stock is calculated using the equation:

$$SCS = BD \times C_{org} \times H$$

Where:

SCB : Soil carbon organic burial rate ($tC.ha^{-1}.yr^{-1}$)

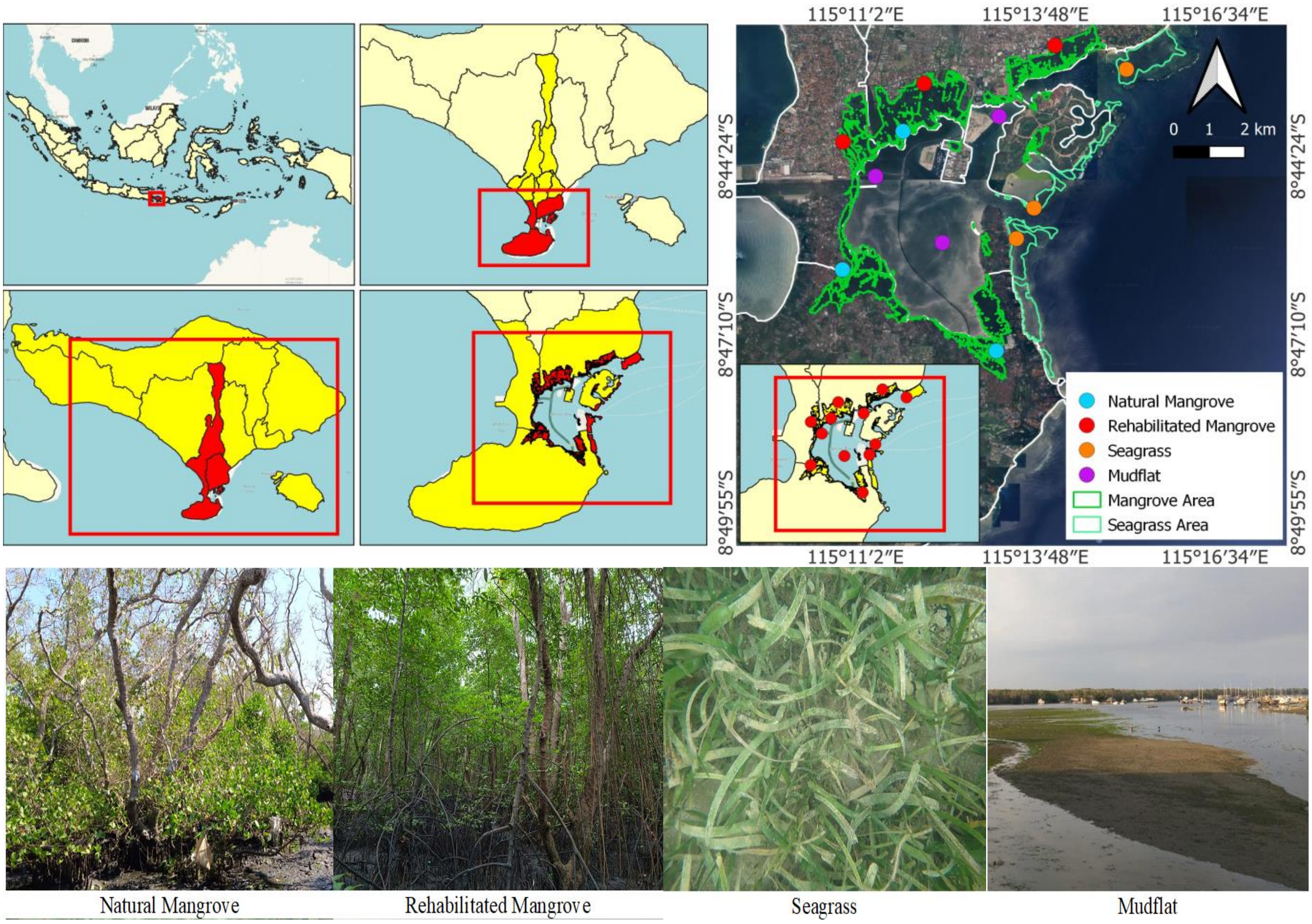
BD : Soil bulk density ($g.cm^{-3}$)

C_{org} : Soil organic carbon percentage (%)

SAR : Soil accretion rate ($mm.yr^{-1}$), The soil accretion rate value at Benoa Bay on average is 2.3 $mmyr^{-1}$ (Maharta et al. 2019), which is almost near to the global SAR of 2.5 $mmyr^{-1}$ (Bouillon et al. 2008; Breithaupt et al. 2012; Pérez et al. 2018).

SCS : Soil carbon stock ($tC.ha^{-1}$)

H : Soil layer thickness (cm)



Natural Mangrove Rehabilitated Mangrove Seagrass Mudflat

Figure 1. Research station and distribution of data collection plots in Benoa Bay, Bali, Indonesia

The soil carbon burial rate and stock values are converted into CO_2 by applying a conversion factor of 3.67, representing the carbon (C) ratio to carbon dioxide (CO_2).

Statistical analysis

Moreover, to ascertain the presence of statistically significant disparities in carbon stock levels and burial rates among the coastal ecosystem, an Analysis of Variance (ANOVA) was employed. According to the results of the Shapiro-Wilk test, it was determined that all the univariate data, including soil carbon stock, burial rates, grain size, and water properties, followed a normal distribution ($\rho>0.05$). The Tukey Honestly Significant Difference (HSD) post hoc test was conducted to determine the location that exhibited statistically significant differences. Meanwhile, the relationship between soil grain size, environmental conditions, and carbon stock was analyzed using Principal Component Analysis (PCA). The normality, ANOVA, and PCA tests were performed using RStudio version 4.0.2 and MVSPW software.

RESULTS AND DISCUSSION

The general condition of the coastal ecosystem at Benoa Bay

Benoa Bay comprises semi-open waters that house three main ecosystems: mangroves, seagrass, and mudflats. We collected mangrove community structure data using guidelines from Dharmawan and Ulumuddin (2021) and seagrass data following guidelines from MarineGeo (https://marinegeo.github.io/modules/seagrass-density). Naturally growing mangroves and those in rehabilitated areas exhibit differences in dominant type, density, diameter, canopy cover, and health condition. In naturally growing mangroves, *S. alba* dominates, whereas rehabilitated mangroves are predominantly occupied by *R. mucronata* (Table 1). These variations in mangrove types lead to differences in stand structure components (Sugiana et al. 2022; Wijana et al. 2023; Wijaya et al. 2023; Sugiana et al. 2024). Based on the Mangrove Health Index (MHI) value, the average health condition of mangroves is classified as moderate, aligning with findings by Sugiana et al. (2022). Meanwhile, in the Seagrass ecosystem, *T. hemprichii* dominates with the highest density (Table 1). The average seagrass coverage is categorized from healthy (>60%) to unhealthy (<60%), following the guidelines outlined in the Indonesian Minister of Environment Decree No. 51 Year 2004.

Meanwhile, measurements of abiotic conditions (soil and water) indicate significant differences in all measurable environmental parameters between the mangrove ecosystem and the seagrass ecosystem (ANOVA, $\rho<0.05$), except for water temperature. No significant differences in environmental conditions were observed between rehabilitated and natural mangroves. Relative to the mudflat condition, parameters such as pH (both soil and water), bulk density, salinity, and Dissolved Oxygen (DO) tend to be lower in the mangrove ecosystem, while water content and organic carbon exhibit the opposite trend. A similar inverse relationship is noted between the seagrass ecosystem and the mudflat condition (Table 2).

The soil and water pH difference between the mangrove and seagrass ecosystems directly correlates with seawater dynamics in both ecosystems. The mangrove ecosystem experiences less exposure to seawater than the seagrass ecosystem, resulting in lower pH levels. Moreover, the presence of mangrove vegetation contributes to trapping higher levels of organic matter than seagrass, as evidenced by the elevated organic carbon levels in mangrove soil. This high organic carbon content reduces both soil and water pH due to the decomposition process facilitated by microorganisms, which release H^+ ions (Li et al. 2018). Additionally, organic carbon decomposition consumes oxygen, resulting in low Dissolved Oxygen (DO) levels in mangrove ecosystems (Hall et al. 2013). Meanwhile, water content and bulk density are influenced by the presence of organic matter. Higher amounts of organic material lead to increased water absorption rates (Gao et al. 2019), consequently lowering bulk density values (Périé and Ouimet 2008; Matus 2021). This pattern is observed in both studied coastal ecosystems.

Soil fraction

Sandy soil types predominate in all observed ecosystems (Figure 2.A). However, upon detailed examination, fine sand soil dominates the Natural mangrove and mudflat, whereas medium sand prevails in the Rehabilitated mangrove and seagrass (Figure 2.B). Shepard's categorization revealed variations in soil composition, ranging from predominantly sandy (with a sand content of at least 75%) to a combination of sand and silt/clay known as sandy loam (with a sand concentration between 50-75% and a combined silt and clay content of at least 25%). The category of predominantly sandy soil is encountered in rehabilitated mangrove, seagrass, and mudflat habitats, while the natural mangrove falls under the category of sandy loam soil. This finding demonstrates that soil types may exhibit variability despite being within the same bay area and ecosystem.

The seagrass ecosystem exhibits the highest proportion of gravel fractions compared to other ecosystems. This attribute is facilitated by its typical proximity to coral reefs, which contribute significantly to the formation of biogenic gravel. Both mangrove and seagrass environments display considerable sand compositions resembling those in mudflat ecosystems. Notably, natural mangroves exhibit the highest silt composition (8-30%) among all ecosystems studied. Most natural mangroves in Benoa Bay are near the coastline and river estuary mouths (Sugiana et al. 2022). Characterized by mostly flat terrain, these areas experience periodic inundation, facilitating the settling of silt soil and thus maintaining higher silt values (Chen et al. 2018). Moreover, a high silt content may indicate an abundance of organic matter in the soil, suggesting a substantial storage of carbon (Matus 2021; Amorim et al. 2023).

Table 1. Community structure of mangrove and seagrass in Benoa Bay (MHI: Mangrove Health Index, RM: *R. mucronata*, RA: *R. apiculata*, BG: *B. gymnorrhiza*, XG: *X. granatum*, TH: *T. hemprichii*, EA: *E. acoroides*, CR: *C. rotundata*)

Object	Parameter	Mangrove		Seagrass
		Natural	Rehabilitated	
Mangrove	Dominated species	*S. alba*	*R. mucronata*	-
	Tree density (Ind.ha^{-1})	2020±175 (SA: 80%, RA: 20%)	3636±303 (RM: 60%, RA: 22%, BG: 15%, XG: 2%)	-
	Diameter (cm)	11.7±0.6	8.5±1.0	-
	Canopy coverage (%)	54.2±6.2	73.2±4.5	-
	MHI (%)	43.4±3.4	54.3±4.8	-
Seagrass	Dominated species	-	-	*T. hemprichii*
	Density (ind.m^{-2})	-	-	(TH: 14±4, EA: 3±2, CR: 7±3)
	Coverage (%)	-	-	56±7

Table 2. Soil and water properties of the coastal ecosystem at Benoa Bay (superscript letters depict significant differences among zones with $\rho<0.05$)

Media	Parameter	Mangrove		Seagrass	Mudflat
		Natural	Rehabilitated		
Soil	pH	6.59 ± 0.26^{a}	6.32 ± 0.17^{a}	7.79 ± 0.11^{b}	7.71 ± 0.14^{b}
	Water content (%)	57.07 ± 1.65^{a}	43.49 ± 1.49^{b}	27.01 ± 2.00^{c}	26.67 ± 2.52^{c}
	Bulk density (g/cm^3)	0.64 ± 0.07^{a}	0.83 ± 0.15^{a}	1.32 ± 0.07^{b}	1.36 ± 0.14^{b}
	Organic carbon (%)	2.11 ± 0.25^{a}	1.16 ± 0.57^{a}	0.52 ± 0.02^{a}	0.40 ± 0.04^{a}
Water	Temperature (°C)	27.77 ± 0.42^{a}	28.67 ± 0.70^{a}	27.56 ± 0.26^{a}	30.27 ± 0.59^{b}
	pH	6.68 ± 0.29^{a}	6.44 ± 0.21^{a}	8.36 ± 0.06^{b}	8.05 ± 0.23^{b}
	Salinity (ppt)	19.32 ± 2.49^{a}	21.68 ± 1.24^{a}	30.92 ± 0.66^{b}	27.53 ± 1.31^{b}
	DO (mg/L)	1.22 ± 0.43^{a}	1.91 ± 1.14^{a}	6.62 ± 1.03^{b}	7.04 ± 0.23^{b}

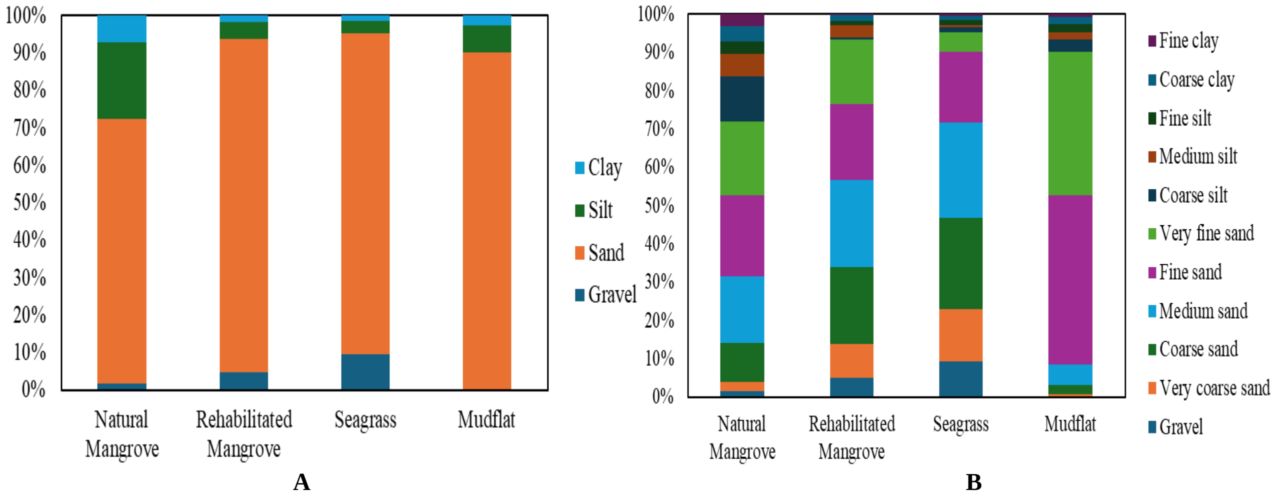


Figure 2. Soil fraction of each media. A. General scale; B. Specific scale

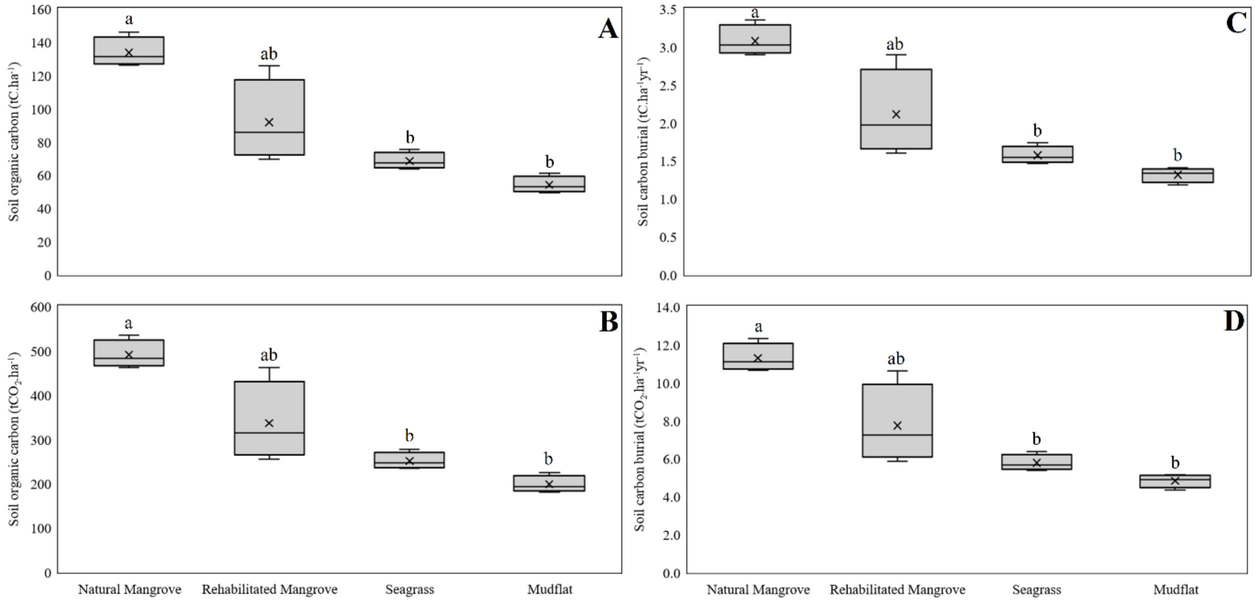


Figure 3. Soil carbon stock: A. $tCha^{-1}$; B. tCO_2ha^{-1}). Burial rate: C. $tCha^{-1}yr^{-1}$; D. $tCO_2ha^{-1}yr^{-1}$, of each coastal ecosystem (superscript letters depict significant differences among zones with $\rho<0.05$)

Soil carbon stock and burial rate

Substantial disparities in carbon stock and burial rate values among mangroves, seagrass, and mudflats are revealed (ANOVA, $\rho<0.05$). The mudflat ecosystem exhibits the lowest carbon stock and burial rate, while the mangrove ecosystem demonstrates the highest (Figure 3). These variations underscore the distinct capabilities of each ecosystem in sequestering carbon within its soil. Rehabilitated mangroves exhibit a greater capacity to absorb and retain carbon than seagrass and mudflat, albeit less effectively than naturally occurring mangroves. This is because rehabilitated mangroves generally have younger vegetation than naturally grown mangroves. Similar results were also found on the South East Coast of India and Northern Vietnam (Gnanamoorthy et al. 2019; Tinh et al. 2020). However, this highlights the potential efficacy of mangrove restoration efforts in reducing atmospheric CO_2 levels. Moreover, the seagrass ecosystem displays higher carbon storage and absorption levels than mudflats, indicating its significant role in CO_2 sequestration. As mangrove and seagrass habitats outperform empty wetlands devoid of vegetation in CO_2 absorption, these findings underscore the effectiveness of these ecosystems in mitigating climate change.

The mangrove habitat boasts diverse flora characterized by numerous tree and shrub species. These intricate ecosystems are conducive to carbon sequestration and organic matter accumulation in the soil, owing to the extensive network of mangrove roots and the decomposition of organic matter (Friesen et al. 2018; Inoue 2019). As Miyajima and Hamaguchi (2019) highlighted, seagrass facilitates effective carbon absorption by deeply penetrating the soil layers with its long, densely packed roots. The biological processes occurring within these habitats and the litter generated by mangroves and seagrasses accelerate organic matter decomposition, enhancing soil carbon accumulation (Friesen et al. 2018; Spivak et al. 2019).

The same approach also applies to mudflats characterized by lower soil carbon levels. Carbon accumulation in mudflats is primarily influenced by the deposition of organic material from the surrounding environment, which includes algae and detritus. However, this organic material's fragile nature in exposed conditions contributes to the relatively lower soil carbon levels in mudflats (Phang et al. 2015; Chen and Lee 2022). Moreover, tidal hydrodynamic processes significantly impact soil carbon accumulation (Spivak et al. 2019; Yang et al. 2021). Unlike mudflats directly exposed to wind and seawater, mangroves and seagrasses benefit from more stable environmental conditions due to their dense vegetation cover (Waycott et al. 2011; Sasmito et al. 2020). Consequently, the comparatively stable environmental conditions in mangroves and seagrasses promote higher soil carbon buildup levels than in mudflats.

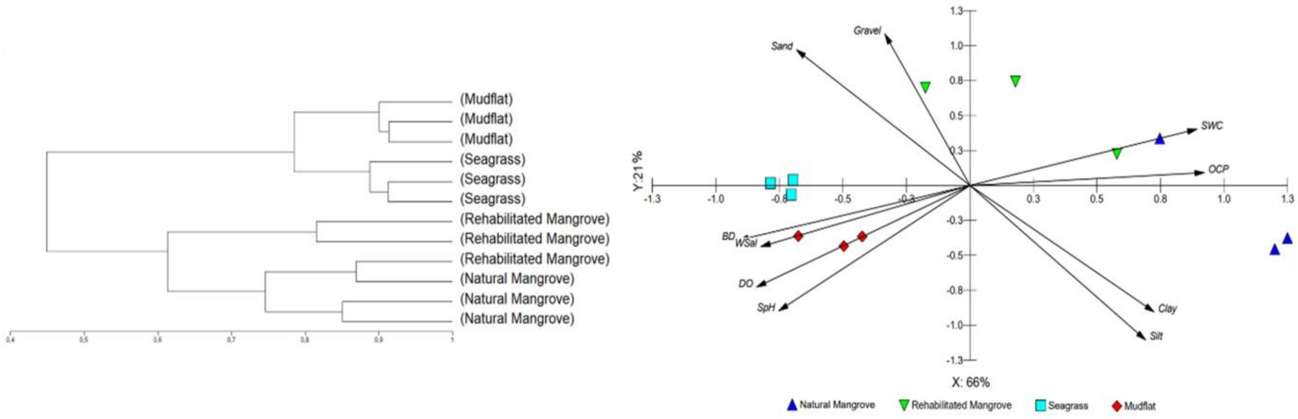
The Benoa Bay mangrove ecosystem exhibits Soil Organic Carbon (SOC) and Soil Carbon Burial (SCB), comparable to those found in many other regions, as shown in Table 3. However, the measured values for SOC and SCB in the seagrass ecosystem at this research site may be comparatively lower. At the same time, in mudflats, they tend to be relatively higher, except for Bintuni Bay in West Papua, Indonesia. Overall, the values of SOC and SCB in mangrove ecosystems are generally higher compared to seagrass and mudflat environments, as shown in Table 3. This study has confirmed that the mangrove environment possesses the highest capacity for carbon storage and uptake among coastal ecosystems, with seagrass and mudflat ecosystems closely behind.

Relationship with environmental conditions and ecosystem clusterization

Mangrove habitats, whether natural or restored, exhibit a high degree of similarity in carbon values and environmental circumstances, with a similarity index of 60.9%. Meanwhile, seagrass and mudflat have a higher similarity index of 82.0%, although both are classified as different ecosystems (Figure 4.A). Seagrass and mudflat environments possess specific characteristics shaped by bulk density, water salinity, Dissolved Oxygen (DO), and soil pH, resulting in these two ecosystems forming adjacent clusters. The clustering of natural mangrove environments is also shaped by two main parameters: Organic Carbon Percentage (OCP) and clay soil content. We found a strong correlation between environmental conditions and soil carbon content, with specific metrics showing either a positive or negative correlation (Figure 4.B). The cumulative Principal Component Analysis (PCA) factor value for X and Y is 87%, indicating high precision in this relationship. Soil carbon content is inversely correlated with soil and water pH, bulk density, percentage of sand, salinity, and Dissolved Oxygen (DO) levels. Conversely, soil carbon content positively correlates with soil water and silt and clay percentages.

Table 3. Comparison of SOC and SCB on several ecosystems (NA: Not Available, NE: Not Explained)

Location	Ecosystem	SOC ($MgCha^{-1}$)	SCB ($MgCha^{-1}yr^{-1}$)	Sampling depth (cm)	Reference
Benoa Bay, Bali	Mangrove	69-145	1.6-3.4	0-100	This study
	Natural	126-145	2.9-3.4		
	Rehabilitated	69-126	1.6-2.9		
	Seagrass	63-75	1.5-1.7		
	Mudflat	49-61	1.2-1.4		
Benoa Bay, Bali	Mangrove	91-127	2.3-3.2	0-100	Sugiana et al. (2024)
Kourou, French Guiana	Mangrove	5-108	0.7-4.9	0-101	Marchand (2017)
Farasan Islands, Saudi Arabia	Mangrove	108-123	5.4	0-50	Eid et al. (2020)
Bintuni Bay, West Papua, Indonesia	Mangrove	68-179	0.5-0.9	0-50	Sasmito et al. (2020)
	Mudlfat	62	Near to 0.5 (NE)		
Aojiang Estuary, China	Mangrove	100	NA	0-100	Zou et al. (2023)
	Mudflat	30			
Egyptian Red Sea Coast	Mangrove	85	0.06	0-40	Eid and Shaltout (2016)
	Mudflat	26	0.02		
Changyi Wetland, China	Mudflat	17-20	NA	0-100	Wang et al. (2017)
Gilimanuk Bay, Bali	Seagrass	13-104	NA	0-100	Vernianda et al. (2022)
Dompak & Berakit Waters, Riau	Seagrass	91-104	NA	0-20	Hertyastuti et al. (2020)
Spermonden Islands, South Sulawesi	Seagrass	44-136	NA	0-30	Yushra et al. (2020)
Fanals Point, NW Mediterranean	Seagrass	NA	1.98	Deposited surface soil	Gacia et al. (2002)
Bay of Calvi, Corsica	Seagrass	NA	0.17	Not explained	Mateo et al. (2006)
Bahamian seagrass meadow	Seagrass	31-114	1.4	0-100	Fu et al. (2023)



A B

Figure 4. A. Similarity coefficient; and B. PCA analysis result. Note: BD: Bulk Density; WSal: Water Salinity; DO: Dissolved Oxygen; SpH: Soil pH; SWC: Soil Water Content; and OCP: Organic Carbon Percentage

The negative correlation between soil carbon content and environmental factors such as soil and water pH, sand percentage, salinity, and Dissolved Oxygen (DO) levels in coastal ecosystems can be attributed to various biogeochemical processes. In environments with lower pH levels and thus acidity, there is an impact on nutrient availability to plants and microbial activity, consequently decreasing the synthesis and storage of organic matter, a source of soil carbon (Li et al. 2018). A higher proportion of sand in the soil usually indicates a more porous soil structure and improved drainage, facilitating the enhanced breakdown of organic matter and reducing soil carbon storage (Matus 2021). Additionally, elevated salinity levels and depleted oxygen levels in water inhibit microbial activity and the breakdown of organic matter, resulting in decreased soil carbon buildup in coastal ecosystems (Luo et al. 2019; Liu et al. 2020).

The positive correlation between moisture level, density, and proportions of silt and clay in the soil with the amount of carbon in the soil indicates that these factors create favorable conditions for storing organic carbon. Elevated soil water content can increase humidity levels and delay the breakdown of organic matter, resulting in more significant soil carbon accumulation. A lower bulk density, indicative of a more porous soil structure, improves soil aeration, promotes microbial activity, and enhances organic matter buildup, consequently increasing soil carbon stocks (Gao et al. 2019). Furthermore, soils with higher proportions of silt and clay typically possess superior water absorption capabilities and facilitate better vegetation growth, leading to increased organic matter production and soil carbon storage (Amorim et al. 2023).

Blue carbon in conservation and economy

In summary, the carbon storage capacity varies among the coastal ecosystems in Benoa Bay, with mangroves exhibiting the most significant carbon stocks, followed by seagrass and then mudflat. An intriguing discovery emerged regarding the comparable soil carbon levels and environmental circumstances between seagrass and mudflat habitats. However, we acknowledge that these findings have limitations and subsequent measurements may differ under conditions affecting coastal ecosystems, whether due to natural factors such as tidal dynamics, seasonal changes in ocean currents, or human activities such as coastal reclamation impacting sediment accretion rates and consequently carbon burial rates. Therefore, further research considering these factors is crucial for accurately estimating soil carbon stocks in coastal ecosystems. Nevertheless, this study has provided a general overview of the role of coastal ecosystems as carbon sinks, potentially contributing to the achievement of SDGs, particularly Goals 13 (Climate Action) and 14 (Life Below Water).

Based on the carbon sequestration rate figures and Table 3, and the carbon tax stipulated in the 2022 Indonesian Macro Policy Framework and Fiscal Policy Principles (KEM and PPKF) document, which sets the rate at IDR 75,000 per tonne of carbon emissions (CO_{2}-$_{\text{equivalent}}$), the economic value of coastal ecosystems can be estimated. These ecosystems can store carbon, translating to approximately 3.7-10.9 million Rupiah per hectare. The carbon storage capacity is also valued at IDR 90,000-255,000 per hectare per year. The economic value of coastal ecosystems is further enhanced by implementing conservation efforts for mangrove and seagrass ecosystems, utilizing mudflat land.

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