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Article

Seagrass Carbon Stock Variability Across Contrasting Coastal Areas on Pari Island, Indonesia

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Abstract: Seagrass meadows are important blue carbon ecosystems, yet integrated estimates of biomass and sediment carbon stocks in small tropical islands remain limited. This study quantified total ecosystem carbon stock in seagrass meadows of Pari Island, Thousand Islands, Jakarta, and compared carbon storage between developed and natural coastal areas. Field sampling was conducted at four stations representing contrasting coastal use settings. Seagrass ecological parameters were assessed using a line transect quadrat, while aboveground biomass, belowground biomass, and sediment carbon stocks were estimated using the Loss on Ignition (LOI) approach. Sediment cores were collected and analyzed across representative depth intervals to estimate profile-based carbon storage. Mean total ecosystem carbon stock was 118.08 Mg C ha $^{-1}$, ranging from 83.15 Mg C ha $^{-1}$ to 135.46 Mg C ha^{-1} among stations. Sediment was the dominant carbon pool, contributing approximately 92-96% of the total carbon stock in the ecosystem, whereas biomass contributed less than 8%. Undisturbed areas showed higher mean sediment carbon stock than anthropogenic areas, although the difference was not statistically significant. In contrast, anthropogenic areas exhibited greater spatial variability in carbon storage. These results show that seagrass meadows in Pari Island function as important blue carbon reservoirs and underscore the importance of sediment integrity in maintaining ecosystem carbon storage.

Keywords: seagrass meadow, blue carbon, sediment carbon stock, small tropical islands, Pari Island

1. Introduction

Seagrass ecosystems are increasingly recognized as important coastal carbon sinks because they sequester atmospheric and dissolved carbon dioxide and store it in both biomass and sedimentary pools (Fourqurean *et al*. 2012; Macreadie *et al*. 2019). Although occupying less than 0.2% of the global ocean floor, seagrass meadows contribute disproportionately to long-term carbon burial. Global syntheses indicate that sedimentary carbon typically accounts for more than 80-90% of total ecosystem carbon storage, highlighting the dominant role of belowground compartments in long-term sequestration (Fourqurean *et al*. 2012).

Carbon stock estimates, however, are strongly influenced by sampling depth and methodological standardization. Many global and regional assessments quantify sediment carbon to a standardized depth of 30 cm to facilitate inter-site comparability (Fourqurean *et al*. 2012; Serrano *et al*. 2014). While this approach enables global synthesis, it may underestimate total carbon stocks in tropical systems where vertical sediment accumulation extends beyond shallow layers. Evidence suggests that deeper sediment horizons can contain substantial legacy carbon pools that significantly increase total carbon stock estimates (Arias-Ortiz *et al*., 2018; Krause *et al*. 2025). Consequently, differences in sediment core depth may partially explain variability among reported carbon stock values.

Indonesia hosts approximately 660.156 hectares of seagrass habitat (SIDAKO, 2026) and represents the center of Indo-Pacific seagrass biodiversity, while also being recognized as a globally significant yet vulnerable blue carbon sink for both seagrass and mangrove carbon (Alongi *et al*. 2016; Murdiyarso *et al*. 2018; Hernawan *et al*. 2021). Despite this ecological significance, site-specific carbon stock measurements remain unevenly distributed, particularly within small tropical island systems. These islands often feature shallow lagoons and semi-enclosed hydrodynamic conditions that may enhance fine sediment deposition and carbon retention. At the same time, small islands are increasingly exposed to localized anthropogenic pressures, including tourism infrastructure, dredging, and boat anchoring activities, which may destabilize sedimentary carbon pools (Waycott *et al*. 2009; Pendleton *et al*. 2012).

The Thousand Islands, located north of Jakarta Bay, represent a socio-ecological setting in which extensive seagrass meadows coexist with intensive coastal use. Previous studies in this region have documented variability in sediment carbon stocks and highlighted disturbance-related reductions in sediment organic carbon (Rahayu *et al*. 2025; Kurniawan *et al*. 2026). However, comprehensive assessments that integrate aboveground biomass, belowground biomass, and deeper sediment carbon pools within a single small-island system remain limited. Furthermore, the implications of sampling depth variability for carbon stock estimation in Indonesian seagrass ecosystems have not been explicitly discussed.

Within the socio-ecological context of Pari Island, this research investigates the variation of total carbon stocks across contrasting coastal use categories of anthropogenic and undisturbed environments on Pari Island. By quantifying integrated biomass and sediment pools and comparing these storage levels, this research aims to test the hypothesis that undisturbed areas harbor larger and more stable carbon stocks. This approach dictates our sampling design, ensuring that the comparison between undisturbed and natural coastal zones accurately captures the nuances of carbon storage in small tropical island environments.

2. Materials and Methods

2.1 Study Area

This study was conducted from January to April 2025 in Pari Island, Thousand Islands Regency, Jakarta, Indonesia (Figure 1), which provides the socio-ecological context required to investigate the variation of total carbon stocks in this area. Pari Island's shallow coastal waters host seagrass meadows distributed across a distinct gradient of anthropogenic and undisturbed areas, making it an ideal location to capture the nuances of carbon storage under varying human pressures. Four sampling stations were selected purposively based on two contrasting site conditions observed directly in the field. Two stations represent anthropogenic areas primarily affected by tourism and settlement activities, while the other two represent undisturbed areas, characterized by high habitat integrity and research protected status. This station classification is fundamental to the sampling design, as it allows for the quantification of integrated biomass and sediment pools needed to test the hypothesis that undisturbed areas harbor larger and more stable carbon stocks.

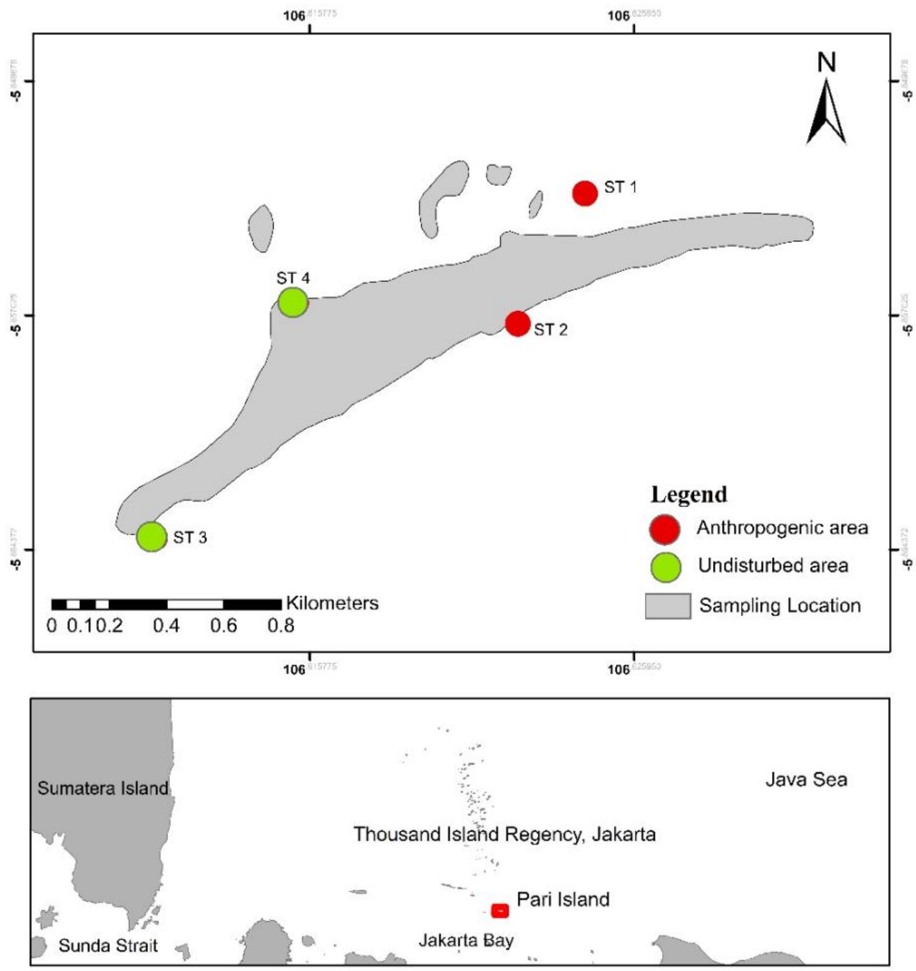

Figure 1. Map of the study area showing the distribution of four sampling stations in seagrass meadows of Pari Island, Thousand Islands Regency, Jakarta. Stations were selected purposively to represent two contrasting coastal use categories: Anthropogenic area (ST1 and ST2) and Undisturbed area (ST3 and ST4)

2.2 Sampling Design

Sampling design was conducted in three complementary stages at each station to characterize seagrass condition and quantify ecosystem carbon stocks across a gradient of human influence. This approach was designed to bridge the relationship between standing biological productivity and long-term carbon burial. To operationalize this comparative framework, four stations were purposively selected and classified into two distinct categories based on their coastal use setting namely, anthropogenic and undisturbed areas.

The anthropogenic area, represented by ST1 and ST2, comprises stations characterized by significant exposure to tourism infrastructure and nearby settlement activities, reflecting areas under high physical pressure. Conversely, the undisturbed area which represented by ST3 and ST4 includes reference sites with high habitat integrity and minimal human interference, such as research-protected zones. At each of these categorized stations, an ecological assessment was first conducted to establish the structural baseline of the meadows such as species composition, cover and density. This was followed by biomass sampling to quantify carbon pools in both aboveground and belowground vegetation, and finally, the collection of sediment cores to evaluate the long-term organic carbon stored within the substrate. By explicitly comparing these two contrasting categories, the study ensures that the resulting data accurately captures the nuances of carbon storage variability in response to anthropogenic pressures.

2.3 Ecological Seagrass Assessment

Seagrass ecological assessment was conducted using a line-transect quadrat method. At each station, two transects were laid perpendicular to the shoreline, each extending 100 m. Along each transect, quadrats measuring 50 cm x 50 cm were placed at 10 m intervals, yielding 11 observation points per transect, including the initial point used as the reference position. Within each quadrat, seagrass species, percent cover, and shoot density were recorded. Seagrass species were identified using regional taxonomic reference following Hernawan *et al*. (2021), while percent cover was estimated visually using standard seagrass cover classes based on Rahmawati *et al*. (2014). Shoot density was calculated as the number of shoots per quadrat and standardized to individuals per square meter (ind m^{-2}).

2.4 Biomass Carbon Estimation

Biomass sampling was conducted at each station by collecting representative samples of the dominant seagrass species from selected quadrats. Whole plant material was harvested, including leaves, rhizomes, and roots, and then separated into aboveground biomass (AGB) and belowground biomass (BGB). All samples were rinsed to remove attached sediment and oven-dried at 70°C until constant weight was achieved. The organic carbon content of the plant material was determined using the Loss on Ignition (LOI) method in the laboratory. Biomass carbon was estimated using the standard conversion factor proposed by Fourqurean *et al*. (2012), as follows:

$$\text{Biomass C} = \text{Dry Biomass} \times 0.34$$

where 0.34 represents the standard conversion factor for seagrass organic carbon (Fourqurean *et al*. 2012). Carbon stock per hectare was calculated by scaling quadrat biomass to area units.

2.5 Sediment Sampling and Carbon Stock Estimation

Sediment sampling and carbon stock estimation followed general blue carbon field assessment principles (Howard *et al*. 2014). Sediment sampling was conducted using a 120 cm length PVC corer with an internal diameter of 6.35 cm. One sediment core was collected at each station. Core recovery depth varied among stations depending on local substrate conditions. After retrieval, each core was sectioned at 5 cm intervals. Due to analytical and budgetary constraints, only selected sediment sections representing the upper, middle, and lower portions of each profile were analysed in the laboratory, while unmeasured intervals were estimated by interpolation to reconstruct profile-based sediment carbon storage. The analysed depth intervals differed among stations according to effective sediment recovery.

All selected sediment samples were oven-dried at 60 ^{0}C to constant weight. Dry Bulk Density (DBD) was calculated as:

$$DBD = \text{Dry weight} / \text{Core volume}$$

Organic carbon content (%Corg) was estimated using the Loss on Ignition (LOI) method, with the following conversion formula applied (Fourqurean *et* al. 2012). %Corg was calculated using:

$$\%Corg = (0.43 \times \%LOI) - 0.33$$

Sediment carbon stock for each depth interval was calculated from DBD, interval thickness, and organic carbon content, and then standardized to Mg C ha^{-1}. Total sediment carbon stock at each station was obtained by summing the estimated carbon stocks across the sediment profile. The use of sediment cores of varying depth has been noted to influence total carbon stock estimates, as deeper horizons may contain substantial legacy carbon pools that significantly affect the overall storage estimate (Dahl *et al*. 2023). The LOI based approach adopted in this study is consistent with recent assessment of sediment organic carbon in Indonesian tropical seagrass ecosystems (Rahayu *et al*. 2023; Ambomasse *et al*. 2024).

2.6 Data Analysis

Seagrass ecological parameters and carbon stocks were summarized for each station and then compared descriptively between anthropogenically influenced stations and relatively undisturbed stations. Seagrass cover and shoot density were calculated from quadrat observations, while biomass carbon and sediment carbon stocks were expressed in Mg C ha^{-1}. Mean, standard deviation, range, and coefficient of variation were used to describe the magnitude and spatial variability of carbon stocks among stations and between site categories. Because the number of stations and sediment cores per category was limited, comparisons between categories were interpreted primarily as descriptive and exploratory rather than as strong inferential tests. All calculations and tabulations were performed using Microsoft Excel.

3. Results

3.1. Seagrass Community Structure

Four seagrass species were identified across the study stations, namely *Thalassia hemprichii*, *Enhalus acoroides*, *Cymodocea rotundata*, and *Halophila ovalis*. *Thalassia hemprichii* and *Enhalus acoroides* were present at all stations and formed the dominant meadow structure, whereas

Halophila ovalis was recorded only at Station 1 (Pantai Perawan). Seagrass cover ranged from 52.27% to 72.50% among stations (Table 1). The highest cover was observed at Station 4 (72.50%), while the lowest was recorded at Station 2 (52.27%). Based on the observed cover values, all stations were categorized as dense seagrass meadows according to the classification by Rahmawati *et al*. (2014). Shoot density ranged from 105.82 to 173.45 ind m^{-2}, with the highest value recorded at Station 4 and the lowest at Station 1.Based on the site categories, undisturbed area Stations (ST3 and ST4) showed higher mean seagrass cover (64.32%) than anthropogenic area Stations (ST1 and ST2), which averaged 54.20% (Table 1).

Table 1. Seagrass percent cover and shoot density recorded at four sampling stations in Pari Island, Thousand Islands, Jakarta. Stations were selected purposively to represent two contrasting coastal use categories: Anthropogenic area (ST1 and ST2) and Undisturbed area (ST3 and ST4). All stations were categorized as dense seagrass meadows based on percent cover values

Station	Category	Coverage (%)	Density (ind m^{-2})
ST1	Anthropogenic area	56.14	105.82
ST2	Anthropogenic area	52.27	147.27
ST3	Undisturbed area	56.14	134.91
ST4	Undisturbed area	72.50	173.45

3.2. Biomass Carbon Stocks

Biomass carbon stock ranged from 3.58 to 5.72 Mg C ha^{-1} across the sampling stations (Figure 2). The highest biomass carbon stock was recorded at Station 2 (5.72 Mg C ha^{-1}), whereas the lowest value was observed at Station 4 (3.58 Mg C ha^{-1}). Belowground biomass (BGB) contributed the largest proportion of biomass carbon at all stations. BGB ranged from 3.003 to 4.865 Mg C ha^{-1}, while aboveground biomass (AGB) ranged from 0.579 to 0.950 Mg C ha^{-1}, indicating that most biomass carbon was stored in rhizomes and roots rather than in aboveground tissues.

Based on the site categories, anthropogenic area stations (ST1–ST2) had a mean biomass carbon stock of 5.26 ± 0.66 Mg C ha^{-1}, whereas undisturbed area stations (ST3–ST4) averaged 3.97 ± 0.54 Mg C ha^{-1}. The coefficient of variation was relatively low in both categories, amounting to 12.5% in anthropogenic areas and 13.7% in undisturbed areas, indicating comparatively limited within-category variability in biomass carbon stock.

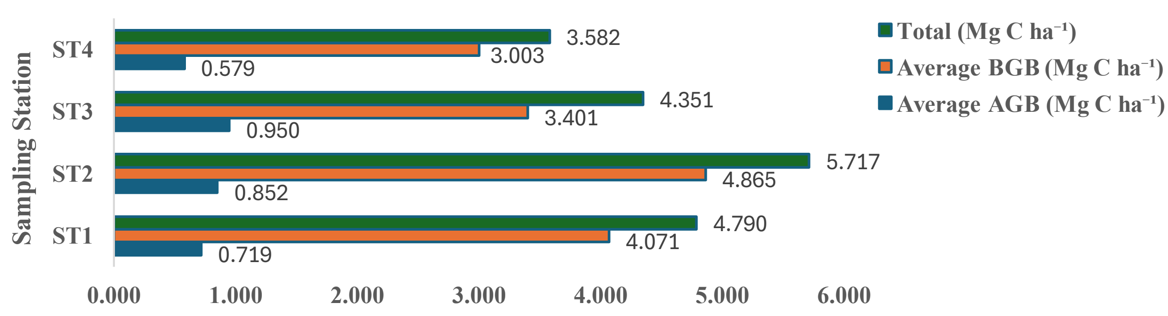

Figure 2. Aboveground biomass (AGB) and belowground biomass (BGB) carbon stocks (Mg C ha^{-1}) of seagrass across four sampling stations in Pari Islands, Thousand Islands, Jakarta. Stations were selected purposively to represent two contrasting coastal use categories: Anthropogenic area (ST1 and ST2) and Undisturbed area (ST3 and ST4)

3.3. Sediment Carbon Stocks

Sediment carbon stock ranged from 77.43 to 131.88 Mg C ha^{-1} across the sampling stations (Figure 3). The highest sediment carbon stock was recorded at Station 4 (131.88 Mg C ha^{-1}), followed by Station 1 (124.99 Mg C ha^{-1}) and Station 3 (119.58 Mg C ha^{-1}), whereas the lowest value was observed at Station 2 (77.43 Mg C ha^{-1}). Based on the site categories, anthropogenic area stations showed a mean sediment carbon stock of 101.21 ± 33.63 Mg C ha^{-1}, while undisturbed area stations showed a higher mean value of 125.73 ± 8.67 Mg C ha^{-1}. Descriptively, the mean sediment carbon stock in undisturbed areas was 24.2% higher than in anthropogenic areas.

A notable result was the strong difference in spatial variability between the two site categories. The coefficient of variation (CV) for sediment carbon stock in Anthropogenic Areas reached 33.2%, which was nearly five times higher than the 6.9% recorded in Undisturbed Areas. This pattern indicates greater heterogeneity in sediment carbon storage within developed coastal settings, whereas sediment carbon stock in Undisturbed Areas was comparatively more consistent. Across all stations, sediment carbon represented the dominant carbon pool within the seagrass ecosystem and substantially exceeded the biomass carbon component.

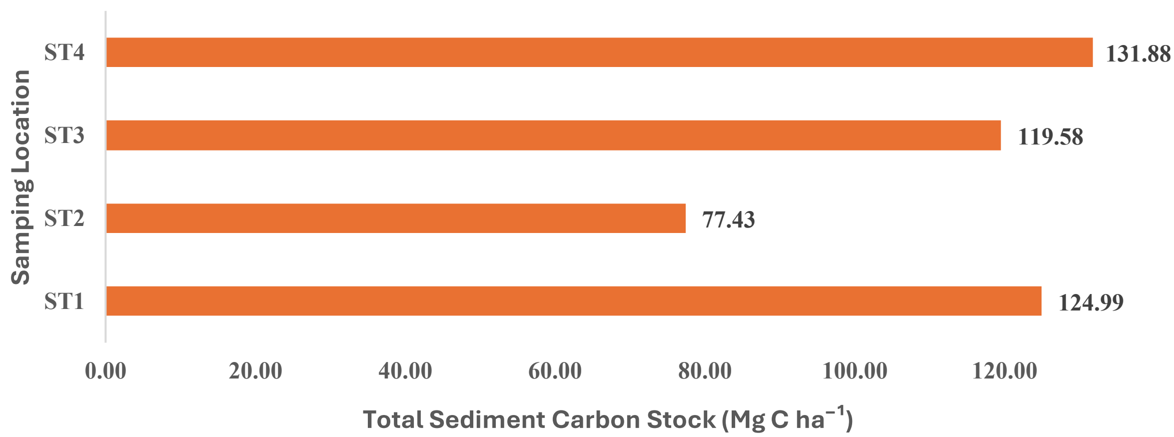

Figure 3. Sediment carbon stocks (Mg C ha^{-1}) across four sampling stations in seagrass meadows of Pari Island, Thousand Islands, Jakarta. Stations were selected purposively to represent two contrasting coastal use categories: Anthropogenic area (ST1 and ST2) and Undisturbed area (ST3 and ST4)

3.4. Total Ecosystem Carbon Stock

Total ecosystem carbon stock, calculated as the sum of biomass and sediment carbon pools, averaged 118.08 Mg C ha^{-1} across all stations. Total carbon stock ranged from 83.15 Mg C ha^{-1} at Station 2 to 135.46 Mg C ha^{-1} at Station 4 (Table 2). Sediment carbon overwhelmingly dominated the total ecosystem carbon pool, contributing approximately 92–96% of total ecosystem carbon stock, whereas biomass carbon contributed less than 8%.

Based on the site categories, undisturbed area stations showed a higher mean total ecosystem carbon stock than anthropogenic area stations. However, the most consistent pattern across all stations was the dominance of sediment carbon, indicating that belowground carbon reservoirs constitute the principal component of ecosystem carbon storage in the seagrass meadows of Pari Island.

Table 2. Total ecosystem carbon stocks, comprising biomass carbon and sediment carbon components, recorded at four sampling stations in seagrass meadows of Pari Island, Thousand Islands, Jakarta. Stations were selected purposively to represent two contrasting coastal use categories: Anthropogenic area (ST1 and ST2) and Undisturbed area (ST3 and ST4)

Station	Area Category	Biomass Carbon (MgC ha $^{-1}$)	Sediment Carbon (MgC ha $^{-1}$)	Total Carbon (MgC ha $^{-1}$)
ST1	Anthropogenic area	4.79	124.99	129.78
ST2	Anthropogenic area	5.72	77.43	83.15
ST3	Undisturbed area	4.35	119.58	123.93
ST4	Undisturbed area	3.58	131.88	135.46

3.5. Sediment Grain Size Composition

Sediment composition across all stations was predominantly sandy, with the combined proportion of coarse and fine sand exceeding 90% at each site (Table 3). Despite this overall sandy character, differences in grain-size distribution were observed among stations. Undisturbed Area stations showed a relatively more diverse sediment texture, particularly at Station 4, which recorded the highest proportions of silt (9%) and clay (3%) among all stations. This station also had the highest sediment carbon stock measured in the study. When the combined silt and clay fraction (cohesive particles) was compared against the sediment carbon stock across stations, a general positive trend was observed. ST4 had the highest silt plus clay content (12%) and the highest sediment carbon stock (131.88 Mg C ha $^{-1}$), whereas ST 1 and ST3 both recorded 3% silt plus clay and intermediate carbon stocks of 124.99 and 119.58 Mg C ha $^{-1}$, respectively, ST2 had a combined silt plus clay fraction of approximately 4-5%, yet recorded the lowest sediment carbon stock of all stations (77.43 Mg C ha $^{-1}$). Notably, ST2 was dominated by fine sand (71%), suggesting that fine sand alone does not function in the same way as silt and clay in retaining organic carbon. These results indicate that it is specifically the cohesive fine particle fraction rather than the overall fineness of the sediment, that appears most associated with higher carbon stocks in the seagrass meadows of Pari Island.

Table 3. Sediment grain size composition (%) across four sampling stations in seagrass meadows of Pari Island, Thousand Islands, Jakarta. Sediment texture was predominantly composed of sand fractions across all sampling stations

Station	Coarse Sand (%)	Fine Sand (%)	Silt (%)	Clay (%)
ST1	90	6	2	1
ST2	24	71	4	<1
ST3	64	32	2	1
ST4	54	35	9	3

In the Anthropogenic Area category, sediment texture was more contrasting. Station 1 was strongly dominated by coarse sand (90%), whereas Station 2 was dominated by fine sand (71%) but had the lowest sediment carbon stock recorded across the study. These results indicate that although sandy fractions dominate the seagrass meadows of Pari Island, the distribution of finer particles varies spatially and may be associated with differences in sediment carbon storage. Ranking all four stations by silt plus clay content yields the following order: ST4 (12%), ST2 (4-

5%), ST1 = ST3 (3%). When compared against the sediment carbon stocks ranking: ST4 (131.88), ST1 (124.99), ST3 (119.58), ST2 (77.43 Mg C ha $^{-1}$) a positive correspondence is observed at the high end (ST 4 leading in both), but the ranking diverges at lower values. ST 2, which had a marginally higher silt plus clay content than ST1 and ST3, nonetheless recorded by far the lowest sediment carbon stock. This divergence suggests that silt and clay content alone does not fully determine carbon storage. Other factors, including depositional stability, seagrass canopy structure, and disturbance history, likely modulate the capacity of sediment to accumulate and retain organic carbon.

4. Discussion

This study shows that seagrass meadows in Pari Island function as important blue carbon reservoirs, with total ecosystem carbon storage strongly dominated by sediment rather than living biomass. This pattern indicates that the blue carbon value of the meadow is determined primarily by the persistence of belowground carbon pools, not by standing biomass alone, which is consistent with broader blue carbon understanding that disturbance may threaten not only future sequestration but also previously stored sediment carbon (Pendleton *et al*. 2012; Krause *et al*. 2025). It confirmed that sediment organic carbon constitutes the largest fraction of total seagrass ecosystem carbon stocks across tropical and subtropical regions, including Southeast Asia, underscoring the critical role of belowground pools for long term blue carbon storage (Stankovic *et al*. 2021). Furthermore, the high variability observed among stations in this study aligns with previous study by Ricart *et al*. (2020) who documented substantial variation in blue carbon storage within seagrass meadows even at the estuary scale, attributing such heterogeneity to differences in sediment characteristics, hydrodynamic conditions, and disturbance history.

The sediment-dominated carbon structure observed in Pari Island should also be interpreted within the broader context of seagrass carbon stock variability. A recent global synthesis showed that seagrass soil organic carbon stocks vary widely across taxa and environments, and that this variability is associated with plant traits, climate, geomorphology, hydrology, soil properties, and hydrodynamic regime (Krause *et al*. 2025). This means that carbon stock estimates from Pari Island should be interpreted as site-specific rather than treated as directly transferable reference values for other tropical seagrass systems. Adding a forwar looking dimension, Song *et al*. (2025) projected that ongoing climate change will increasingly threaten seagrass carbon storage and associated ecosystem services globally, with tropical systems being particularly vulnerable. At a global scale, it is estimated that seagrass biomass alone contains tens of millions of tons of carbon, reinforcing the importance of both living and sedimentary compartments in comprehensive carbon accounting. (Gomis *et al*. 2025).

The mean total ecosystem carbon stock of 118.08 Mg C ha $^{-1}$ recorded in this study is broadly consistent with published estimates for Indonesian and Indo-Pacific seagrass systems, though direct comparison requires caution due to differences in core depth and analytical methods. A global median seagrass soil carbon stock of approximately 139.7 Mg C ha $^{-1}$ has been reported for a standardized depth of 30 cm, whereas the present study used profile-based cores extending beyond 30 cm at several stations, which likely contributes to the higher values observed at ST1 and ST4 (Fourqurean *et al*. 2012). At the national scale, Hernawan *et al*. 2021 reported that Indonesian seagrass meadows are in moderate condition with average cover of approximately 39%. The comparatively higher cover observed at all four stations in this study (52-72%) may partly explain above-average carbon accumulation relative to national averages. For Indonesian archipelagic settings specifically, Kurniawan *et al*. (2026) documented sediment carbon stocks in intertidal seagrass meadows across multiple Indonesia islands ranging widely across disturbance categories, with disturbed sites consistently at the lower end, a pattern echoed by the spatial variability observed between ST2 (77.43 Mg C ha $^{-1}$) and ST4 (131.88 Mg C ha $^{-1}$) in the present study. Carbon offset assessments for Indonesian seagrass habitats confirm that tropical seagrass systems in this region represent significant but highly variable blue carbon reservoirs (Wahyudi *et al*. 2022). Pari island values fall within the range documented for Indo-Pacific systems, and the dominance of sediment carbon over biomass carbon (92-96%) is consistent with the pattern observed globally and across Indonesia.

Based on the site categories, undisturbed area showed higher mean sediment carbon stocks than anthropogenically influenced areas. However, the stronger pattern in this study was the much greater variability within the anthropogenically influenced stations. This suggests that anthropogenic pressure in small-island seagrass systems may be expressed more clearly through increased spatial patchiness in carbon storage than through a simple uniform decline in mean stock. A similar interpretation has been reported from Indonesian intertidal seagrass meadows across multiple islands, where carbon stocks differed significantly across spatial settings and anthropogenic use categories, indicating that a single average value cannot reliably represent seagrass carbon storage in dynamic archipelagic environments (Kurniawan *et al*. 2026). The pattern of heightened variability under anthropogenic pressure observed in this study is further supported by broader evidence that land-use change and urban development can reduce carbon sequestration efficiency in tropical seagrass sediments while simultaneously increasing spatial heterogeneity in carbon stock distribution (Dahl *et al*. 2022). At the global level, it already demonstrated that anthropogenic pressures and life history traits jointly predict the trajectory of seagrass meadows extent, with disturbance sensitive species and meadows experiencing accelerated loss and associated carbon stock decline (Turschwell *et al*. 2021). Moreover, the societal costs of seagrass loss extend beyond biodiversity to include major reduction in sediment carbon stocks, which are difficult to recover over short management timeframes (Moksnes *et al*. 2021)

The contrast between Station 1 and Station 2 further supports this interpretation. Although both stations were classified as anthropogenically influenced, their sediment carbon stocks differed markedly, suggesting that local disturbance type and environmental setting matter. In blue carbon science, disturbance effects are understood to depend not only on whether vegetation is affected, but also on how deeply disturbance propagates into the soil profile, how much buried carbon is ultimately lost as CO2, and the extent to which these processes depend on local environmental context (Macreadie *et al.* 2019). Therefore, the low sediment carbon stock at Station 2 is more appropriately interpreted as a site-specific response to localized disturbance and depositional conditions than as evidence that all anthropogenically influenced coastlines necessarily store less carbon than relatively undisturbed ones.

This site-specific interpretation is strongly supported by recent findings from Pari Island itself. Rahayu *et al*. (2025) found that sediment organic carbon concentrations in persistent seagrass meadows were higher than in dredged, restored, and bare-sand habitats, and that dredged sediments at Pantai Perawan had organic carbon concentrations 17% lower than those of persistent meadows. The same study also reported that, although restored seagrass area had expanded considerably, there had been no measurable increase in sediment organic carbon concentration or stock after 13 years of restoration. These findings are highly relevant to the present study because they indicate that sediment carbon storage in Pari Island is sensitive to physical disturbance, while recovery of sedimentary carbon may lag far behind the apparent recovery of seagrass cover.

The species composition observed across stations also provides important context for interpreting carbon storage differences. All four stations were dominated by *Thalassia hemprichii* and *Enhalus acoroides*, both large-bodied seagrass species with extensive belowground rhizome networks, supplemented by *Cymodocea rotundata* at all stations and *Halophila ovalis* only at ST1. Among these, *T. hemprichii* and *E. acoroides* are widely recognized as high carbon species because their dense root rhizome systems contribute disproportionately to the sediment organic carbon pool and mechanically stabilize the substrate against resuspension (Kennedy *et al.* 2022; Krause *et al.* 2025). In this study, the station with the highest seagrass cover and shoot density which is in the ST4 72.50%, 173.45 ind m^{-2}, composed predominantly of *T. hemprichii* and *E. acoroides* under undisturbed conditions, also recorded the highest sediment carbon stock 131.88 Mg C ha^{-1}. Conversely, ST2, despite registering the highest biomass carbon stock (5.72 Mg C ha^{-1}), showed the lowest sediment carbon (77.43 Mg C ha^{-1}), likely because the meadow at this boat-mooring station experiences recurrent physical disturbance that limits long-term organic carbon accumulation regardless of current vegetative standing stock. This contrast highlights that among the seagrass ecosystem types present at Pari Island, dense and structurally intact meadows of large-bodied species under undisturbed conditions represent the highest carbon storage type, while meadows of the same species under active physical disturbance represent the lowest, regardless of their surface-level canopy structure.

The observed mismatch between biomass carbon and sediment carbon here strengthens that point. In this study, the station with the highest biomass carbon did not coincide with the station with the highest sediment carbon, showing that present-day vegetation structure and long-term sedimentary carbon storage do not necessarily covary directly. This is consistent with broader evidence that large and persistent seagrass taxa tend to be associated with larger soil carbon stocks because greater belowground biomass contributes directly to the soil carbon pool and helps maintain more stable sedimentary environments (Kennedy *et al*. 2022; Krause *et al*. 2025)**.** Thus, biomass carbon reflects current standing stock, whereas sediment carbon integrates longer-term burial and preservation processes.

The results of this study point to several interacting factors that regulate sediment carbon storage in the seagrass meadows of Pari Island. First, sediment texture specifically the cohesive silt and clay fraction is a primary physical control on carbon retention capacity. ST4 with the highest silt plus clay content (12%), also recorded the highest sediment carbon stock, while station 2, despite its fine sand dominance, showed the lowest. Silt and clay particles have higher specific surface areas and stronger adsorptive capacity for organic matter, enabling more stable organo mineral associations that resist microbial decomposition (Macreadie *et al.* 2019). Second, seagrass meadows structural integrity and long-term persistence serve as biological regulators. Dense canopies of large bodied species reduce near bed hydrodynamic energy, facilitating fine particle settling and progressive belowground organic matter accumulation (Kennedy *et al.* 2022; Rahayu *et al.* 2025). Third, anthropogenic disturbance particularly physical disturbance from boat mooring and historical dredging acts as a primary disruptive force that increases spatial heterogeneity in carbon storage by selectively removing or degrading the biological and physical condition necessary for organic matter preservation, rather than causing a uniform reduction to mean stock. Fourth, at the methodological level, differences in sediment core recovery depth across stations introduce additional variability in total sediment carbon estimates that is independent of ecological conditions, underscoring the importance of standardizing core depth in future assessments on environmental and biological drivers of seagrass organic carbon. Together, these factors indicate that carbon storage in small tropical island seagrass systems is the product of co-occurring physical, biological, and disturbance related processes operating across multiple timescales, and that no single variable can serve as a reliable standalone predictor of ecosystem carbon stock.

The sediment grain-size pattern observed in this study also suggests that depositional conditions play an important role in carbon retention. All stations were predominantly sandy, the station with the highest sediment carbon stock also had the highest proportion of silt and clay, whereas Station 2, despite having a high fine-sand fraction, had the lowest sediment carbon stock. This interpretation is consistent with observations from restored and persistent seagrass meadows at Pari Island, where denser, more persistent meadows were discussed as more effective at entraining organic carbon, whereas insufficient seagrass density may allow greater sediment resuspension (Rahayu *et al*. 2025). In other words, vegetation presence alone is not enough; burial conditions and sediment stability determine whether carbon can persist over time. The contrast between fine sand and silt plus clay fractions is particularly informative in this context. ST4, which had the highest combine silt and clay content, (12%) among all stations, also recorded the highest sediment carbon stock 131.88 Mg C ha^{-1} , whereas ST2, despite its high fine sand content (71%) had the lowest carbon stock (77.43 Mg C ha^{-1}) of all stations. This pattern suggests that it is the cohesive fraction silt and clay rather than fine sand, that is more important for carbon retention. Fine sand particles, while smaller than coarse sand, remain relatively mobile and are less effective at forming stable organo mineral associations that protect organic carbon from decomposition or equivalent on grain size and organic carbon stabilization in coastal sediments. Silt and clay particles, by contrast, have higher specific surface areas and adsorptive capacity, allowing stronger binding of organic matter and more effective protection against microbial remineralization. The anomalously high carbon stock at ST1 despite its coarse sand dominance (90%) may reflect the role of seagrass canopy structure in trapping allochthonous organic particles under low energy conditions, or may be related to the depth of the core recovered at that station, this interpretation warrants further investigation. Taken together, these results indicate that within the predominantly sandy seagrass meadows of Pari Island, the presence of even a modest cohesive fraction exerts a disproportionate influence on sediment carbon storage, a finding consistent with broader evidence that organo mineral interactions are a primary mechanism of blue carbon stabilization in seagrass sediment.

From a management perspective, these results suggest that conserving existing seagrass meadows with intact sedimentary carbon pools may be more effective that relying solely on restoration after disturbance. This is especially important in Indonesia, where seagrass habitat is recognized as a globally significant blue carbon habitat, yet national assessment indicates that seagrass meadows are generally in moderate condition, with average cover around 39% and a mean SEQI of 0.68 ± 0.02 (Hernawan *et al*. 2021). These findings are also relevant to broader blue carbon science, management, and policy integration across tropical coastal landscapes (Friess *et al*. 2023). Accordingly, protection of sediment integrity should be considered a central target of blue carbon management, particularly in areas exposed to dredging, anchoring, mooring, intensive tourism, and other nearshore pressures. In the context of small island states and archipelagic nations such as Indonesia. It emphasized that seagrass blue carbon represents an underutilized asset for climate mitigation that warrants formal recognition in national carbon accounting frameworks (Friess 2023). At the policy implementation level, experiences from Japan that have demonstrate developing credible blue carbon offset crediting mechanisms for seagrass meadows is both scientifically feasible and practically achievable when database on carbon stocks and sequestration rates are systematically available (Kuwae *et al*. 2022). Looking forward, the management choice is fundamentally determines whether seagrass recovery meets both ecological and carbon mitigation goals, reinforcing the need for science based, adaptive management strategies in study sites such as Pari Island where restoration and conservation efforts are already underway (Ward *et al*. 2025).

The climate implications of disturbance should also not be overlooked. Earlier blue carbon work emphasized that degradation of vegetated coastal ecosystems may release not only future sequestration potential but also large standing carbon pools stored in sediments. (Pendleton *et al*. 2012) More recent global synthesis further notes that seagrass loss and degradation can of exposure to erosion, resuspension, and remineralization, turning carbon accumulated over long timescales into a new greenhouse gas source. (Krause *et al*. 2025) Therefore, the main implication of this study is that blue carbon conservation in small tropical islands should focus not only on preserving seagrass presence, but also on maintaining the physical conditions that keep buried sediment carbon stable. A systematic ranking of CO_2 emission risks from seagrass soil carbon stocks confirms that sites exposed to frequent physical disturbance and high organic matter content are among the highest risk categories for carbon release under global change (Dahl *et al*. 2023), a classification into which anthropogenically influenced meadows of Pari Island clearly fall. Additionally, mobile demersal activities, including boat anchoring and bottom disturbance, have been shown to directly reduce carbon storage in seabed sediments (Epstein *et al*. 2022), further substantiating the need for effective management of physical pressures on seagrass sedimentary carbon pools in small island settings.

5. Conclusions

Seagrass meadows in Pari Island store substantial ecosystem carbon, with sediment representing the principal carbon pool. The study showed that undisturbed areas generally had higher mean sediment carbon stocks, whereas anthropogenically influenced stations exhibited greater spatial variability. These findings indicate that local human pressure may affect the distribution and consistency of carbon storage more strongly than mean total carbon stock alone. In addition, the mismatch between biomass carbon and sediment carbon confirms that standing vegetation cannot be used as the sole indicator of blue carbon value. Therefore, effective blue carbon management in small tropical islands should emphasize sediment protection alongside seagrass conservation, as long-term ecosystem carbon storage depends primarily on the persistence of belowground carbon pools.

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