ORIGINAL RESEARCH

Environmental drivers of seagrass biomass and carbon stocks in a threatened Indonesian ecosystem

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ABSTRACT. Seagrass meadows play a critical role in coastal blue carbon sequestration, yet they are increasingly threatened by anthropogenic activities, especially in tourism-intensive islands. This study aimed to estimate seagrass biomass, carbon stocks, and assess the influence of environmental parameters on these ecological indicators in Tabuhan Island, Banyuwangi, East Java. Field research was conducted during August-September 2023 at two stations (North and East). Data collection involved 50 × 50 cm quadrat transects for seagrass sampling, *in situ* measurements of environmental parameters (temperature, salinity, pH, dissolved oxygen, brightness, current velocity, and substrate type), and laboratory analysis of biomass and organic carbon content using the Loss-on-Ignition method. Four seagrass species were identified: *Cymodocea rotundata*, *Halophila ovalis*, *Enhalus acoroides*, and *Thalassia hemprichii*. The seagrass ecosystem was in poor condition, with very low coverage (0.46% and 0.45%) and density (< 0.02 shoots m^{-2}). The average total biomass was 0.017 g DW m^{-2}, with below-ground biomass dominating. The estimated carbon stock was 0.0035 g C m^{-2}, stored primarily in below-ground tissues. Multivariate analysis revealed patterns among measured variables, with salinity and current velocity loading on one principal component and pH, biomass, and carbon stocks loading on another. This study underscores the urgent need for integrated coastal management and conservation strategies to protect and restore these vulnerable ecosystems, particularly in developing tourist destinations, to maintain their Nature's Contributions to People (NCP), including climate change mitigation.

Key words: Blue carbon, coastal ecosystem, environmental monitoring, seagrass ecology, tourism impact.

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Received: 10 December 2025
Accepted: 4 February 2026

ISSN 2683-7595 (print)
ISSN 2683-7951 (online)

https://ojs.inidep.edu.ar

Journal of the Instituto Nacional de Investigación y Desarrollo Pesquero (INIDEP)

Factores ambientales determinantes de las reservas de carbono en la biomasa de pastos marinos en un ecosistema indonesio amenazado

RESUMEN. Las praderas de pastos marinos desempeñan un papel crucial en el secuestro de carbono azul costero, sin embargo, están cada vez más amenazadas por actividades antropogénicas, especialmente en islas con un turismo intensivo. Este estudio tuvo como objetivo estimar la biomasa y el *stock* de carbono de los pastos marinos, y evaluar la influencia de parámetros ambientales sobre estos indicadores ecológicos en la Isla Tabuhan, Banyuwangi, Java Oriental. La investigación de campo se llevó a cabo entre agosto y septiembre de 2023 en dos estaciones (Norte y Este). La recolección de datos incluyó transectas con cuadrantes de 50 × 50 cm para el muestreo de pastos marinos, mediciones *in situ* de parámetros ambientales (temperatura, salinidad, pH, oxígeno disuelto, transparencia, corriente y sustrato), y análisis de laboratorio de la biomasa y el contenido de carbono orgánico mediante el método de Pérdida por Ignición. Se identificaron cuatro especies de pastos marinos: *Cymodocea rotundata*, *Halophila ovalis*, *Enhalus acoroides* y *Thalassia hemprichii*. El ecosistema de pastos marinos se encontró en mal estado, con una cobertura muy baja (0.46% y

0.45%) y una densidad baja (< 0.02 brotes m^{-2}). La biomasa total promedio fue de 0.017 g PS m^{-2}, dominando la biomasa subterránea. El *stock* de carbono estimado fue de 0.0035 g C m^{-2}, almacenada principalmente en los tejidos subterráneos. La salinidad y el pH fueron los principales factores ambientales que diferenciaron las dos estaciones y mostraron una fuerte asociación con los valores de biomasa y stocks de carbono de los pastos marinos. A pesar de su estado degradado, la pradera de pastos marinos de la Isla Tabuhan conserva un reservorio de carbono almacenado principalmente en los tejidos subterráneos. Este estudio subraya la necesidad urgente de estrategias integradas de gestión costera y conservación para proteger y restaurar estos ecosistemas vulnerables, particularmente en destinos turísticos en desarrollo, a fin de mantener las Contribuciones de la Naturaleza a las Personas (CNP), incluida la mitigación del cambio climático.

Palabras clave: Carbono azul, ecosistema costero, monitoreo ambiental, ecología de pastos marinos, impacto del turismo.

INTRODUCTION

Coastal marine ecosystems are essential for maintaining global biodiversity, supporting fisheries, and protecting shorelines from erosion (Barbier 2017). Among these key habitats, seagrass meadows are recognized as foundational species creating complex three-dimensional structures in shallow coastal waters. They provide essential nursery grounds for commercially important fish and invertebrates, stabilize sediments, and enhance water clarity through their filtration capacity (Cullen-Unsworth et al. 2014). Beyond these well-known ecological roles, seagrasses have attracted attention in climate change discussions due to their remarkable ability to sequester atmospheric carbon dioxide and store it as organic carbon, a Nature's Contribution to People (NCP) now widely known as 'blue carbon' (Schindler Murray et al. 2023). Although they occupy less than 0.2% of the ocean floor, seagrass ecosystems are highly effective carbon sinks, with their organic-rich sediments locking away carbon for centuries or even millennia, making their conservation a strategic natural climate solution (Fourqurean et al. 2012; Macreadie et al. 2021). Despite their crucial importance, seagrass meadows are among the world's most threatened ecosystems. Global estimates show a loss rate comparable to that of coral reefs and tropical rainforests, mainly driven by human-related stressors (Waycott et al. 2009; Dunic et al. 2021). Coastal development, nutrient and sediment pollution from land-based sources, and destructive fishing practices degrade water quality and reduce light availability, which is essential for seagrass photosynthesis (Orth et al. 2020). More recently, the rapid growth of marine tourism has introduced new pressures, including physical damage from boat anchors, propeller scars, and trampling by swimmers and snorkelers (Unsworth et al. 2019). This degradation not only reduces biodiversity and fishery productivity but also threatens the carbon sequestration function of seagrass beds, potentially transforming them from carbon sinks into sources of greenhouse gases (Pendleton et al. 2012; Röhr 2019).

In the Indonesian archipelago, home to some of the world's largest and most diverse seagrass beds, these threats are especially severe (Hernawan et al. 2021). The country's rapid economic growth has led to increased coastal development and a booming marine tourism industry, exerting immense pressure on sensitive nearshore ecosystems (Supriyadi et al. 2024). Tabuhan Island, a small uninhabited island in the Bali Strait off the coast of Banyuwangi, East Java, illustrates this trend. Designated as a tourism zone, the island attracts daily visitors for activities like snorkeling, concentrating human impact in a minimal area (Mira and Kurniawan 2020). While the island's coral reefs have been studied to some extent, a significant scientific gap remains: there is no published data on the status, composition, or ecological function of Tabuhan Island's seagrass meadows. This lack of baseline information hampers evidence-based management and obscures the island's full role in regional ecosystem services, including its potential as a blue carbon reservoir. Effective management of seagrass ecosystems requires not only documenting their condition but also understanding the environmental factors affecting their health. Seagrass distribution, growth, and productivity are highly sensitive to physical and chemical conditions such as salinity, pH, temperature, dissolved oxygen, and hydrodynamic energy (Koch et al. 2007; Roca et al. 2016). Therefore, characterizing natural environmental gradients is a crucial step in diagnosing causes of decline and predicting ecosystem resilience amid ongoing environmental changes, including climate change and local human impacts (Maxwell et al. 2017).

This study aimed to fill these gaps by providing the first comprehensive ecological assessment of the seagrass ecosystem around Tabuhan Island. The unique aspect of this work lies in its integrated approach: it establishes a quantitative baseline of seagrass community structure for this emerging tourist destination; offers the first estimates of standing biomass and *in situ* organic carbon stocks stored within seagrass tissues, contributing to regional and global blue carbon inventories (Howard et al. 2017); and uses multivariate statistical analysis to explore patterns among measured environmental variables and seagrass indicators. Accordingly, this research aimed to evaluate the ecological condition of seagrass meadows in Tabuhan Island by identifying species composition, measuring percent cover and shoot density, quantifying standing biomass, and estimating organic carbon stored within seagrass biomass. Additionally, it sought to examine relationships between measured environmental parameters and seagrass ecological indicators (Grech et al. 2012). By combining structural assessment, functional carbon measurement, and environmental diagnostics, this study intended to provide a scientific foundation for the sustainable management of Tabuhan Island, supporting conservation strategies that balance tourism development with the preservation of vital Nature's Contribution to People (NCP), including climate change mitigation (Nordlund et al. 2018).

MATERIALS AND METHODS

Study area and sampling design

This research was conducted in the coastal of Tabuhan Island, a small, uninhabited limestone island covering approximately 5 ha (Figure 1). The island is located in the Bali Strait (8° 2′ 13.998″ S and 114° 26′ 36.965″ E), administratively part of Bangsring Village, Wongsorejo District, Banyuwangi Regency, East Java Province, Indonesia. Characterized by a tropical monsoon climate, Tabuhan Island has been formally designated as a marine tourism zone under local spatial planning regulations. The island experiences significant seasonal visitation, with snorkeling being the primary recreational activity, leading to concentrated anthropogenic pressure in shallow coastal areas.

Field sampling was carried out during the dry season, from August to September 2023. A targeted sampling approach was employed based on preliminary surveys, which is a method commonly used in seagrass ecology to target areas where seagrass is known or suspected to exist (Short et al. 2007). Seagrass meadows were found only at two coastal sites: the northern coast (North Station: 8° 2′ 10.14″ S, 114° 27′ 40.15″ E) and the eastern coast (East Station: 8° 2′ 11.31″ S, 114° 27′ 45.51″ E). No seagrass was found at the southern and western exposures due to strong wave energy from the Indian Ocean, consistent with known limitations of seagrass distribution in high-energy environments (Fonseca and Bell 1998). At each station, a 50-m line transect was deployed parallel to the shoreline, starting from the point where seagrass was first encountered. Along each transect, ten 50 × 50 cm (0.25 m^2) quadrats were placed at approximately 5-m intervals in a zig-zag pattern for sampling following standard seagrass monitoring protocols (Mckenzie 2003).

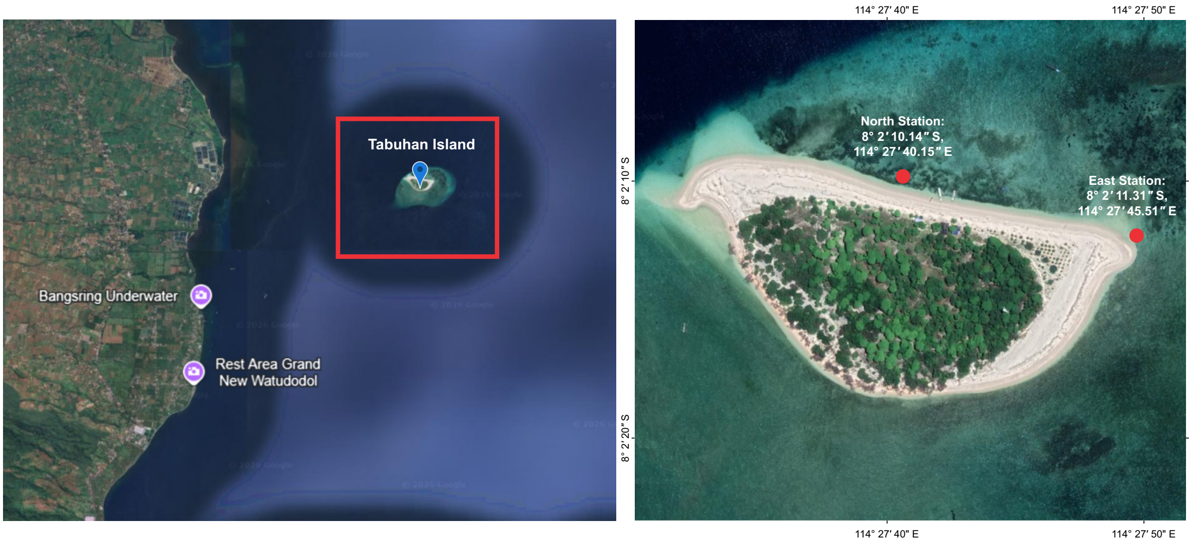

Figure 1. Sampling stations in the study area of Tabuhan Island, eastern Java.

Field data collection

Seagrass community structure was assessed within each quadrat. All seagrass shoots were identified to species level and counted to determine shoot density. Species identification followed visual morphological characteristics as described in standard seagrass identification guides (Den Hartog and Kuo 2007) and validated against the Seagrass-Watch monitoring protocol (Mckenzie 2003). Percentage cover for each species was visually estimated using a modified Braun-Blanquet scale adapted for seagrass studies, where cover classes were defined as: 0 (absent), + (< 1%), 1 (1-5%), 2 (6-25%), 3 (26-50%), 4 (51-75%), and 5 (76-100%) (Hemminga and Duarte 2000). Station-level percent cover was calculated as the average cover across all ten quadrats per transect, including quadrats with zero seagrass cover. For biomass and carbon analysis, one intact individual of each species, including leaves, rhizomes, and roots, was carefully excavated from each quadrat using a small shovel to minimize sediment disturbance following non-destructive sampling guidelines (Duarte and Kirkman 2001). Samples were rinsed *in situ* to remove loose sediments, placed in labeled zip-lock bags, stored in a cooler with ice packs, and transported to the laboratory within 24 h for further processing.

Environmental parameters were measured at each station during sampling. Water quality parameters (temperature, salinity, pH, and dissolved oxygen) were measured in the water column just below the surface using a calibrated multi-parameter water quality meter (Mediatech TDS). Water clarity was assessed as percent brightness using a Secchi disk under calm sea conditions (Kirk 2011). Substrate type was characterized descriptively at each quadrat based on visual and tactile inspection. Current velocity data (m s^{-1}) for the sampling period were derived from secondary sources, including hydrodynamic modeling outputs and remote sensing data processed using ArcGIS 10.3 software, following established methods for coastal current estimation (Klemas 2012).

Laboratory analysis

In the laboratory, seagrass samples were thoroughly rinsed with distilled water to remove epiphytes, salts, and residual sediments. Each sample was carefully separated into above-ground biomass (AGB), comprising leaves and sheaths, and below-ground biomass (BGB), consisting of rhizomes and roots (Fourqurean et al. 2012). The components were oven-dried at 60 °C to constant weight (approximately 48-72 h) and then weighed using an analytical balance (Superior I200, precision ± 0.01 g) to determine dry weight (DW). Biomass for each species per square meter (g DW m^{-2}) was calculated by multiplying the average dry weight per individual by its corresponding shoot density (ind. m^{-2}) (Duarte and Chiscano 1999).

The organic carbon content of the dried seagrass biomass was determined using the Loss-on-Ignition method (LOI) (Heiri et al. 2001; Howard et al. 2014). Briefly, dried samples were ground into a fine powder using a mortar and pestle. Approximately 5 g of homogenized powder from each sample (AGB and BGB separately) were placed in pre-weighed porcelain crucibles. The crucibles were then combusted in a muffle furnace (B-Onc) at 550 °C for 4 h to oxidize all organic matter (Wang et al. 2011). After combustion, crucibles were cooled in a desiccator for 45 min and reweighed. The organic matter content was calculated as the weight lost during ignition. Organic carbon content was calculated by dividing the organic matter content by the conversion factor of 1.724, as per the combustion method outlined by (Helrich 1990). This factor corresponds to a carbon content of approximately 58% in organic matter and aligns with methodologies used in previous seagrass carbon assessments in Indonesia (Supriadi et al. 2014). It is noted that alternative protocols, such as those in international blue carbon guidelines (Howard et al. 2014) recommend a conversion factor of 0.34 for seagrass biomass. The factor applied here was selected to maintain consistency with regional studies. For quality control in carbon analysis, the LOI method was performed in duplicate for 10% of the samples.

Data calculation and analysis

Seagrass percent cover was classified into condition categories according to the Indonesian Minister of Environment Decree No. 200/2004 on standard criteria for seagrass damage assessment (Ministry of Environment 2004) as 'Good/Rich/Healthy' (< 60%), 'Damaged/Less Rich/Less Healthy' (30-59.9%), and 'Poor' (< 29.9%).

Seagrass shoot density was categorized according to the density-based condition scale adapted from Rahadiarta et al. (2019) (Table 1).

Seagrass density (D, shoots m^{-2}) for each species was calculated according to Supriadi et al. (2014) as:

$$D = \frac{\sum N_i}{A}$$

where N_i is the total number of shoots of species i and A is the total sampled area (m^2). Seagrass biomass was estimated following Duarte et al. (2013) as:

$$B = W \times D$$

where B is the biomass of seagrass species i (g DW m^{-2}) and W is the average dry weight per individual of species i (g DW). Total biomass per station was calculated as the sum of the above-ground biomass (AGB) and below-ground biomass (BGB) across all species. The ash content was calculated as:

$$\text{Ash content (\%)} = \frac{c - a}{b - a} \times 100$$

where a is the weight of crucible (g), b is the weight of crucible + dried sample (g), and c is the weight of crucible + ash after combustion (g).

Organic matter content was then derived from:

$$\text{Organic matter (\%)} = \frac{(b - a) - (c - a)}{b - a} \times 100$$

Finally, organic carbon content was estimated using the Van Bemmelen conversion factor:

$$\text{Organic carbon (\%)} = \frac{\text{Organic matter content}}{1.724}$$

where 1.724 is the conventional factor assuming organic matter contains 58% carbon (Helrich 1990). Measured environmental parameters (temperature, pH, DO, salinity) were compared to the seawater quality standards set by the Government of Indonesia (Government of Indonesia 2021) to assess compliance. To identify the key environmental drivers influencing seagrass biomass and carbon stocks, a multivariate statistical analysis was performed. Principal Component Analysis (PCA) was conducted using Minitab Statistical Software (version 22). The PCA was employed to synthesize the environmental and biological dataset and explore patterns of variability among stations and variables. The analysis included seven environmental variables (temperature, DO, pH, salinity, brightness, current velocity, substrate type) and one biological response variable (total seagrass biomass). The PCA reduces the dimensionality of the dataset to principal components (PCs) that explain the maximum variance, allowing visualization of patterns and correlations between variables and sampling stations (Legendre 2019). A scree plot was used to determine the number of significant PCs to retain for interpretation (Jackson 1993).

RESULTS

Environmental conditions at sampling stations

In situ measurements revealed distinct environmental conditions between the two sampling stations. The East Station recorded a higher mean water temperature (29.45 ± 0.26 °C) compared to the North Station (28.83 ± 0.38 °C). Conversely, salinity was higher at the North Station (29.80 ± 0.33) than at the East Station (27.87 ± 0.37). Both stations exhibited slightly alkaline pH levels, with near-identical values of 8.23 and 8.22, respectively. Dissolved oxygen (DO) was marginally higher at the East Station (6.09 ± 0.18 mg l^{-1}) compared to the North Station (5.50 ± 0.15 mg l^{-1}). Water brightness was 100% at both locations during morning measurements. Model-derived current velocities were nearly identical at both stations (~ 0.56 m s^{-1}), indicating similar hydrodynamic exposure. The substrate at both sites was predominantly composed of coral rubble mixed with coarse sand.

Table 1. Seagrass condition scale based on shoot density (shoots m^{-2}).

Scale	Density	Condition
5	> 625	Very dense
4	425-625	Dense
3	225-424	Moderately sparse
2	25-224	Sparse
1	< 24	Very sparse

Seagrass species composition and community structure

Field surveys identified a total of four seagrass species across the study area, representing two families (Table 1). All four species were present at both the North and East Stations. *Cymodocea rotundata* and *Enhalus acoroide*s were visually dominant in terms of frequency of occurrence within quadrats. Total coverage was very low, measuring 0.46% at the North Station and 0.45% at the East Station (Table 2).

Both meadows are classified as 'Poor' by the Indonesian Minister of Environment Decree (Ministry of Environment 2004) (≤ 29.9%). At the species level, *C. rotundata* contributed the most to cover at the East Station (0.36%), while *E. acoroide*s was highest at the North Station (0.19%). The shoot density mirrored the cover results, with total density being extremely sparse: 0.018 shoots m^{-2} at the North Station and 0.017 shoots m^{-2} at the East

Table 2. Seagrass coverage (%) and seagrass shoot density (shoots m^{-2}) at the North and East Stations in Tabuhan Island. Condition of meadows are according to the Ministry of Environment (2004) (ME2004), and Rahadiarta et al. (2019) (RA2019).

	North Station		East Station		Condition of meadows	
Species	Coverage	Shoot density	Coverage	Shoot density	(ME2004)	(RA2019)
Cymodocea rotundata	0.18	0.007	0.36	0.014	Poor	Very sparse
Halophila ovalis	0.05	0.002	0.05	0.002	Poor	Very sparse
Enhalus acoroides	0.19	0.008	0.03	0.001	Poor	Very sparse
Thalassia hemprichii	0.04	0.001	0.01	0.0002	Poor	Very sparse
Total	0.46	0.018	0.45	0.017	Poor	Very sparse

Station. Based on established density categories, this qualifies as 'Very Sparse' (< 24 shoots m^{-2}). *Cymodocea rotundata* showed the highest density at the East Station (0.014 shoots m^{-2}).

Seagrass biomass and carbon stocks

Based on the biomass calculations, the highest above-ground biomass (AGB) was observed for *Thalassia hemprichii* at the North Station (0.002 g DW m^{-2}), followed by *C. rotundata* at the East Station (0.001 g DW m^{-2}) (Figure 2). *Halophila ovalis* at the East Station exhibited the lowest overall AGB value (0.0003 g DW m^{-2}). Below-ground biomass (BGB) followed a similar distribution pattern. The highest BGB was found in *C. rotundata* at the East Station (0.006 g DW m^{-2}), followed by *E. acoroides* at the North Station (0.004 g DW m^{-2}). *Enhalus acoroides* at the East Station exhibited the lowest overall BGB value (0.002 g DW m^{-2}). Total seagrass biomass was low at both stations, with the East Station recording slightly higher total biomass (0.011 g DW m^{-2}) than the North Station (0.010 g DW m^{-2}). Below-ground biomass constituted the majority of total biomass, accounting for approximately 80% of the total, while AGB contributed only 20%. Among species, *E. acoroides* at the North Station exhibited the highest below-ground biomass (0.004 g DW m^{-2}).

Environmental and biological drivers

The PCA considered all measured environmental variables, though brightness was uniform (100% at both stations) and substrate type was categorical; thus, these do not appear in the loading plot but were included in the analysis. The loading plot revealed that PC1 was strongly and positively associated with salinity and current velocity, while PC2 showed strong positive loadings for seagrass biomass, carbon stock, and pH (Figure 3). Variables such as temperature and dissolved oxygen exhibited weaker or orthogonal relationships with these components, suggesting a lesser direct influence on the observed seagrass patterns under current conditions.

DISCUSSION

The findings of this study reveal that the seagrass meadows of Tabuhan Island are in a state of ecological degradation. Their percent cover (≤ 0.5%) and shoot density (< 0.02 shoots m^{-2}) are significantly lower than those reported for healthy meadows in nearby Indonesian regions such as the Seribu Islands (> 60% cover, > 100 shoots m^{-2}; Ambo-Rappe et al. 2019; Hernawan et al. 2021),

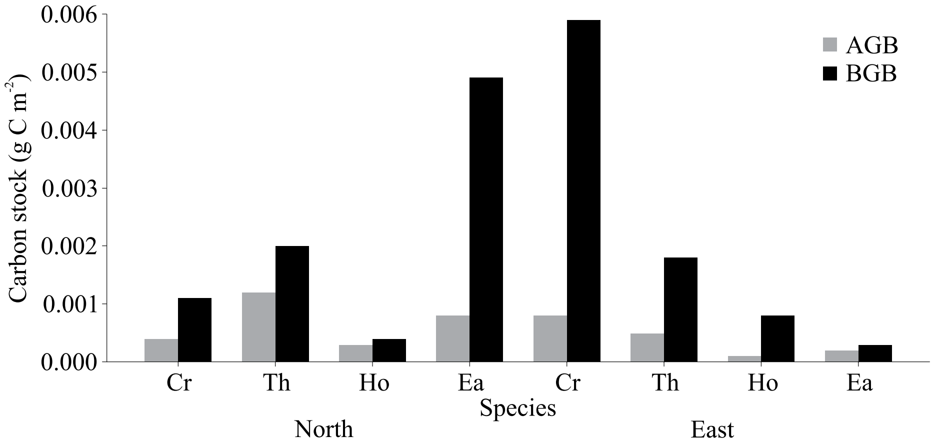

Figure 2. Carbon stock in seagrass biomass by species and station partitioned into above-ground biomass (AGB) and below-ground biomass (BGB). The Y-axis represents biomass in g C m^{-2}, with AGB shown as the upper segment of each bar and BGB as the lower segment. Cr: *Cymodocea rotundata*, Th: *Thalassia hemprichii*, Ho: *Halophila ovalis*, Ea: *Enhalus acoroides*.

indicating severe habitat decline and limited biomass and carbon stocks. These conditions are consistent with seagrass ecosystems experiencing chronic anthropogenic pressure, particularly in small island settings where tourism activities are concentrated (Unsworth et al. 2019; Baltranaitė et al. 2025). These values are orders of magnitude below the ‘Poor’ classification threshold of Indonesia’s environmental standards (Ministry of Environment 2004) and align with global observations of declining seagrass coverage in tourism-affected coastal zones (Waycott et al. 2009; Dunic et al. 2021). For context, healthy meadows in nearby regions of Indonesia, such as the Seribu Islands, typically exhibit covers exceeding 60% and densities over 100 shoots m^{-2} (Ambo-Rappe et al. 2019; Hernawan et al. 2021b).

The community is dominated by *C. rotundata*, a disturbance-tolerant species, while more sensitive species, such as *E. acoroides* and *T. hemprichii*, are present only in sparse numbers. This species composition, where stress-tolerant taxa dominate and sensitive taxa are rare, is consistent with patterns observed in other seagrass ecosystems experiencing chronic anthropogenic pressure (Marbà et al. 2015; McKenzie et al. 2020). This degraded condition is not an isolated phenomenon, but mirrors trends observed in other small island tourism destinations across Southeast Asia, where unmanaged recreational activities directly contribute to habitat fragmentation and loss (Jones et al. 2022). The proximate cause of this decline is most likely the intense and localized anthropogenic pressure from marine tourism. Tabuhan Island, as a focal point for daily snorkeling and boating, is subject to physical damage from anchor drops, propeller scarring, and tourist trampling, all documented agents of seagrass meadow degradation (Creed et al. 1999; Unsworth et al. 2019). Unlike gradual stressors like nutrient pollution, physical destruction causes immediate and often irreversible loss of above-ground tissue and can destabilize the sediment, hindering recovery (Creed et al. 1999; Erftemeijer and Lewis 2006; Unsworth et al. 2019). This creates a ‘negative footprint’ where the very activity that drives the local economy simultaneously erodes the natural capital that sustains it.

A key finding of this study is the pronounced allocation of biomass and carbon to below-ground tissues (~ 80% of total). This ratio exceeds the 40-60% below-ground allocation typically reported for healthy tropical seagrass meadows (Duarte and Chiscano 1999; Fourqurean et al. 2012), providing quantitative evidence of a stress response where

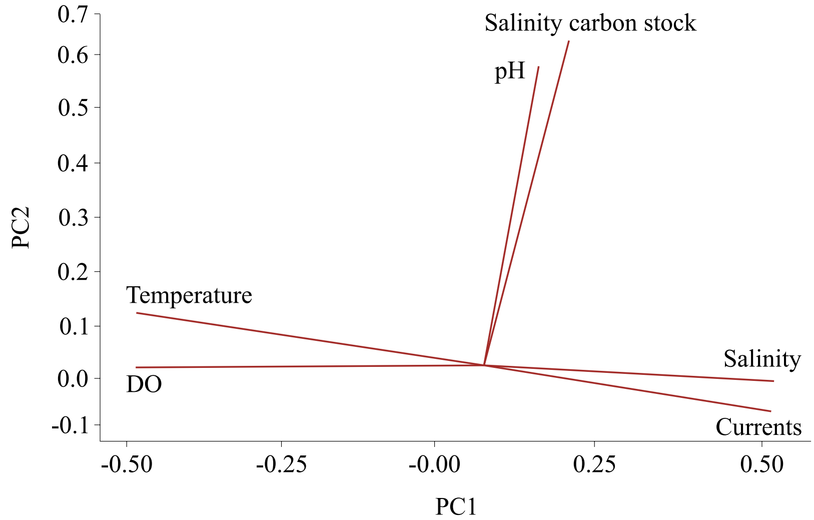

Figure 3. Biplot of principal component analysis (PCA). The first component (PC1, x-axis) is primarily associated with salinity and current velocity, while the second component (PC2, y-axis) is strongly influenced by pH and seagrass carbon stock. Vector direction indicates variable correlation with each component; vector length represents the strength of contribution. Variable units: current velocity (m s^{-1}), temperature (°C), dissolved oxygen (DO) (mg l^{-1}), salinity carbon stock (g C m^{-2}).

resources are prioritized to anchorage and storage organs. Under conditions of physical disturbance, herbivory, or nutrient limitation, seagrasses often invest more resources into below-ground structures to enhance anchorage, storage, and resilience (Fourqurean et al. 2012; Olsen et al. 2012). Similar patterns have been reported in seagrass meadows exposed to boat traffic and trampling, where below-ground biomass serves as a critical reserve for regrowth (Peralta et al. 2000; Garrard and Beaumont 2014). This morphological strategy may partially explain the persistence of seagrass in Tabuhan Island despite evident anthropogenic pressure.

Carbon stocks measured in this study are orders of magnitude lower than those reported from healthier Indonesian meadows, such as ~ 250 g C m^{-2} in Bintan Island (Hernawan et al. 2021) and ~ 180 g C m^{-2} in the Spermonde Archipelago (Ambo-Rappe et al. 2019). This discrepancy underscores the impact of habitat degradation on carbon sequestration capacity. Degraded meadows not only store less carbon but may also experience reduced sediment carbon accumulation due to erosion and rhizome exposure (Lovelock and Duarte 2019; Macreadie et al. 2021). Nevertheless, the fact that carbon is still stored, primarily below-ground, highlights the continued, albeit diminished, role of these meadows as blue carbon sinks. This finding supports the argument that even degraded seagrass systems warrant conservation attention for their climate mitigation potential (Howard et al. 2014; Röhr 2019).

It is important to note that this study quantified carbon stored in seagrass biomass only. In seagrass ecosystems, most carbon is typically stored in the underlying sediments, which can represent a long-term reservoir spanning centuries to millennia (Fourqurean et al. 2012; Macreadie et al. 2021). Our biomass carbon estimates therefore represent only a fraction of the total carbon stock ecosystem. Future research should include sediment core sampling to quantify the full blue carbon potential of Tabuhan Island's seagrass meadows, particularly given that degraded meadows may experience sediment carbon loss through erosion (Lovelock and Duarte 2019).

The low seagrass metrics observed in Tabuhan Island, percent cover, shoot density, and standing biomass,are likely compounded by tourism-related impacts. Snorkeling, anchoring, and trampling can directly damage shoots, reduce light penetration via sediment resuspension, and fragment rhizome networks (Unsworth et al. 2019). Previous studies in similar tropical tourism destinations have documented reduced seagrass cover and altered species composition in high-visitation areas (Franco et al. 2013). Without management intervention, continued pressure may diminish seagrass resilience and carbon storage function. This study provides the first quantitative baseline of seagrass structure and carbon stocks for Tabuhan Island, filling a critical knowledge gap for this emerging tourist destination. The integration of ecological metrics offers a replicable framework for assessing seagrass condition in data-limited regions.

The demonstration of measurable, though limited, carbon storage reinforces the importance of including seagrass ecosystems in local and regional blue carbon strategies, even when their aboveground coverage appears marginal (Duarte et al. 2013). While this study provides the first quantitative baseline for seagrass on Tabuhan Island, certain limitations must be acknowledged. The assessment was conducted during the dry season (August-September) and is thus a temporal snapshot; seasonal variations in monsoon rainfall, water quality, and seagrass growth dynamics were not captured (Erftemeijer 1993). Furthermore, the spatial replication was limited to two stations where seagrass was found, which restricts our ability to generalize conditions across the entire island's coastline. However, these stations were purposively selected to represent the only identifiable meadows under active tourism pressure, and the integrated methodological approach (structural, functional, and environmental) provides a robust and replicable framework for future monitoring efforts. Future studies would benefit from seasonal sampling and a broader spatial survey to better understand the full extent and temporal dynamics of Tabuhan Island's seagrass ecosystems (Grech et al. 2012; Maxwell et al. 2017).

CONCLUSIONS

This study establishes the first ecological baseline for the seagrass meadows of Tabuhan Island, confirming a system in a state of severe degradation driven predominantly by unmanaged tourism. Despite critically low structural integrity, the persistence of below-ground biomass and residual carbon storage signals latent ecological resilience and a biological foundation for potential recovery. Multivariate analysis highlighted patterns among the measured environmental variables, though these subtle gradients are overshadowed by the dominant impact of physical disturbance from tourism activities. Consequently, effective management must prioritize direct mitigation of anthropogenic pressures, such as anchor damage and trampling, while maintaining environmental monitoring to detect any compounding effects of water quality or hydrodynamic changes.

The findings translate into clear management priorities: immediate implementation of protective measures like mooring buoys and visitor zoning; establishment of a long-term monitoring program based on the parameters validated here; and exploration of community-involved restoration that utilizes the remaining below-ground network. By aligning tourism development with evidence-based conservation, Tabuhan Island can pursue a sustainable pathway where economic and ecological objectives are mutually supportive rather than conflicting. This research provides the necessary scientific foundation to inform such integrated coastal management, emphasizing that even degraded seagrass systems retain ecological value and recovery potential if timely and informed intervention is applied.

Conflict of interest

According to the authors, there is no conflict of interest.

Artificial intelligence uses declaration

During manuscript preparation, AI-based tools (specifically ChatGPT version 3.5) were used solely for grammar correction and text fluency improvement. The prompts used were generic requests for 'improve grammar' or 'enhance readability'. All study design, data collection, analysis, interpretation, and scientific conclusions were developed by the authors without AI assistance.

Author contributions

Faiz Ni'matul Haq: conceptualization; process; research; materials; composing the first draft; composing the review, and editing. Medy Ardianto Wijaya: conceptualization; process; software; verification; formal analysis; inquiry; materials; data curation; composing the review, and editing.

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