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MORALITY BEFORE KNOWLEDGE

Seagrass community structure as an indicator of ecosystem response on Pramuka Island

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ABSTRACT
Background: Seagrass ecosystems are important blue carbon habitats but are increasingly threatened by anthropogenic activities. This study analyzed seagrass community structure and ecological responses across different levels of human pressure on Pramuka Island, Indonesia. **Methods:** A quantitative approach was employed using quadrat transects at 3 stations subjected to different pressure A quantitative field survey was conducted using quadrat transects at 3 stations. Seagrass species composition, cover, diversity, evenness, dominance, and Importance Value Index (IVI) were analyzed. Water quality was measured in situ, while carbon sequestration was estimated using literature-based coefficients. **Findings:** A total of 6 seagrass species were identified, with *Thalassia hemprichii* as the dominant species. Station 2 showed the highest dominance and lowest diversity, whereas Station 3 had the highest diversity despite the lowest seagrass cover. Overall seagrass cover remained below 30%, while estimated carbon sequestration ranged from 0.42 to 0.55 tons C ha^{-1} $year^{-1}$. Similar water quality among stations suggests that differences in community structure were more strongly influenced by habitat characteristics and hydrodynamic conditions than by physicochemical factors. **Conclusion:** The findings indicate that seagrass community structure is a more sensitive indicator of ecosystem condition than seagrass cover alone. Integrating community structure with cover measurements can improve ecological assessments and support evidence-based management of seagrass ecosystems under varying anthropogenic pressures. **Novelty/Originality of this article:** This study demonstrates the value of biodiversity-based indicators alongside seagrass cover for assessing ecosystem condition and informing blue carbon and coastal conservation strategies.

KEYWORDS: anthropogenic pressure; carbon sequestration; coastal ecosystem; Pramuka Island; seagrass community.

1. Introduction

Seagrass meadows are highly productive coastal ecosystems that support biodiversity, stabilize sediments, regulate nutrient cycling, and contribute to long-term coastal carbon storage. Seagrass meadows are one of the key coastal ecosystems in this framework, which hold a strategic position even though they cover less than 0.2% of the total global ocean area (Nugraha et al., 2020). Seagrass ecosystems offer many ecological benefits, such as providing spawning grounds, shelter, and a food source for various marine organisms such as fish, mollusks, and other invertebrates (Rustam, 2019). The benefits of seagrass ecosystems include sediment stabilisation, protection from coastal erosion and filtration of nutrients and pollutants from the surrounding environment (Sholihah et al., 2020). Beyond these ecosystem functions, seagrass meadows have increasingly been recognised as

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strategic natural capital because they simultaneously support biodiversity conservation, coastal resilience, climate-change mitigation, and sustainable coastal livelihoods. Seagrass ecosystems also function as important ecological indicators of coastal environmental conditions. Changes in community structure, including species composition, diversity, dominance, and evenness, can directly reflect environmental stress and habitat quality (Jones et al., 2022). Rather than merely describing current ecological conditions, community structure provides an early-warning signal of ecosystem degradation resulting from anthropogenic disturbances (Potouroglou et al., 2021). Therefore, analyzing the structure of seagrass communities represents a comprehensive ecological approach for assessing the condition and stability of coastal ecosystems (Thomsen et al., 2020).

The carbon uptake rate of seagrasses is reported to reach 208.83 g cm^{-2} of biomass, with a carbon sequestration efficiency up to 35 times faster than that of tropical forests (Nugraha et al., 2020). Estimated carbon sequestration rates in some Indonesian seagrass meadows have been reported to exceed global averages, underscoring the strategic role of this ecosystem in coastal ecosystem-based climate change mitigation (Hernawan et al., 2021). In addition to serving as a carbon sink, seagrasses can reduce wave energy by up to 40% (Coxon, 2026), making them an important natural infrastructure for coastal protection and ecosystem stability (Sholihah et al., 2020). Collectively, these multiple ecosystem services provide a scientific basis for sustainable coastal management and ecotourism development (Lincoln et al., 2021). Seagrass directly supports the tourism sector by serving as a nursery habitat for reef fish, improving water quality and clarity (Infantes et al., 2022), and shaping the underwater landscape (do Amaral et al., 2023) that supports snorkeling, educational tourism, and conservation-based ecotourism. Thus, seagrass is an ecological and tourism economic asset, as well as a carbon sink (Darmawan et al., 2020). Estimated carbon sequestration rates in some Indonesian seagrass meadows have been reported to exceed global averages (Krause et al., 2025).

Indonesia contains approximately 1.8 million hectares of seagrass habitat and supports high seagrass species richness and is the country with the highest level of seagrass diversity in Southeast Asia, with 16 species (Hernawan et al., 2021). In recent decades, seagrass ecosystems have experienced considerable pressure, r despite their ecological importance, Indonesian seagrass meadows have experienced substantial degradation and spatial loss as a result of coastal development and other anthropogenic pressures (Sjafrie et al., 2018), despite their wide range of ecological benefits. Seagrass meadows are under serious global pressure, losing 29% of their area in the past century from an estimated total of 56,930 km^2 (Blume et al., 2023). These are linked to environmental change, deteriorating water quality, disease, coastal alterations, mechanical damage, overfishing and land-sea interactions (Manca et al., 2024). These different environmental stressors not only cause a reduction in the extent of seagrass but also result in shifts in species composition and community structure. Anthropogenic pressures are increasing in tandem with population growth, particularly in the Thousand Islands.

According to Minister of Environment Decision No. 200 of 2004, the condition of seagrass beds in the Thousand Islands is classified as poor, with coverage of less than 29% indicating poor condition. Field measurements conducted in this study recorded seagrass cover ranging from 21.8% to 28.6% across the observation stations on Pramuka Island. These values fall below the 29% threshold and indicate that the observed seagrass meadows are within the low-cover category according to the applicable Indonesian ecological criteria. Official tourism statistics indicate that the number of tourist visits increased from 23,149 in 2021 to 58,498 in 2023, suggesting a substantial increase in recreational use of the Thousand Islands. Tourist visits to the Thousand Islands increased from 23,149 in 2021 to 58,498 in 2023. Independently, national assessments have documented substantial seagrass degradation in Indonesia. Although these trends occur at different spatial and temporal scales, increasing tourism pressure provides a rationale for evaluating seagrass condition at intensively used small islands such as Pramuka Island (Hernawan et al., 2021), with reported degradation rates reaching 30–60% due to coastal land conversion and anthropogenic pressures. The primary pressures occur in inhabited coastal areas and tourist destinations, including unregulated snorkeling activities, the use of tourist boat anchors, and the construction of coastal tourism facilities (Hernawan et al., 2021). These pressures have the potential to cause changes in seagrass community structure, reflected in a decline in biodiversity, increased dominance of certain species, and ecosystem imbalance.

Degradation and loss of ecological resilience in seagrass meadows may reduce their capacity to provide ecosystem services, including carbon storage and tourism-related benefits (Hernawan et al., 2021). The contrast between the ecological importance of seagrass meadows and their reported degradation highlights the need for more effective ecological monitoring and site-specific management (Unsworth et al., 2018). Seagrass cover, biomass, blue carbon storage, ecosystem services, and coastal economic values have been extensively investigated (Unsworth et al., 2022). However, these studies generally treat seagrass cover or biomass as the primary indicators of ecosystem condition, while relatively limited attention has been given to community structure attributes such as species diversity, dominance, evenness, and the Importance Value Index (IVI), despite their higher ecological sensitivity to environmental disturbance (Zamani et al., 2018). Moreover, relatively few site-level assessments have considered seagrass community structure together with percentage cover, local environmental conditions, and observed human activities in a small inhabited-island context, particularly in small inhabited islands experiencing intensive tourism development. Nordlund et al. (2018) highlighted similar research gaps, emphasizing the need for ecological indicators capable of detecting early ecosystem degradation before substantial declines in seagrass cover become clear.

A remaining question is whether percentage cover alone adequately represents seagrass ecosystem condition in small inhabited islands where local environmental conditions and human activities vary over short spatial scales. Recent reviews have highlighted the need for integrated ecological approaches that simultaneously evaluate biodiversity, ecosystem functioning, and anthropogenic pressures within seagrass ecosystems (Nordlund et al., 2024). Although previous studies have primarily focused on seagrass cover, biomass, blue carbon, and ecosystem services (Unsworth et al., 2024), the ecological sensitivity of community structure, including species diversity, dominance, evenness, and the Importance Value Index (IVI), remains insufficiently explored as an integrated indicator of ecosystem condition. Studies linking community structure, carbon sequestration potential, and tourism-induced anthropogenic pressures in small inhabited islands are still limited (Nordlund et al., 2024). In addition, a literature-based estimate of carbon sequestration was calculated for the sampled seagrass area to provide an indicative assessment of potential blue-carbon function.. The novelty of this study lies in combining biodiversity metrics, carbon sequestration, and tourism-related disturbances within a single analytical framework, providing a more comprehensive assessment of ecosystem health than approaches based solely on seagrass cover or biomass.

2. Methods

2.1 Study area

This research was conducted on Pramuka Island, located at 106°36'45.00" East and 05°44'45.00" South. According to Government Regulation Number 55 of 2001, Pramuka Island is one of the islands in the Thousand Islands Administrative Region, North Thousand Islands Subregion, Pulau Panggang Village (Figure 1). Pramuka Island was selected because seagrass habitats occur in close proximity to residential areas, tourism activities, and conservation areas, providing contrasting local settings for evaluating spatial variation in seagrass community condition. The combination of the three factors makes Pramuka Island an appropriate area conducting research on the connection between the seagrass ecosystem and its environment. This research is being conducted using the quantitative research method to examine the ecological condition of the seagrass ecosystem against environmental pressure in Pramuka Island, Thousand Islands. Three stations were selected to represent contrasting local settings based on preliminary field observations: Station 1 on the western coast, characterized by relatively intensive tourism and boating activities; Station 2 on the southern coast, characterized by lower visible recreational activity but the presence of coastal infrastructure and boat mooring; and Station 3 on the eastern coast, located adjacent to a conservation area and characterized by relatively limited visible human activity.The data used in this study was collected through field ecological surveys, observations of human activities, and measurement of both the physical and chemical properties of water. The study was conducted in February 2026.

2.2 Data collection

Data collection was conducted using three main approaches: seagrass ecosystem surveys, aquatic environmental quality measurements, and anthropogenic pressure evaluation. For the seagrass ecosystem surveys, three sampling stations were established on Pramuka Island. At each station, three 50-m transects were positioned perpendicular to the shoreline and separated by 5 m. A 50 × 50 cm quadrat, divided into four subplots, was placed at 5-m intervals along each transect, resulting in 10 quadrats per transect and 30 quadrats per station. Thus, a total of 90 quadrats were sampled across the three stations. This method follows McKenzie et al. (2003) monitoring protocol for tropical seagrass ecosystems and has been widely adopted in seagrass ecology studies (Unsworth et al., 2018). Each square was used to identify seagrass species based on the morphological characteristics of the leaves and rhizomes, the number of shoots of each species within each quadrat was counted and used as the abundance measure for community-index calculations and to percentage seagrass cover was visually estimated within each gridded quadrat as the proportion of the quadrat area occupied by seagrass canopy. Quadrat-level cover estimates were subsequently averaged at the transect and station levels. The substrate in each square is visually classified into sand, rubble (coral fragments), or a combination of the three to support the interpretation of seagrass habitat conditions (Rifai et al., 2023). The square transect method was chosen for its ability to accurately estimate the spatial distribution and community structure of seagrass.

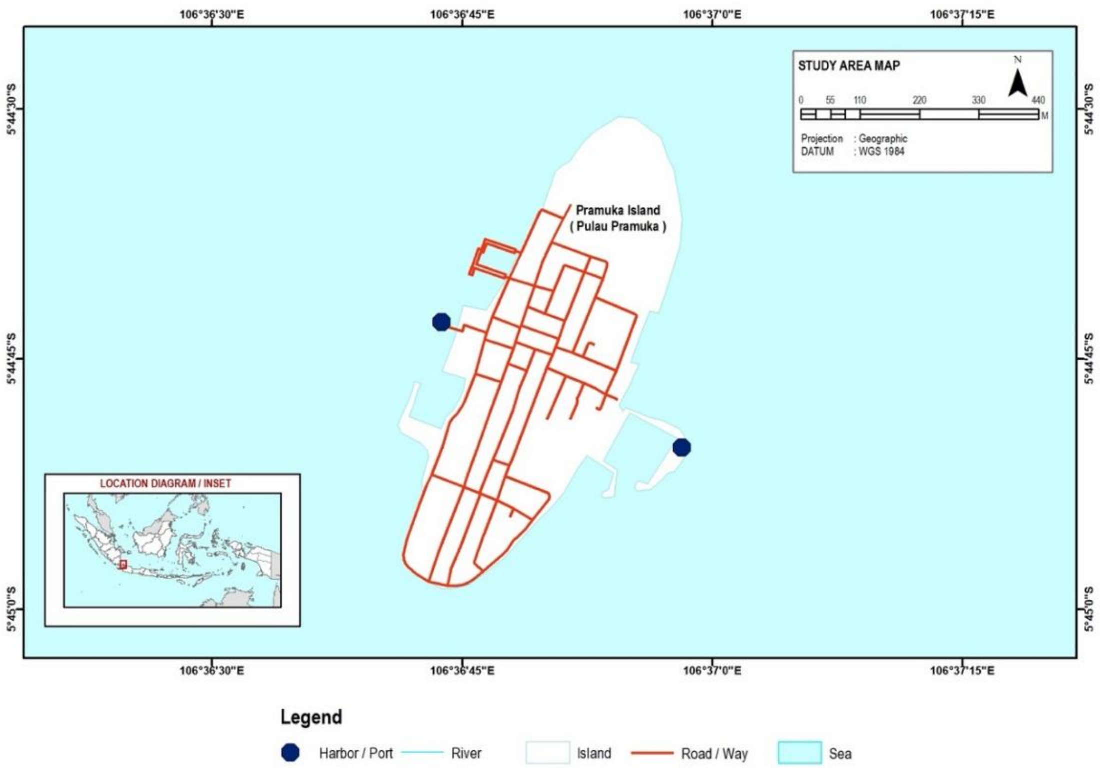

Fig. 1. Research location

According to Short et al. (2011), this method allows for a systematic assessment of the structure and distribution of seagrass communities, and can be used to observe temporal changes in seagrass ecosystems. This method is effective for describing variations in the structure of seagrass communities among stations with different levels of anthropogenic pressure. Water temperature, salinity, pH, and dissolved oxygen (DO) were measured in situ using a calibrated Lutron DO-5510 multiparameter meter at approximately 60 cm water depth. The instrument was calibrated according to the manufacturer's instructions before field measurements. At each station, three replicate measurements were recorded and averaged for analysis. Temperature, salinity, pH, and dissolved oxygen (DO), were measured at each observation station. Assessing water quality is critical because physicochemical changes, such as temperature, pH, and salinity, can influence the productivity, distribution, and sustainability of seagrass ecosystems (Khairunnisa et al., 2024a, 2024b). Additionally, dissolved oxygen (DO) plays a crucial role in supporting organism respiration and reflects overall water quality (Prayogo et al., 2021). Human activities and coastal infrastructure were documented qualitatively at each station to provide contextual information on local anthropogenic influence. Observations included the presence of piers, boat traffic, boat mooring, recreational activities, and other coastal facilities.

The observations focused on identifying the types of human activities and facilities present around the seagrass beds at each station, such as the presence of piers, boat traffic and mooring, tourism activities (snorkeling and beach recreation), and other supporting facilities. Nordlund & Gullstrom (2013) found that human activities (such as fishing and working at ports) can adversely affect the biodiversity of seagrass ecosystems; therefore, The observations were intended to characterize the types of potential physical disturbance occurring around each sampling station (due to these activities). Similarly, Zhou et al. (2024) found that other types of anthropogenic activities (e.g., coastal development and eutrophication) also have detrimental effects on seagrass ecosystem resilience, which is characterized by decreased species diversity and/or increased habitat fragmentation (Zhou et al., 2024). Therefore, identifying the presence of activities and infrastructure around the stations studied allows researchers to create the anthropogenic pressure classification at each station. Photographic documentation was used to support and contextualize the field observations at each station.

Data analysis in this study includes an evaluation of the seagrass community structure, aquatic environmental quality parameters, and anthropogenic pressures to understand the impact of environmental pressures and human activities on the seagrass ecosystem on Pramuka Island. The analysis of seagrass species diversity focused on compositional diversity group types, including species diversity, species dominance, species evenness, species richness, and the Importance Value Index (IVI), whose index values were calculated using mathematical models as recommended by Magurran (1988), Odum (1971), Krebs (1989), Pielou (1976), and Curtis & McIntosh (1951). The diversity index was calculated using the Shannon-Wiener formula (Magurran, 1988), as follows Equation 1.

$$\bar{H} = -\sum \left(\frac{n_i}{\mathrm{N}}\right) In \left(\frac{n_i}{\mathrm{N}}\right) \quad \text{(Eq. 1)}$$

The Shannon-Wiener diversity index is calculated based on the number of individuals of each species and the total number of individuals across all species. In this calculation, H′ represents the Shannon-Wiener diversity index, n_i represents the number of individuals of species *i*, and N represents the total number of individuals of all species. The Shannon-Wiener diversity index is categorized into three levels: $H' \leq 1.00$ indicates low diversity, $1.00 < H' \leq 2.00$ indicates moderate diversity, and $H' > 2.00$ indicates high diversity. The collected data are organized into tables based on the required categories. The data is analyzed using descriptive statistical methods.

The dominance index is calculated according to Odum (1971) as follows Equation 2. The dominance index (C) is calculated based on the number of individuals of each species and the total number of individuals across all species. In this calculation, C represents the dominance index, n_i represents the number of individuals of species i, and N represents the total number of individuals of all species. A dominance index value close to 0 indicates that almost no individual species dominates the community, whereas a value close to 1 indicates that one species is dominant.

$$C = \sum \left(\frac{n_i}{N}\right) 2 \qquad \text{(Eq. 2)}$$

The uniformity index of the seagrass species is calculated based on the Shannon-Wiener species diversity index (Krebs, 1989), as follows Equation3. The species evenness index is used to describe the distribution of individuals among the species in a community. In this calculation, E represents the species evenness index, H' represents the Shannon-Wiener diversity index, H Max represents the maximum possible value of the diversity index, which is calculated as ln S, and S represents the total number of species. According to Pielou (1977), an evenness index value of 0.00–0.25 indicates that species distribution is not uniform, 0.26–0.50 indicates that the distribution is somewhat even, 0.51–0.75 indicates that it is fairly even, 0.76–0.95 indicates that it is nearly uniform, and 0.96–1.00 indicates a uniform distribution of individuals among species.

$$\overline{E}_1 = \frac{\overline{H}}{H\ Max} \qquad \text{(Eq. 3)}$$

According to Odum (1971), the Margalef species richness index is as follows Equation 4. The species richness index is used to describe the number of species present in a community relative to the total number of individuals. In this calculation, R represents the species richness index, S represents the total number of species, and N represents the total number of individuals of all species.

$$R_1 = \frac{(S-1)}{Ln\ (N)} \qquad \text{(Eq. 4)}$$

The Importance Value Index (IVI) according to Curtis and McIntosh (1951) is as follows Equation 5.

$$IVI_i = RD_i + RF_i + RC_i \qquad \text{(Eq. 5)}$$

Notes:

IVI_i = Importance Value Index

$RD_i = \frac{density\ of\ type\ i}{\text{total density of all types}} \times 100\%$

$RF_i = \frac{frequency\ type\ i}{\text{total frequency of all types}} \times 100\%$

$RC_i = \frac{dominance\ of\ type\ i}{\text{total dominansi of all types}} \times 100\%$

2.3 Data analysis

The seawater quality parameters were descriptively analyzed based on field measurement results. Parameters such as temperature, pH, salinity, and dissolved oxygen were compared with seawater quality standards for the protection of marine biota in accordance with Minister of Environment Decree No. 51 of 2004. Pollution levels at the study site were assessed using the Pollution Index as specified in the regulation. This approach was used to assess the extent to which water conditions, particularly seagrass ecosystems, still support the sustainability of marine ecosystems.

The total carbon sequestration potential of seagrass beds was analyzed using a literature-based estimate of carbon sequestration was calculated using a published annual sequestration coefficient and the estimated seagrass-covered area within the sampling footprint which involves multiplying the existing area of seagrass beds in the study area by the Carbon Sequestration Rate Coefficient (CSRlit) obtained from credible scientific literature. The sampled seagrass area was obtained from the spatial mapping results (Sub-variable A in the community structure data) and presented in hectares (ha). The existing area was calculated based on the total area of sample plots (transects) conducted at 3 observation stations. Each station consists of 3 transect lines with dimensions of 50 m × 0.5 m, so the total area per station is 75 m^2or 0.0075 Ha. The carbon sequestration potential was calculated using the following Equation 6.

$$\text{Total Carbon Sequestration Potential (tons of C/year)} = \text{Existing Area} \times \text{CSRlit} \qquad \text{(Eq. 6)}$$

In this study, the CSRlit value was adapted from a study on the carbon sequestration rate conducted on Pramuka Island, Thousand Islands, amounting to 1.93 Ton C/Ha−1/Year−1 (Purwanto et al., 2013), which is considered the most representative for local ecosystem conditions. The calculation results are expressed in tons of C per year. The calculation of the existing area was modified by incorporating the percentage of seagrass cover as a correction factor to obtain results that are more representative of field conditions. The CSRlit coefficient used is the average annual carbon uptake rate measured directly at the study site or in ecologically similar tropical aquatic areas.

3. Results and Discussion

Seagrass communities on Pramuka Island exhibit species composition variations across observation stations. Seagrass species composition was assessed at three stations representing contrasting local settings and patterns of observed human activity on Pramuka Island, , thereby providing an initial overview of the distribution and presence of seagrass at the study site. Table 1 presents the results of seagrass species identification at each station. Six seagrass species have been reported in Pramuka Island; Cymodocea rotundata (Cr), Enhalus acoroides (Ea), Halophila uninervis (Hu), Halophila ovalis (Ho), *Thalassia hemprichii* (Th), and Syringodium isoetifolium (Si). The species assemblage recorded at Pramuka Island includes taxa commonly reported from tropical Indo-Pacific seagrass (Ambo-Rappe et al., 2025). There is variation in the number of species in each station, with Station 1 and Station 3 recording more species than Station 2. Such a trend suggests variation in the ecological factors that affect the growth and survival of the seagrass species. The observed differences in species occurrence among stations may be associated with local habitat characteristics; however, hydrodynamic conditions and other potential drivers were not directly quantified in this study (Zamani et al., 2018). Some seagrass species , such as Halophila uninervis, are highly restricted in their distribution, which was limited to Station 3 only.

Table 1. Seagrass species on Pramuka Island

Seagrass Species	Station		
	1 West	2 South	3 East
Cymodocea rotundata	X	-	X
Cymodocea serrulata	-	-	-
Enhalus acoroides	X	X	X
Halophila uninervis	-	-	X
Halophila ovalis	X	X	X
Thalassia hemprichii	X	X	X
Syringodium isoetifolium	X	-	X

Species within the Halophila genus (common name: seagrass) have high levels of adaptability to continually fluctuating environmental conditions, such as high turbidity, and unstable substrates, and are generally found in habitats that are under stress and/or disturbance (Nguyen et al., 2022). The occurrence of *T. hemprichii*, *E. acoroides*, and *H. ovalis* at all three stations indicates broad distribution within the surveyed area. Previous studies have reported relatively broad environmental tolerances for some of these species, which may contribute to their occurrence across contrasting local habitats., indicating high adaptability to fluctuating environmental conditions. *T. hemprichii* is a climax species with the ability to successfully dominate and maintain tropical seagrass ecosystems because of its tolerance to various substrate compositions and environmental conditions (Ambo-Rappe et al. 2025). Moreover, Qi et al. (2024) demonstrated that *T. hemprichii* exhibits a high level of tolerance toward increased salinity levels and ocean acidification. Therefore, it is, being an important producer in maintaining coastal ecosystem functions under current changing climates. Additionally, Shi et al. (2025) note that the presence of *T. hemprichii* is significantly associated with the structure of the epifaunal community and nitrogen uptake, illustrating its regulatory role on water quality and seagrass productivity in a coastal habitat.

Areas with Cymodocea rotundata are characterized by high water visibility, a clean sandy substrate, and void of places with high levels of sedimentation. This is consistent with the findings of Lincoln et al. (2021), who suggest that aquatic plants such as Cymodocea require strong environmental filters and limited exposure to anthropogenic disruption. However, some seagrasses, such as Syringodium isoetifolium, are capable of withstanding environmental fluctuations of nutrient and salinity levels, indicating their usefulness as indicators of habitat quality (Rijal, 2025) and as integral components of stabilizing ecosystems in the face of hydrodynamics disturbances (Olive et al., 2022). The difference in the distribution of seagrass species reflects both the variation in local environmental conditions and the relative degree of anthropogenic disturbances at various seagrass sites. For example, human activities such as boat traffic, coastal development, and tourism may cause physical damage or decrease habitat quality to the extent that they can negatively affect the distribution patterns and population densities of seagrass species (Unsworth et al., 2022). Figure 2 presents an analysis of the percentage relative abundance of all seagrass species found at each site within a seagrass community to facilitate the comprehension of the quantitative composition of seagrass communities.

Station 1 had a very high percentage of only one species (*Cymodocea rotundata*), indicating that the community of seagrasses was not balanced as it was dominated by a single species (63% of total). The high relative abundance of *C. rotundata* at Station 1 indicates an uneven distribution of species abundance. Such dominance may arise from species-specific competitive advantages or environmental filtering; however, the present study cannot determine the underlying mechanism. This also suggests that only those under environmentally selective conditions, species with traits suited to the local habitat may become disproportionately and grow in that type of habitat (Rifai et al., 2022). For example, *Thalassia hemprichii* is classified as a climax-type seagrass species (i.e., a species that is the final stage of development of a vegetation/habitat type) and has a very strong competitive potential for using space and other resources. Therefore, it may compete very well for space and other resources in an environment with relatively stable substrate conditions (Rahayu et al., 2019). In contrast, Cymodocea rotundata appears to be a species that can adapt to and thrive in a light dynamic environment, which usually consists of a mixture of sand and coral fragments. Thus, there is substantial evidence of a more complexly structured seagrass community structure at Station 3, which has been characterized by a relatively high degree of diversity and uniformity of distribution. The greater number of seagrass species coexisting at Station 3 than at Stations 1 and 2 can be attributed to the more stable environmental conditions found in this area (Unsworth et al., 2019). This framework demonstrates The greater number of co-occurring species and more even abundance distribution at Station 3 indicate a more compositionally diverse community relative to Stations 1 and 2. This structure typically represents more stable environmental conditions that allow multiple seagrass species to coexist in the same habitat (Unsworth et al., 2019). The fact that spring species are found along with established community members indicates that ecosystem dynamics allow the natural processes of colonization and regrowth to occur in the seagrass habitat.

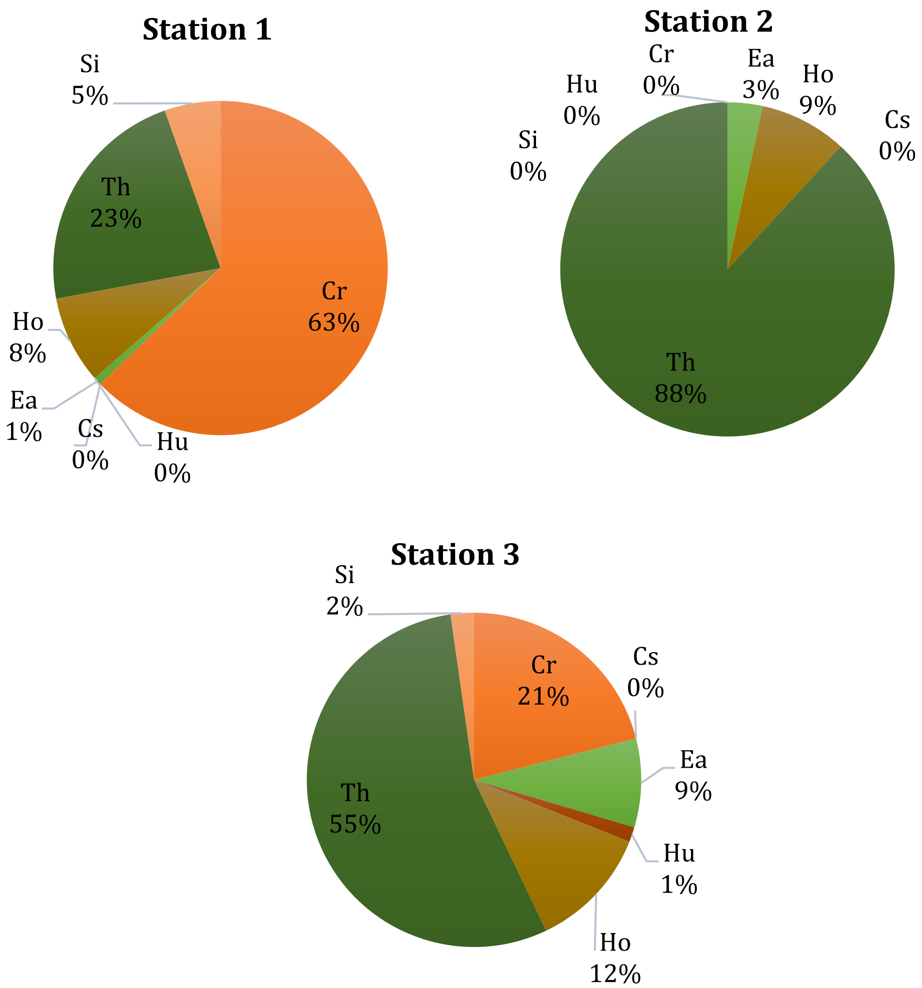

Fig. 2. Composition of seagrass at three stations on Pramuka Island

The contrasting patterns among stations indicate that visible human activity alone does not fully explain the observed variation in seagrass community structure. Other unmeasured habitat characteristics may also contribute to these spatial differences. Station 1, which is more human-influenced than Station 2, appears to be more diverse than Station 2, but Station 2, which less human-influenced, is dominated by one species. Therefore, many other variables , including (but not limited to) substrate stability, hydrodynamics, and chronic disturbances, affect the community structure of seagrasses that are not readily observable (Needelman et al., 2018). This is supported by the species composition presented in Figure 3, which provides a general idea of seagrass dominance at each site but does not quantify the complexity of the total community structure. Consequently, the analysis of the total seagrass community structure was continued by examining the ecological indices of diversity, evenness, dominance, and richness of each station to provide a better understanding of seagrass community conditions. This is important because the presence or absence of individual species and their dominance influence the community structure their representation in the community as well as the degree of balance in the entire community (Unsworth et al., 2022).

According to the data from the index analysis shown in Figure 3, a noticeable distinction in the composition of seagrass communities among the different sampling locations was observed. Station 3 demonstrates the greatest community diversity (H') and community evenness (E); therefore, the numbers are 1.27 and 0.65, respectively, resulting in a community exhibiting stabilizing characteristics by having individuals equally distributed amongst many species of seagrass. This indicates communities that live in conditions that allow diverse species of seagrass to co-exist without being dominated by any single species of seagrass. Communities like this are usually connected with a relatively stable system as they have undergone limited disturbance to allow for the formation of balanced ecological relationships (Unsworth et al., 2019). In comparison, Station 2 shows very low levels of diversity and evenness (H' = 0.43 and E = 0.22) but has an extremely high dominance index (C = 0.79); therefore the combination of low levels of diversity and evenness and the extremely high dominance index indicates that Station 2 has a structural imbalance within its seagrass community that is primarily due to one type of seagrass dominating the other types of seagrasses present. Structural imbalances occur when environmental stresses and/or strong selection processes are affecting organisms when they are attempting to occupy a particular area and prevent the establishment of other organism species (Stankovic et al., 2021). Station 1 has index values that reflect some characteristics between the two extreme values of species lists of stations 2 and 3; thus, its index values (H' = 1.03, E = 0.53, C = 0.46) would suggest that it represents a community with balanced characteristics but is in the process of reaching equilibrium.

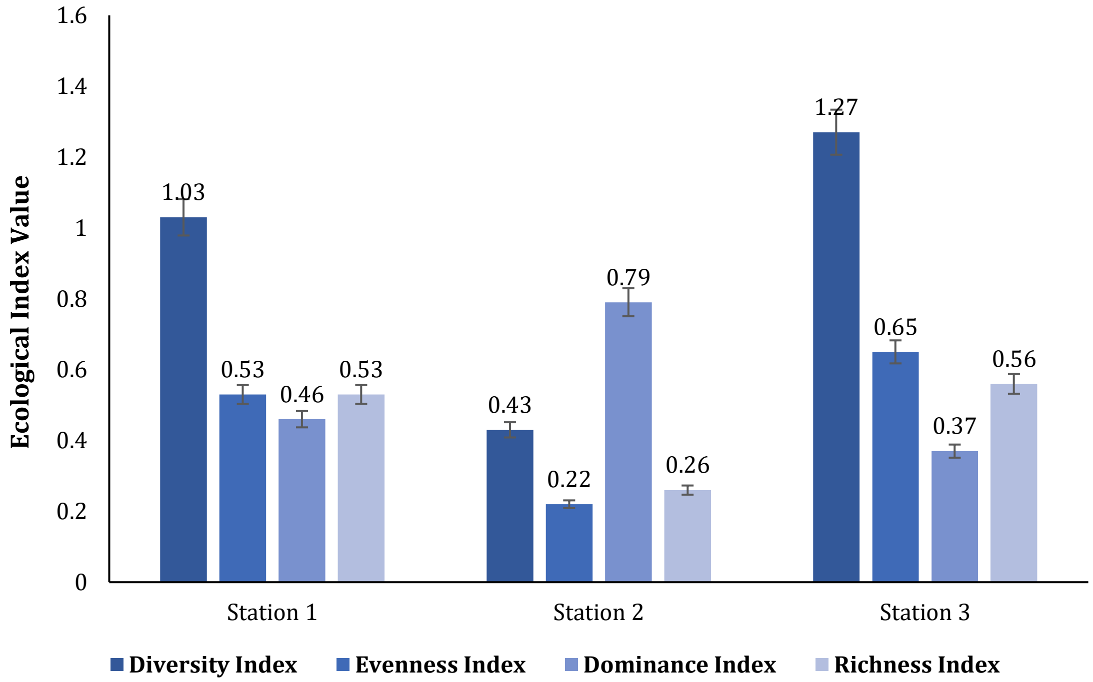

Fig. 3. Diversity, evenness, dominance, and richness index of seagrass ecosystems

Although one specific species dominates at this station, there is still a fair diversity of seagrass present at this site. Thus, the environmental pressures affecting this site are insufficient to create a substantial change in the seagrass community structure y. The difference in index values at the different stations illustrates that the seagrass community structure on Pramuka Island is influenced not only by the presence of species of seagrass, but also by the relative number of individual seagrass species present, and the dominance of each community (Angellica et al., 2024). However, these ecological indices have not specifically identified any species that play a dominant role in determining Community Structure. Thus, an Importance Value Index (IVI) analysis was performed to identify the relative contributions of seagrass species to the overall seagrass community at each station, providing more definitive information regarding the ecological contributions of individual seagrass species (Nordlund et al., 2018).

The IVI analysis results in Figure 4 show that IVI patterns differed among stations. *Cymodocea rotundata* had the highest IVI at Station 1 (170.9), whereas *Thalassia hemprichii* had the highest IVI at Station 2 (242.3) and Station 3 (156.8), with the highest value at

Station 2. The high IVI value of this species indicates its ability to occupy space, use resources, and adapt to varying environmental conditions. Ecologically, *Thalassia hemprichii* is a climax species with a competitive growth strategy, including high biomass and a strong root system, enabling it to dominate the habitat under certain conditions (Hernawan et al., 2021). The very high dominance at Station 2 reinforces previous findings indicating the high IVI of *T. hemprichii* at Station 2 is consistent with the low diversity, low evenness, and high dominance observed at this station, suggesting a simplification of community structure due to the dominance of a particular species (Hertyastuti et al., 2020). In contrast, Station 3 showed a more even distribution of IVI values among species, reflecting a more balanced and complex community. This finding is consistent with the higher diversity and evenness indices at that station and Although *T. hemprichii* had the highest IVI at Station 3, dominance was less concentrated than at Station 2, and several other species contributed substantially to the community. Such a balanced community structure is generally associated with stable environmental conditions and supports more complex ecological interactions, including competition and coexistence among seagrass species (Campbell et al., 2020).

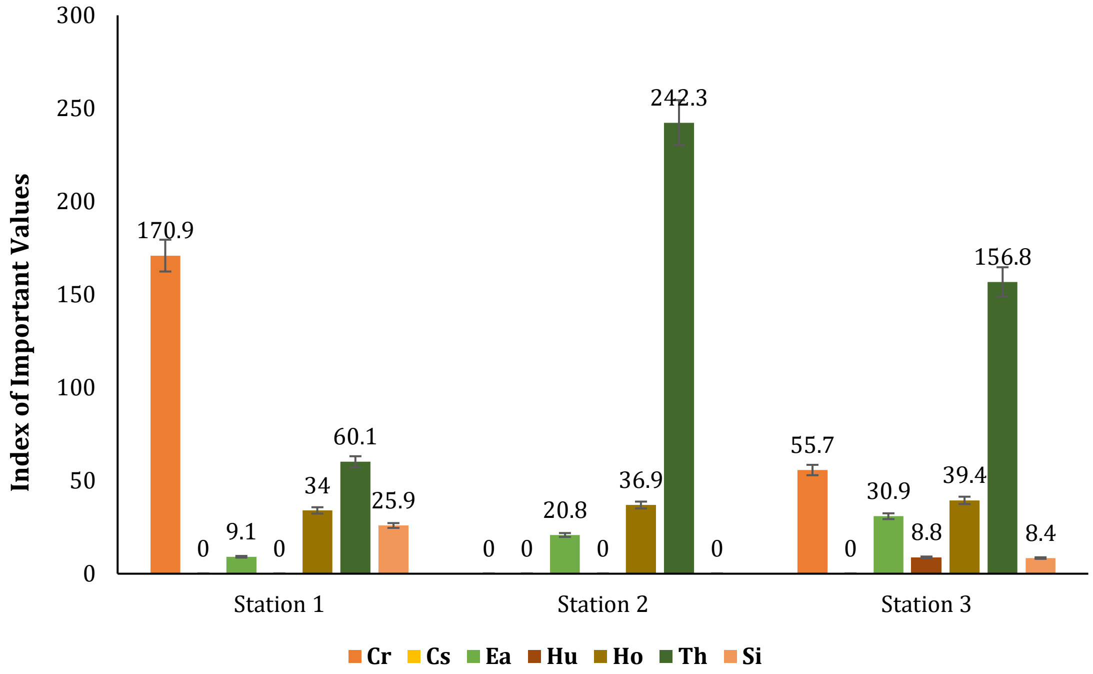

Fig. 4. Seagraee importance value index (IVI)

At Station 1, the community exhibited a less concentrated pattern of species dominance compared to Station 2, with the relative importance of seagrass species showing greater variation. Seagrass at this station showed an intermediate community structure, which may be associated with differences in species composition and their responses to local environmental conditions. The co-occurrence of several seagrass species, including those with different ecological characteristics, contributed to the observed variation in species dominance (Thomsen et al., 2020). Overall, the results show that anthropogenic pressures and complex interactions with various other environmental factors influence the structure of seagrass communities on Pramuka Island. The difference in anthropogenic pressures and seagrass community structure conditions at Stations 2 and 3 indicates that factors such as substrate, sediment stability and hydrodynamic dynamics have a large influence on the patterns of seagrass distribution and dominance across the sites in this study.

The ecological patterns observed on Pramuka Island are generally consistent with those of other tropical seagrass ecosystems. Similar relationships between low seagrass cover, reduced carbon sequestration potential, and changes in community structure have been reported in Indonesian coastal waters (Hernawan et al., 2021; Wahyudi et al., 2020), as well as in Australia and the Mediterranean, where habitat conditions and local disturbances jointly influence seagrass resilience rather than a single environmental driver (Unsworth et al., 2019; Vanderklift et al., 2022). These comparisons suggest that the ecological responses observed in this study are not unique to Pramuka Island but reflect broader patterns reported in tropical and subtropical seagrass ecosystems.

Previous studies have shown that physical habitat characteristics, including hydrodynamics and sediment conditions, can influence seagrass colonization and species dominance (Kennedy et al., 2022). In addition to seagrass cover, community-level indices provide complementary ecological information by describing species dominance, diversity, and evenness. This complementarity is evident in the observed differences among the surveyed stations. Station 2 had the highest seagrass cover but the lowest diversity and evenness, whereas Station 3 had the lowest seagrass cover but the highest diversity and evenness. These findings indicate that seagrass cover alone does not fully describe differences in community structure among the surveyed stations (Risandi et al., 2023). While assessing a seagrass community structure - as measured by indices and IVI - provides evidence of the dominant species and balance within the community, these values do not provide adequate information on the causal factors that resulted in those community structures. Seagrass community structures are primarily a reflection of the aquatic environmental conditions that influence the growth, distribution, and competition of different species (water quality, nutrient availability, and physical habitat conditions) (Ambo-Rappe et al., 2025). To develop a better understanding of the main factors responsible for creating these community patterns, the water quality parameters were analyzed (Table 2).

Table 2. Water quality at three stations on the Pramuka Island

Station	Temperature (°C)	pH	Salinity (%)	DO (mg/L)
1	25.3	7.9	3.0	7.9
2	25.7	7.7	3.1	7.8
3	24.2	7.8	3.4	8.3

According to the data presented in Table 2, the measured water-column parameters were relatively similar among the three stations at the time of sampling.Additionally, temperature, pH, salinity, and dissolved oxygen (DO) levels consistently fell within an ecological level that would allow for seagrass growth as specified in Decree of the Minister of Environment #51/2004, which specifies seawater quality standards for marine life. These ranges generally do not indicate the presence of extreme conditions that could directly inhibit seagrass growth; thus, they remain physiologically supportive of photosynthesis, respiration, and metabolism (Duarte, 1991). The measured water quality parameters, including temperature, pH, salinity, and dissolved oxygen (DO), showed relatively little variation among stations. Therefore, these parameters alone do not readily explain the observed differences in seagrass community structure. In many cases, small variations in parameters such as temperature and salinity may not be sufficient to cause substantial changes in seagrass community composition, particularly in tropical ecosystems that naturally possess a relatively wide tolerance range (Thomsen et al., 2020). The contrasting differences in community structure among stations were not accompanied by substantial differences in the measured water quality parameters. Because no inferential statistical comparison was conducted, these differences in water quality parameters are interpreted descriptively. On the contrary, other factors will dominate the process, especially habitat conditions, including substrate conditions, sediment stability, and mechanical disturbance. An unstable substrate, such as sand with coral rubble, will negatively affect the growth of seagrasses and make it vulnerable to sediment resuspension and low light (Vanderklift et al., 2022). Furthermore, physical disturbances resulting from anthropogenic activities, such as tourism, can directly damage the seagrass and worsen its habitat (Ambo-Rappe et al., 2025). Although water quality parameters remain favorable, the structure of the seagrass community in Pramuka Island is determined more by the interplay of physical habitat factors and anthropogenic disturbances. This means that when assessing the state of the seagrass ecosystem water quality factors and direct factors such asseagrass cover and habitat conditions must be considered. Hence, in this context, seagrass cover and substrate conditions were considered the key indicators of ecosystem condition, as shown in Table 3.

Table 3. Average percentage of the total seagrass cover and substrate

Station	Substrate	Average total coverage (%)	Carbon sequetrations potential (tons C ha^{-1} $year^{-1}$)
1	Sand, rubble	27.5	0.53
2	Sand, rubble	28.6	0.55
3	Sand, rubble	21.8	0.42

Based on Table 3, seagrass cover across the sampling stations ranged from 21.8% to 28.6%, with the highest value recorded at Station 2 (28.6%) and the lowest at Station 3 (21.8%). According to the seagrass status classification adopted from Decree of the Minister of Environment No. 200 of 2004, seagrass cover of ≥60% is classified as “rich/healthy,” 30–59.9% as “less rich/less healthy,” and ≤29.9% as “poor,” corresponding to a “damaged” seagrass condition. Therefore, the seagrass cover recorded at all stations on Pramuka Island falls within the “poor” category, indicating a damaged seagrass condition based on the adopted national classification criterion (Kennedy et al., 2022). Although the visually classified substrate type was similar among stations, unmeasured differences in grain size, sediment stability, or hydrodynamic exposure may have contributed to variation in seagrass cover. These mechanisms remain hypotheses because they were not directly measured (Macreadie et al., 2021). Stable substrates support root and rhizome development, thereby enhancing long-term carbon accumulation (Wahyudi et al., 2020).

Although seagrass ecosystems make up less than 0.1% of the surface area of the world’s oceans, they can have a carbon pool in the upper sediment layer that is up to 40 times greater than the carbon pool found in terrestrial forests (Chang et al., 2024). Low seagrass cover throughout all sites indicates that Pramuka Island’s seagrass ecosystems are either stressed or degraded. Such an ecosystem condition negatively affects seagrass ecological function, such as providing habitat for organisms, stabilizing sediments, and acting as a carbon sink (blue carbon) (Duarte et al., 2005). Ren et al. (2024) demonstrated that human-induced decreases in seagrass density could decrease the proportion of recalcitrant sediment organic carbon (RSOC) by as much as 40%. An increase in nutrient levels also facilitates the decomposition of seagrass detritus and increase CO_2 emissions from the seagrass ecosystem (Liu et al., 2023). The decline of seagrass coverage has been shown to correlate with a reduced capacity of coastal ecosystems to store and sequester carbon and, as such, may affect the ability of coastal ecosystems to mitigate climate change (Macreadie et al., 2021).

The literature-based carbon estimates were relatively low across all three stations and the maximum amount of potential carbon sequestered is from seagrass Station 2 at 0.55 tons C ha^{-1} $year^{-1}$ and Station 3 at 0.42 tons C ha^{-1} $year^{-1}$. The estimated sequestration value was highest at Station 2 and lowest at Station 3, reflecting the percentage-cover correction used in the calculation. In terms of how seagrass ecology supports carbon storage, aboveground biomass and density of vegetation play crucial roles as they relate to the cover area and percentage of the seagrass beds (Alongi et al., 2016). The carbon sequestration values are expressed in tons C ha^{-1} $year^{-1}$ following the standard reporting unit widely adopted in seagrass blue carbon studies. Based on previous findings of carbon storage in other Indonesian coastal ecosystems, where sediments can store substantially higher amounts of carbon than seagrass biomass, with reported values of up to 558 tons of carbon per hectare (Wahyudi et al., 2020), the carbon estimates obtained in this study should be regarded as indicative literature-based estimates. Direct measurements of biomass carbon, sediment organic carbon, and carbon accumulation rates would be required to further validate these estimates. Key challenges for sustainable management of the area include the need for greater inter-sectoral cooperation and an integrated national information forum (Sjafrie et al., 2023). In the future, seagrass restoration in this area may be considered through approaches such as seed-based restoration, which has been proposed as a feasible and scalable approach for enhancing seagrass ecosystem recovery and fisheries productivity (Unsworth et al., 2018).

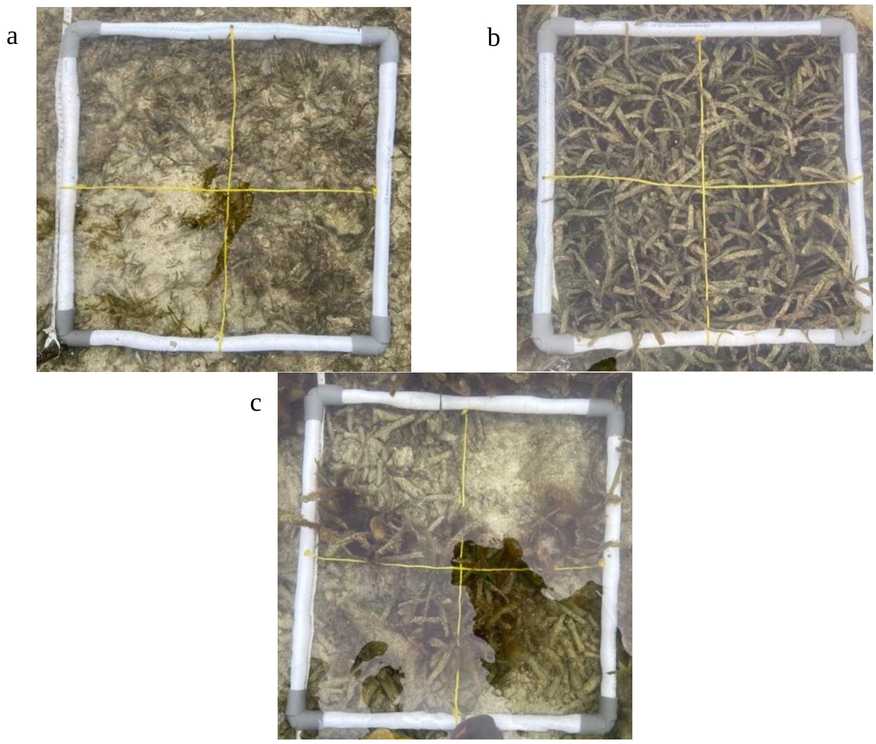

Fig. 5. Conditions of the seagrass ecosystem on Pramuka Island: (a) Station 1; (b) Station 2; and (c) Station 3

Figure 5 illustrates the visual differences in seagrass distribution among representative quadrats from the three stations, complementing the quantitative cover and community data , even though the percentage of coverage and substrate type were quite similar. At Station 2, there was a high density of seagrasses with a uniform distribution, as predicted from the high dominance of *Thalassia hemprichii*. This pattern may indicate that the species is well adapted to local habitat conditions, although the ecological processes underlying its dominance were not directly evaluated in the present study. *T. hemprichii* can form dense stands under suitable environmental conditions (Hernawan et al., 2021). Nevertheless, species dominance alone should not be interpreted as evidence of a healthy ecosystem because relatively low diversity may reduce ecosystem resilience to environmental change (Ambo-Rappe et al., 2025).

Station 3 had a more dispersed seagrass distribution, with fairly large open spaces. This situation corresponds with the lowest coverage percentage (21.8%) and The relatively low cover at Station 3 may be associated with limitations on meadow expansion or local habitat conditions; however, sediment stability and hydrodynamic exposure were not measured and therefore cannot be identified as confirmed for seagrass attachment. These types of seagrass distribution can be associated with physical disturbance factors or sediment dynamics that could prevent seagrass from rooting and regrowth (Sudo et al., 2021). However, these environmental variables were not directly measured in this study and should therefore be interpreted as possible explanations rather than confirmed drivers.

This phenomenon is a result of the equilibrium between the variables responsible for facilitating and inhibiting seagrass proliferation, making way for the existence of multiple species while ensuring that no single species becomes overwhelmingly abundant. It can be observed within ecosystems in a delicate balance between stability and environmental stress (Serrano et al., 2016). Based on the analysis of this particular ecosystem, there is evidence that equal seagrass coverage cannot be used to infer similar community dynamics. Station 2 had the highest seagrass coverage (28.6%) but was characterized by strong dominance of a single species, as indicated by its high IVI, together with relatively low community diversity and evenness. In contrast, Station 3 had the lowest seagrass coverage (21.8%) but showed a more even distribution of seagrass species and higher diversity and evenness values. These contrasting results indicate that seagrass coverage and community structure provide complementary information on the ecological condition of the surveyed stations and are therefore better interpreted together. This observation highlights the limitations associated with using seagrass coverage alone in explaining the conditions of an ecosystem.

a b c

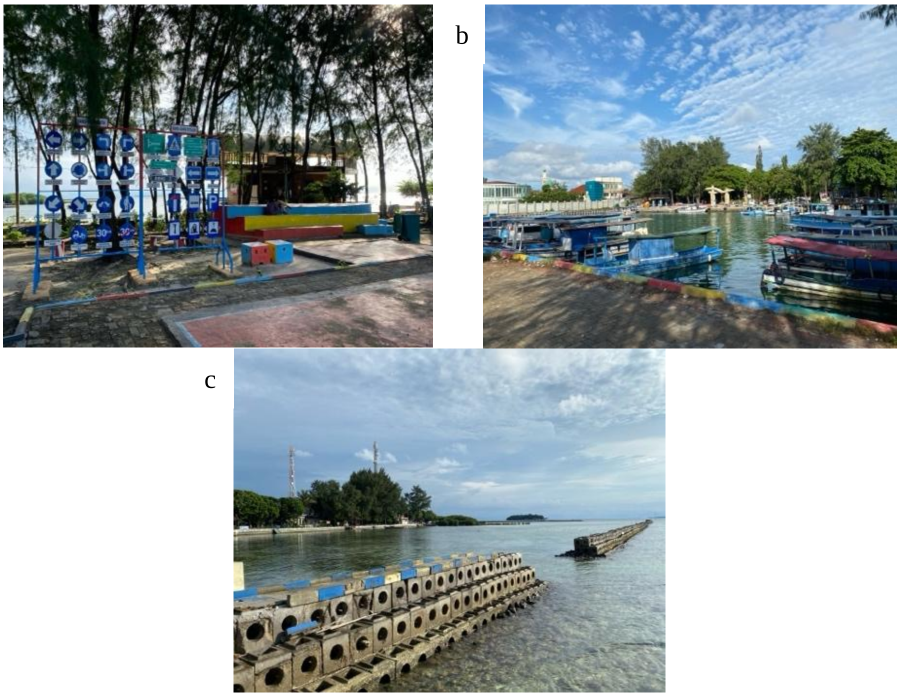

Fig. 6. Human activities around Station 1: (a) recreation at the RPTRA; (b) docking and loading/unloading at the pier (dam); (c) jet ski access and use

The first station also features many signs of anthropogenic impact, as shown in Figure 6. For instance, there are many RPTRA and other facilities, an active pier, and many water sports and tourism activities, including jet-skiing. They involve the use of stable infrastructure and the motorization of many other kinds of activities; thus there may be an opportunity to exert direct physical pressure on seagrass communities (Assuyuti et al., 2018). For instance, boats can exert mechanical disturbance due to the functioning of their propellers, increasing sediments through resuspension, and potentially damaging the integrity of the seabed substrate (Bockel et al., 2024). Disturbance has been listed as one of the major causes of seagrass loss and fragmentation in areas with a high level of anthropogenic impact (Unsworth et al., 2019). The current findings show that the seagrass community structure at the first station does not exhibit much simplification, rather than having an intermediate pattern concerning the overall seagrass community structure, where the levels of diversity and evenness remain high.

Ecological resilience can be explained by habitat characteristics (e.g., a mixture of rubble/sand as a substrate that still permits seagrass to root there) and the presence of species tolerant to disturbance (Cymodocea rotundata)(Lincoln et al., 2021). This species has a high adaptive capability to unstable subgradients and physical stressors and therefore tend to dominate at locations that experience moderate disturbance (Hernawan et al., 2021). The difference between high human-related impacts and little evidence of significant community degradation suggests that the effects of disturbances are often not proportional. For example, if the spatial extent and duration of isolated disturbances remain below the ecological tolerance limits of seagrass communities, they may be able to maintain their community structure, a concept that can be associated with a disturbance threshold (Rifai et al., 2022). Therefore, physical stress at Station 1 is likely localised and not continual in nature, which will permit natural recovery from disturbances.

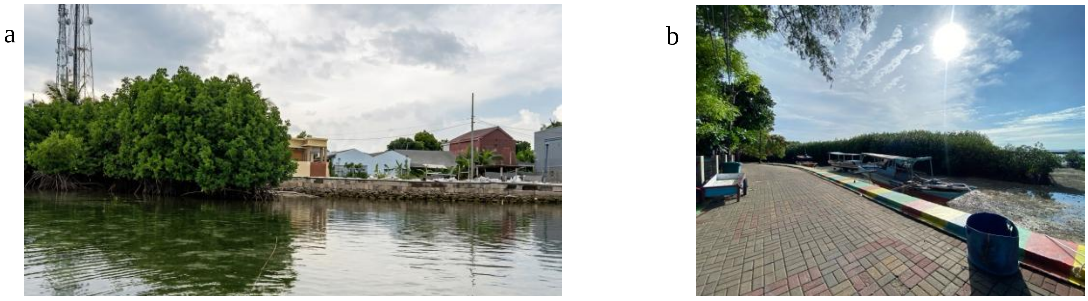

Fig. 7. Human activity around Station 2: (a) traffic on the main access road; (b) parking and boat mooring

Compared to Station 1, Station 2 has a lower level of human activity, predominantly through terrestrial mobility, with the presence of parking lots and mostly stationary boat moorings (Figure 7). The lack of intense motorized recreation, such as jet skiing or heavy boat traffic, suggests that the direct physical pressure placed on the seagrass beds is relatively low. However, the coastal structures and mooring of boats can still potentially have an indirect effect on the environmental conditions through changes in hydrodynamic features and the physical disturbance of the substrate (Thomsen et al., 2020). The ecological analysis results suggest that This pattern is consistent with strong ecological filtering or competitive dominance, although the specific environmental mechanism cannot be identified from the present data. Station 2 has the most stressed conditionsseagrass community conditions, as evidenced by the very high dominance of *Thalassia hemprichii* (88%) and low diversity and evenness values. This pattern shows evidence of community simplification, as only certain species can survive under restricted or stressed environmental conditions (Stankovic et al., 2021).

Seagrass community responses may reflect cumulative or long-term disturbances that are not always evident from short-term visual observations, which often results in changes the structure of the seagrass community over time (Qi et al., 2024). As shown by the results from the seagrass research conducted by Qi et al. (2024), environmental disturbances may not always show up as obvious and immediate impacts on the ecosystem, but may have a cumulative and indirect effect (Shi et al. 2025). Abnormal water circulation due to various types of coastal structures may create increased sedimentation, and repeated disturbances from boat mooring activities can create a generally low-level environmental disturbance that can reduce the ability of many other species to regenerate (Vanderklift et al. 2022). Table 2 shows that the water column had very similar conditions throughout the study area suggesting that physico-chemical characteristics are not as limiting to community structure, whereas environmental characteristics, including substrate conditions, may also contribute to differences in community structure. However, these factors were not directly measured in this study.

Activities at Station 3 are relatively more limited and localized, dominated by small-scale beach tourism, community-based operations, and boat mooring in more controlled areas (Figure 8). The absence of intensive motorized activities or large-scale coastal infrastructure indicates that the direct physical pressure on the seagrass beds is low compared with the other two stations. These conditions are generally associated with minimal levels of anthropogenic disturbance in the context of coastal ecology, which theoretically supports the formation of more stable seagrass communities (Vanderklift et al., 2022). Station 3 showed the highest Shannon diversity and evenness values among the three stations, while its dominance value was lower than that observed at Station 2, suggesting greater uniformity across species in this station because there was no evidence of extreme dominance of one or more species.

a b c


Fig. 8. Activities of residents around Station 3: (a) tourism in the coastal area; (b) MBG kitchen operations; (c) boats moored in the anchorage

Communities with these characteristics generally exhibit higher levels of complexity and greater resilience to disturbances (Hertyastuti et al., 2020). However, the seagrass cover at this station was actually the lowest among the three stations (21.8%), indicating that a complex community structure does not always correlate with the extent of vegetation cover. The observations at Station 3 suggest that relatively limited visible human activity does not necessarily correspond to the highest seagrass cover. This situation is also indicative of the fact that other limiting factors tend to be more dominant limiting factors than anthropogenic pressures. The dominant factors are those associated with the physical characteristics of the environment. For example, the stability of the substrate, the grain size of the sediments, and the hydrodynamic conditions (currents and waves) of the water are have a significant effect on the ability of a seagrass to populate, root, and create large beds (Stankovic et al., 2021).

Even in areas with little human activity, seagrasses will not grow as densely as they would in stable substrates or where there is much energy from water. Thus, Station 3 had much diversity, but the cover was low. While Station 3 had little pressure from seagrass, the low coverage may be related to habitat conditions that restrict the potential for seagrass expansion. This information indicates that two indicators of seagrass ecosystem conditions, namely, seagrass community structure and seagrass cover (McKenzie et al., 2020), are affected by different factors; therefore, an integrative approach must be used to evaluate seagrass ecosystem conditions. As such, the development and implementation of ecotourism-based management programs can support local communities' conservation and economic development while balancing seagrass ecosystems (Hertyastuti et al., 2020).

The ecological indices presented in this study are intended to provide descriptive comparisons among sampling stations. Accordingly, the observed differences should be interpreted as indicative ecological patterns rather than statistically significant differences. This study has several limitations that should be acknowledged. Environmental variables such as current velocity, wave exposure, sediment characteristics, and anthropogenic disturbance intensity were not directly measured. Consequently, the discussion regarding their influence on the structure of the seagrass community is based on field observations and evidence from previous studies, and should therefore be interpreted as potential explanations rather than direct causal relationships. Future studies incorporating quantitative environmental measurements and inferential statistical analyses would provide a more comprehensive understanding of the dynamics of seagrass communities.

4. Conclusions

Seagrass communities on Pramuka Island showed clear spatial variation in species composition and community structure across the three surveyed stations. Dominance patterns differed among stations: Cymodocea rotundata had the highest IVI at Station 1, whereas *Thalassia hemprichii* had the highest IVI at Stations 2 and 3, however, its dominance was accompanied by relatively lower species diversity and evenness, particularly at Station 2. The observed patterns suggest that visible human activity alone does not fully explain differences in seagrass community condition among the surveyed stations, suggesting a complex response of seagrass communities to multiple interacting factors. Unmeasured habitat characteristics, including substrate stability and water column dynamics, may also contribute to the observed variation in seagrass community structure. Seagrass cover was below 30% at all three stations, placing the surveyed sites within the low-cover category according to the classification criterion adopted in this study. Cover-adjusted, literature-based carbon sequestration estimates ranged from 0.42 to 0.55 t C ha^{-1} $year^{-1}$ across the three stations. These values should be interpreted as indicative estimates rather than direct measurements of site-specific carbon flux. These values are reported using the standard area-normalized unit commonly adopted in seagrass blue carbon studies to facilitate comparison with previous studies.

Therefore, seagrass habitat management should adopt a multi-parameter approach that considers both ecological conditions and environmental characteristics to support conservation initiatives and enhance blue carbon functions. Future research should incorporate longer-term monitoring, broader spatial coverage across different seagrass habitats, direct measurements of sediment and biomass carbon stocks, and quantitative assessments of environmental and anthropogenic drivers. Such approaches would provide a more comprehensive understanding of seagrass ecosystem dynamics and strengthen the scientific basis for sustainable conservation and blue carbon management.

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Author Contribution

Conceptualization, A.N.F.; Methodology, A.N.F.; Investigation, A.N.F.; Data Curation, A.N.F.; Formal Analysis, A.N.F.; Writing – Original Draft Preparation, A.N.F.; Writing – Review & Editing, E.F. and Y.M.A.W.; Supervision, E.F. and Y.M.A.W. All authors have read and agreed to the published version of the manuscript.

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Ethical Review Board Statement

This study is part of a broader research project that has obtained ethical clearance from the Ethics Committee of the School of Environmental Science, Universitas Indonesia (Reference No. KET-082/UN2.F13.D1.KE1/PPM.00/2025). However, the specific analysis presented in this article is based solely on ecological field surveys, environmental measurements, and non-individual observational data, and does not involve human subjects.

Informed Consent Statement

Not available. This study does not involve human participants.

Data Availability Statement

The data presented in this study are available on request from the corresponding author. The data are not publicly available due to research data management considerations.

Conflicts of Interest

The authors declare no conflict of interest.

Declaration of Generative AI Use

During the preparation of this work, the authors used QuillBot to assist in paraphrasing and DeepL Translator to support translation. After using these tools, the authors reviewed and edited the content as needed and took full responsibility for the content of the publication.

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