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Assessment of Ecosystem Health and Carbon Stocks in the Seagrass Meadows of Mengiat Beach, Bali, Indonesia

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Abstract

Seagrass meadows provide many important ecosystem services. They are now recognized as blue carbon ecosystems that are crucial in the mitigation of global climate change. This study was conducted at Mengiat Beach in Bali, Indonesia, where there are extensive seagrass meadows along the shorelines, but also considerable anthropogenic activity that pose threats to the ecosystem. The objectives of this study were to: (1) describe the seagrass community at Mengiat Beach; (2) assess the health status of the seagrass ecosystem; and (3) estimate carbon stocks stored within the ecosystem. Vegetation analysis was conducted to describe the seagrass community in terms of density, cover, biomass and species importance. Spatial Sentinel-2 satellite data with unsupervised classification was used to determine the extent of seagrass meadows. Carbon stocks in sediment and biomass were estimated using the loss on ignition method. The seagrass community at Mengiat Beach consists of at least five different species, dominated by Cymodocea rotundata. The meadows are characterized by high density (588 ind.m^{-2}) and good cover (60.7%). They are considered healthy, with good ecological quality, as indicated by a SEQI (Seagrass Ecological Quality Index) of 0.69. The seagrass ecosystem stores a significant amount of carbon, with 99.23% of it stored in sediment. Total carbon stock in sediment and seagrass biomass is estimated at 133.39 MgC.ha^{-1}. When extrapolated to the total seagrass area of 43.21 ha, the meadows at Mengiat Beach store a total carbon stock of 5.76 GgC, highlighting their potential as high-carbon reservoirs and importance in climate change mitigation efforts.

Keywords: blue carbon, carbon stock, climate change, seagrass

Introduction

Seagrass meadows are vital coastal ecosystems that provide important ecosystem services, including coastal protection, food and livelihood for local communities, habitat for commercially important fish and other biota, water quality improvement, and tourism (Duarte *et al*., 2008; Irawan *et al*., 2018; Nordlund *et al*., 2018; Lima *et al*., 2023). Furthermore, seagrass ecosystems are increasingly being recognized as blue carbon ecosystems because of their ability to sequester and store large amounts of carbon (Nellemann *et al*., 2009; Macreadie *et al*., 2019). Healthy natural ecosystems, such as seagrass meadows, can help address the issue of global climate change by storing significant amounts of carbon. Therefore, preserving the health of these natural ecosystems is seen as one of the nature-based solutions to mitigate the impact of human activities on the global climate system (Gregg *et al*., 2021). Unfortunately, however, these valuable ecosystems face significant threats from human activities, resulting in widespread decline in seagrass meadows worldwide. Consequently, there is an urgent need to monitor and protect seagrass ecosystems for the benefit of the environment and future generations (Syukur *et al*., 2017).

Extensive seagrass meadows can be found along the shorelines of Nusa Dua in Bali, Indonesia, including the area of Mengiat Beach, which is a part of the Indonesia Tourism Development Corporation (ITDC) Nusa Dua area in South Bali. The ITDC Nusa Dua itself is an area that has been intensively developed since the 1980s, with most of it functioning as hotels and resorts right on the beach (Sari and Suarka, 2015). In addition to hotel and tourism development, the Bali Coastal Protection Project (*Proyek Pengamanan Pantai Bali*/PPPB) was carried out at Nusa Dua Beach, which is located very close to Mengiat Beach, to reduce erosion by building retaining structures in the form of groins and sand-filling (Estradivari, 2004; Dharma, 2010). The groin construction has changed the composition of biotic communities, as seen, for example, in the reduced seagrass and hard coral cover, mainly due to a significant increase in turbidity (Estradivari, 2004). Being a popular tourist destination, Mengiat Beach faces threats from various anthropogenic activities that pose risks to the seagrass ecosystem (Syukur *et al*., 2017). These activities include tourism, boating, fishing, and coastal development in general (Sari and Suarka, 2015). Although Mengiat Beach has potential as a vast seagrass resource (Rahadiarta *et al*., 2018; Wandiani *et al*., 2020), few studies have been conducted in this area. The current focus of attention on coral reefs has overshadowed the role and potential of seagrass meadows in the area (Wandiani *et al*., 2020).

In regard to blue carbon information, data for Mengiat Beach is still scarce. While it is known that carbon stocks in seagrass meadows are mainly stored in the sediment compartment, carbon stock data for this area is limited to the biomass compartment (e.g., from a study by Rahadiarta *et al*., 2018). Therefore, there is a need to assess the present condition of seagrass meadows at Mengiat Beach and examine their role as blue carbon ecosystems. The objectives of this study were to: (1) describe the seagrass community at Mengiat Beach; (2) assess the health status of the seagrass ecosystem; and (3) estimate the carbon stocks stored within the ecosystem. Results of the study are expected to enrich the scientific knowledge base regarding carbon storage in the seagrass ecosystem, as reference for the future development and management of Mengiat Beach, including its management as a potential nature-based solution for climate change mitigation.

Materials and Methods

Field data collection was conducted at Mengiat Beach, Indonesia Tourism Development Corporation (ITDC) Nusa Dua in Badung Regency, Bali. The study site encompassed the beach area, bordered by Pura Geger to the south and the Waterblow tourist site to the north, while a reef crest marked the seaward boundary. Seagrass meadows sampled in this study were located approximately 50 m from the shoreline at low tide. Sampling and measurements were conducted along six transects with relative position and coordinates as shown in Figure 1. Seagrass biomass and sediment samples were collected outside the transect lines and taken to the laboratory for further analysis.

Description of seagrass community and environmental condition

Seagrass and other biotic data were collected from quadrat plots along transect lines which were positioned 100 m offshore with at least 50 m distance between them (Rahmawati *et al*., 2019). Along these transects, 50x50cm quadrats were placed at every 10 m to record information on seagrass species and cover, as well as macroalgae and epiphyte cover. The amount of cover within a

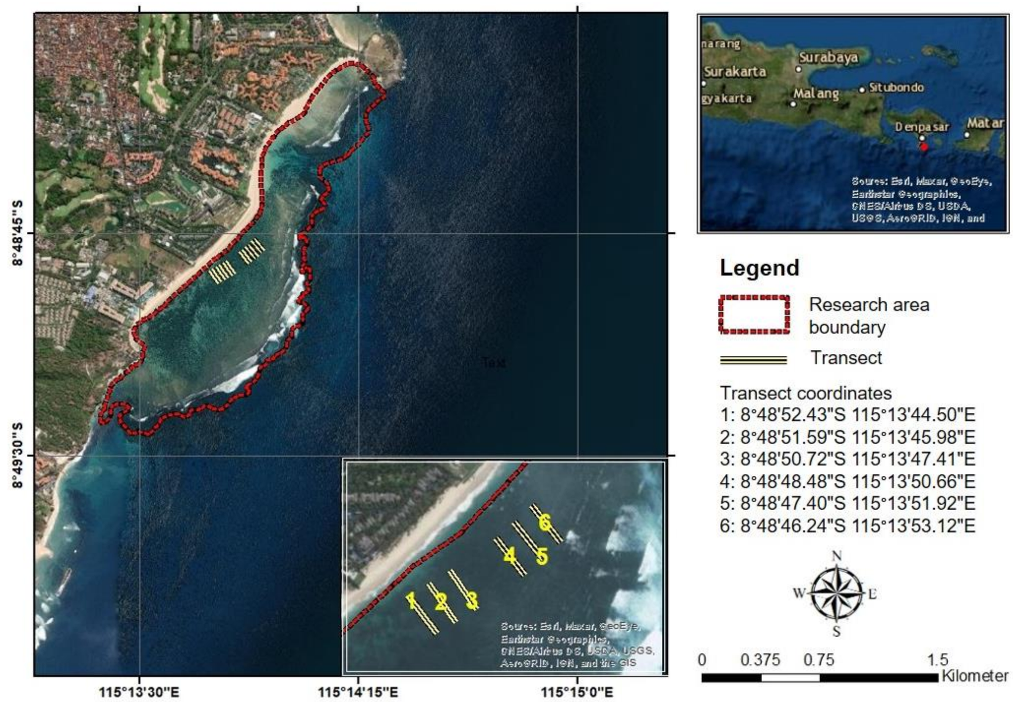

Figure 1. Study site and transect location for seagrass data collection in Mengiat Beach, Bali, Indonesia

sampling plot was estimated using percent cover standards from McKenzie (2003). Additionally, 25x25cm quadrats were placed at every 30 m to collect data on the density of each seagrass species, defined as the number of individual seagrasses (shoots or stands) of a species per unit area. Seagrass species were identified following guidelines from Lanyon (1986) and McKenzie (2003), then confirmed by consulting the World Register for Marine Species website (https://www.marinespecies.org/) for taxonomic information.

The Importance Value Index (IVI) for each seagrass species was calculated to identify dominant species. The higher the IVI value of a species in its community, the more significant is its role compared to others, and can thus be considered as the dominant species (Sugianti and Mujiyanto, 2020). To determine the IVI, measures of cover, frequency, and relative density of each seagrass species were first calculated using the following formula (Mueller-Dombois and Ellenberg, 1974; Brower *et al*., 1989; Dewi and Sukandar, 2017):

$$Rc_i = \frac{c_i}{\sum c}$$
$$Rf_i = \frac{f_i}{\sum f}$$
$$Rd_i = \frac{d_i}{\sum d}$$
$$IVI_i = Rc_i + Rf_i + Rd_i$$

where (Rc_i) is relative cover of species-i; (c_i) is cover of species-i; (Σc) is total cover of all species; (Rf_i) is relative frequency of species-i; (f_i) is the number of quadrats containing species-i; (Σf) is number of quadrats used; (Rd_i) is relative density of species-i; (d_i) is density of species-i; (Σd) is total density of all species; (IVI_i) is the importance value index of species-i.

In addition to the above biotic parameters, physico-chemical parameters of water were measured across the seagrass meadows to obtain a general description of environmental conditions. These parameters include dissolved oxygen (DO) and temperature, measured using a DO-meter; pH measured using a pH-meter; and salinity measured using a refractometer. Water transparency was qualitatively assessed using a scoring system adapted from Hernawan *et al*. (2021) which assigned a score of 0 for turbid water, a score of 1 for moderately clear water, and a score of 2 for clear water. Nine replications were taken for each measurement.

Estimation of seagrass areal extent

A geographic information system was used to estimate the extent of the seagrass meadows. Analysis utilized images from the Sentinel-2 satellite, sourced from https://scihub.copernicus.eu/ in 2021, selected based on minimal cloud cover for more accurate estimation. Pre-processing procedures were conducted on previously acquired satellite image data to enhance image quality. These processes included radiometric correction, composite image creation, cropping, and image sharpening using the QGIS Desktop application version 2.18.22.

The classification process was carried out using an unsupervised approach with a K-means clustering tool for grids and a hill-climbing algorithm, as referenced in the work of Rahmawati *et al*. (2019). To ensure the highest level of accuracy, the parameter for the number of classes was set to double the number of cover classes identified in the field, following the approach outlined by Green *et al*. (2000). The model was then subjected to a thorough validation process, comparing it with ground-truth conditions in the field. This validation process was adapted to distinguish between seagrass and non-seagrass areas (Prayuda, 2014), providing a reliable and accurate estimation of the seagrass meadow area.

Assessment of seagrass ecosystem health

The health status of the seagrass ecosystem was determined using the Seagrass Ecological Quality Index (SEQI) developed by Hernawan *et al*. (2021). SEQI considers various biotic and abiotic parameters and compares them with reference values for the Indonesian region. The calculation formula for SEQI is as follows:

$$\mathrm{SEQI} = 0{,}2 \times [\frac{\mathrm{St}}{S_{ref}} + \frac{\mathrm{Ct}}{C_{ref}} + \frac{\mathrm{Wt}}{W_{ref}} + \left(1 - \frac{\mathrm{Mt}}{M_{ref}}\right) + \left(1 - \frac{\mathrm{Et}}{E_{ref}}\right)]$$

where (S) is species richness; (C) is seagrass cover; (W) is water transparency; (M) is macroalgae cover; and (E) is epiphyte cover. The subscript (t) denotes observed values, while the subscript (*ref*) denotes the maximum possible value for a parameter, i.e., 9 for species richness, 2 for water transparency, and 100% for cover. SEQI values are interpreted using a qualitative scale which places the calculated values into five categories (Table 1.). These values range from 0 to 1; the closer to 1, the healthier is the seagrass meadow.

To complement results from SEQI calculations, seagrass health status was also rated according to the criteria provided in the government regulation that is currently still in effect, *i.e.,* Minister of Environment Decree Number 200/2004 concerning Standard Damage Criteria and Guidelines for

Table 1. Interpretation of SEQI (Seagrass Ecological Quality Index) values into categorical status (Hernawan *et al*., 2021)

SEQI Value	Ecological Status
0.00 – 0.36	Bad
0.37 – 0.52	Poor
0.53 – 0.68	Moderate
0.69 – 0.84	Good
0.85 – 1.00	Excellent

Determining Seagrass Meadow Status (Ministry of Environment, 2004). According to this decree, seagrass meadows with a cover of more or equal to 60% fall into the category of rich/healthy; a cover between 30 to 59.9% fall into the category of unhealthy, while a cover below 29.9% indicates poor category.

Estimation of ecosystem carbon stocks

Seagrass samples were collected from multiple individuals in seagrass meadows using a knife to ensure that all parts of the plant, including roots and rhizomes, were taken entirely (Rahadiarta *et al*., 2018). The samples were then cleaned of epiphytes and washed with distilled water. The seagrass samples were divided into aboveground parts, *i.e.,* leaves and vertical stems, and belowground parts, *i.e.,* roots and rhizomes. Each sample was oven-dried at 60°C and weighed daily until considered dry, with a weight reduction of no more than 4% between measurements. Once dried, samples were sub-sampled at 5 g (or 1 g for small seagrass species). Aboveground and belowground sub-samples were fumigated in a furnace at 450°C for eight hours. The results were weighed and recorded for further analysis. The formulas used to calculate carbon stock in biomass are as follows (Rahmawati *et al*., 2019):

$$Biomass = \frac{dry\ weight}{number\ of\ individuals}$$

$$LOI = \frac{(W_1 - W_2)}{W1} \times 100\%$$

for LOI < 0.2; $C_{org} = 0.4 \times \mathrm{LOI} - 0.21$

for LOI > 0.2; $C_{org} = 0.4 \times \mathrm{LOI} - 0.33$

$$Biomass\ carbon\ stock = Biomass \times C_{org}$$

where (LOI) is loss on ignition; (W_1) is dry weight before ashing; (W_2) is weight after ashing, (C_{org}) is percent carbon content.

Sediment was collected through random sampling, nine times throughout the seagrass meadows using a PVC core sampler with a 2.2 cm diameter and 50 cm height. Sediment compaction factor was determined following the methods of Rahmawati *et al*. (2019), based on measurements of the total length of the PVC pipe used for sampling (A), the PVC length that penetrated the sediment/core length (E), the remaining PVC length which did not penetrate (B), the length of the sediment sample (D), and the part of the PVC pipe that was not filled with sediment (C). The formula used to determine the compaction correction factor is as follows:

$$Compaction\ Correction\ Factor = \frac{Length\ of\ sediment\ sample\ (D)}{Depth\ of\ core\ (E)}$$

$$Corrected\ Sample\ (H') = Correction\ factor \times Length\ of\ sediment\ sample\ (H)$$

where (H') is length of sample collected; (H) is length of original sample (the length of sample without compaction).

Sediment samples were separated according to depth stratification, *i.e*., 0–5 cm, 5–25 cm, and 25–50 cm. This was done to compare the amount of carbon stored at different depths (Gullström *et al*., 2018). Samples from each layer were then dried in an oven at 60°C and weighed daily until constant weight, *i.e*., with a weight reduction of no more than 4% between measurements. After drying, the samples were sub-sampled for 5 g and fumigated in a furnace at 450°C for eight hours. The results were recorded for further analysis. Formulas used for calculating carbon deposits in sediments are provided by Rahmawati *et al*. (2019).

$$DBD = \frac{Dry\ weight}{Sample\ volume}$$

$$LOI = \frac{(W_1 - W_2)}{W1} \times 100\%$$

for LOI < 0.2; $C_{org} = 0.4 \times \mathrm{LOI} - 0.21$

for LOI > 0.2; $C_{org} = 0.4 \times \mathrm{LOI} - 0.33$

where DBD is dry bulk density; LOI is loss on ignition; (W_1) is dry weight before ashing, (W_2) is weight after ashing, (C_{org}) is percent carbon content.

Results and Discussion

Seagrass community and environmental condition

Five seagrass species were identified in this study, *i.e., Cymodocea rotundata*, *Halophila* sp., *Syringodium isoetifolium*, *Thalassia hemprichii* and *Thalassodendron ciliatum*. This suite of species differed slightly from the species composition reported in two previous studies which identified other seagrass species in the area, *i.e., Cymodocea serrulata, Halodule uninervis* (reported by Rahadiarta *et al*., 2018) and *Halodule pinifolia* (identified by Wandiani *et al*., 2020) (Table 2.). This difference suggests the high variability in the seagrass community of Mengiat Beach.

Kilminster *et al*. (2015) classified seagrass species based on attributes of their life history, habitat and meadow form. A seagrass community may consist of species whose life history strategy can be described as colonizing, opportunistic or persistent. By that classification, *Thalassia hemprichii* and *Thalassodendron ciliatum* are classified as persistent seagrass species; *Cymodocea rotundata* and *Syringodium isoetifolium* as opportunistic species; and *Halophila* sp. as colonizing species. In Indonesia, *Thalassodendron ciliatum* is known to be a climax species that grows with *Thalassia hemprichii* and *Enhalus acoroides* in developed or matured seagrass meadows (Green and Short, 2003). Seagrass habitats are defined by the range and variability of their abiotic environment; thus, meadows can be either transitory or enduring (Kilminster *et al*., 2015). The seagrass community described in the present study consisted of mostly persistent and opportunistic species; marked by the presence of *Thalassodendron ciliatum* and *Thalassia hemprichii.* Similarly, species recorded a few years prior to the present study (Table 2.) also fall mostly in the category of persistent or opportunistic. This indicates that the seagrass meadows at Mengiat Beach are tending towards an enduring type, *i.e.,* mature meadows that tend to be stable and resilient but will require a long time to recover if severely damaged (Kilminster *et al*., 2015).

Collective data from all transects revealed a seagrass individual density of 588 ind.m^{-2}, which falls into the category of very dense (Tahir *et al*., 2023). However, this total seagrass density was significantly lower than the figure reported in an earlier study by Rahadiarta *et al*. (2018), *i.e*., 1,093 ind.m^{-2}. The most common species found in the present study was *Cymodocea rotundata*, with a density of 209.3±206.4 ind.m^{-2}, followed by *Syringodium isoetifolium* with 148.0±232.9 ind.m^{-2}, *Thalassia hemprichii* with 100.7±171.1 ind.m^{-2}, and *Thalassodendron ciliatum* with 72.0±137.5 ind.m^{-2}, with the least common being *Halophila* sp. with 58.0±130.5 ind.m^{-2} (Figure 2A.). It should be noted that a particular species was not found in all plots, but calculations of the mean included these plots with zero density values. This explains the very large standard deviations in the mean values presented above. A similar pattern was observed in terms of seagrass cover. *Cymodocea rotundata* exhibited the highest cover at 20.7±19.3%, followed by *Syringodium isoetifolium* at 12.0±19.1%, *Thalassia hemprichii* at 10.9±19.1%, and *Thalassodendron cilliatum* at 10.8±24.1%, with the lowest cover exhibited by *Halophila* sp. at 1.6±4.1% (Figure 2B.). These patterns provide a clear picture of the characteristic form of the seagrass meadow at Mengiat Beach. The total seagrass cover from all transects collectively amounted to 60.7% which is slightly above the minimum threshold (*i.e.,* 60%) to be categorized as rich/healthy according to the Minister of Environment Decree Number 200/2004 (Ministry of Environment, 2004). Other studies that have used the same guidelines set in this decree have found that seagrass meadows in Indonesia exhibit varying

Table 2. Seagrass species recorded at Mengiat Beach in three studies. ✓ = present, x= absent.

Seagrass Species	Rahadiarta *et al*. (2019)	Wandiani *et al*. (2020)	This Study (2022)
Cymodocea rotundata Asch. & Schweinf	✓	✓	✓
Cymodocea serrulata (R.Brown) Ascherson & Magnus, 1870**	✓	x	x
Halodule pinifolia (Miki) Hartog	x	✓	x
Halodule uninervis (Forsskål) Ascherson, 1882	✓	x	x
Halophila ovalis (R.Brown) J.D.Hooker, 1858	x	✓	x
Halophila sp.	x	x	✓
Syringodium isoetifolium (Ascherson) Dandy, 1939	✓	✓	✓
Thalassia hemprichii (Ehrenberg) Ascherson, 1871	✓	✓	✓
Thalassodendron ciliatum (Forsskål) Hartog, 1970	✓	✓	✓

**current accepted name = *Oceana serrulata* (R.Brown) Byng & Christenh.

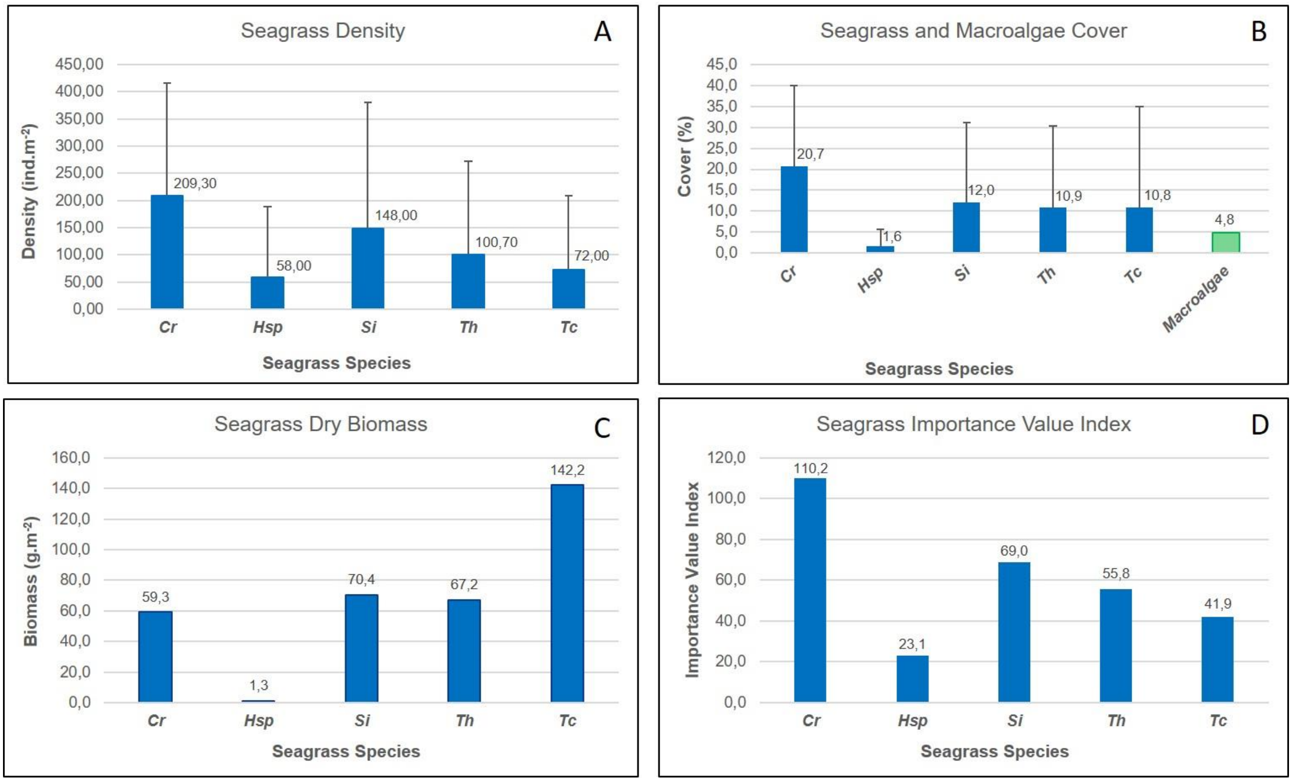

Figure 2. (A) Density, (B) Cover, (C) Biomass, and (D) Importance Value Index of each seagrass species encountered in this study. Cr=*Cymodocea rotundata*, Hsp=*Halophila* sp., Si=*Syringodium isoetifolium*, Th=*Thalassia hemprichii*, Tc=*Thalassodendron ciliatum*. Figure (B) also shows the total cover of all macroalgae (green bar). Vertical lines on top of the bars in (A) and (B) indicate standard deviations from the mean (see text for further explanation).

health status. For example, seagrass cover in sites around Java Island ranges from 3% to 80%, covering the categories of poor to healthy (Dewi *et al*., 2024). The health status of seagrass meadows in northern Bali varies between unhealthy and healthy (30% to 60%) (Widagti *et al.,* 2021), while those in southern Bali range from poor to healthy (16% to 63%) (Wijana *et al*., 2019). Given these figures, the condition of seagrass meadows at Mengiat Beach seems comparable to other healthy sites in Bali, *i.e*., having a seagrass cover of around 60%.

In terms of biomass (dry weight) per unit area, *Thalassodendron ciliatum* exhibited the highest biomass with a total measure of 142.17 $g_{dw}.m^{-2}$, followed by *Syringodium isoetifolium* with 70.41 $g_{dw}.m^{-2}$, *Thalassia hemprichii* with 67.22 $g_{dw}.m^{-2}$, *Cymodocea rotundata* with 59.30 $g_{dw}.m^{-2}$, and *Halophila* sp. as the lowest with 1.26 $g_{dw}.m^{-2}$ (Figure 2C.). Despite *Cymodocea rotundata* being the most common seagrass species in Mengiat Beach, *Thalassodendron ciliatum* exhibited the highest biomass. It was observed that *Thalassodendron ciliatum* has hardened and thickened rhizomes and a wider leaf size than other encountered species, contributing to the high biomass per unit area (Lanyon, 1986).

The species Importance Value Index (IVI) was highest for *Cymodocea rotundata* at 110.19, and lowest for *Halophila* sp. at 23.11 (Figure 2D.). These results reveal that *Cymodocea rotundata* is the dominant seagrass species in the area and therefore indicate that the seagrass meadows may not have reached the climax stage. In a mature seagrass meadow, persistent species such as *Enhalus acoroides, Thalassia hemprichii* and *Thalassodendron ciliatum* should dominate (Green and Short, 2003). Although *Cymodocea* is classified as an opportunistic seagrass species, it is relatively stable in the ecosystem and is used in monitoring programs (Kilminster *et al*., 2015). Seagrass meadows dominated by opportunistic species may signify a disturbance preventing the community from reaching its climax (Rasheed, 2004).

Besides collecting data for seagrass, measurements were also conducted on non-seagrass biota, i.e., macroalgae and epiphytes. These biotic components play a crucial role in determining the general health status of the ecosystem (Hernawan *et al*., 2021). In healthy natural ecosystems, macroalgae, epiphytes and seagrasses co-exist and contribute to a complex food web. However, the interaction of these three groups can be destabilized by disturbances, such as excess nutrient addition. This can lead to overgrowth of macroalgae or epiphytes, which then compete with seagrasses causing a decline in seagrass meadow quality (Irlandi *et al*., 2004). In the seagrass meadows of Mengiat Beach, macroalgae cover was consistently low across all sites at 4.8%. They were not found coexisting with seagrasses but tended to grow on substrates without seagrass growth or where seagrass density was low. The average epiphyte cover in the seagrass meadows was (26.2±5.8)%. The most abundant epiphytes were found growing on *Thalassodendron ciliatum* as opposed to other seagrass species, with a total epiphyte cover of (30.0±15.3)%. The other species had similar epiphyte covers, except *Halophila* sp. which had very little epiphyte cover of (3.3%±8.9)% (Figure 3.). Variation in seagrass morphology and size can produce differences in the epiphytic cover found on them. *Halophila* sp. is very small compared to other species and has a small surface area resulting in low epiphyte cover (Mabrouk *et al*., 2014). The variation in epiphyte cover among seagrass species is important in understanding the health status of the ecosystem.

Water quality parameters were measured to provide a general description of the environment supporting the seagrass community. These measurements were compared to the quality standard values stated in the Republic of Indonesia Government Regulation No. 22/2021 concerning the Implementation of Environmental Protection and Management (Appendix VIII: Sea water quality standards) (Government of Indonesia, 2021). Mean measurements for dissolved oxygen and pH from Mengiat Beach fell within the permissible range for marine biota as specified in the regulation, while mean temperature and salinity measurements were slightly higher than the threshold limit (Table 3.). However, slight deviation from the seasonal mean could still be viewed as an acceptable natural variation. Therefore, it can be concluded that the quality of sea water at Mengiat Beach generally met the required standard quality and is suitable for the growth of seagrasses.

Mapping and seagrass areal extent

Mapping and modeling results revealed that the extent of seagrass meadows at Mengiat Beach covers an area of 43.21 ha, accounting for 32.8% of the total area cover. This makes seagrass meadows the second largest cover category after sand substrate which covers 46.05 ha. Other substrate cover classifications were rubble, backreef and reef crest (Figure 4.). All seagrass meadows in this location are shallow subtidal and are sheltered by the reef crest. This type of seagrass meadow is typical of those found in the Indo-Pacific region and is characterized by species such as *Thalassia hemprichii*, *Syringodium isoetifolium* and *Halodule uninervis* (Short *et al*., 2007). Mapping results show that most of the seagrass meadows are located close to the shoreline in the southern part of the area.

Table 3. Mean values of water quality parameters measured in the seagrass meadows of Mengiat Beach compared to the standard reference for sea water quality in Government Regulation 22/2021.

Parameter	Mean Value	Quality Standard
Dissolved Oxygen (mg.L^{-1})	7.9 ± 0.5	> 5
Temperature (^{o}C)	30.6 ± 1.4	28 – 30
pH	8.2 ± 0.0	7.0 – 8.5
Salinity (ppt)	34.7 ± 0.8	33 – 34
Water Transparency**	1.3 ± 0.5	--

**Scoring system based on Hernawan *et al*. (2021)

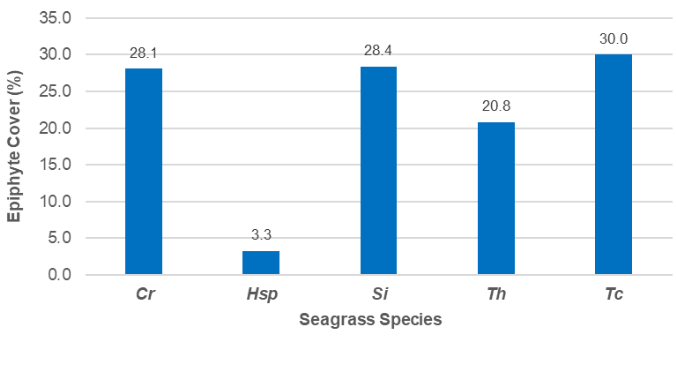

Figure 3. Epiphyte cover on each seagrass species. Cr=*Cymodocea rotundata*, Hsp=*Halophila* sp., Si=*Syringodium isoetifolium*, Th=*Thalassia hemprichii*, Tc=*Thalassodendron ciliatum*.

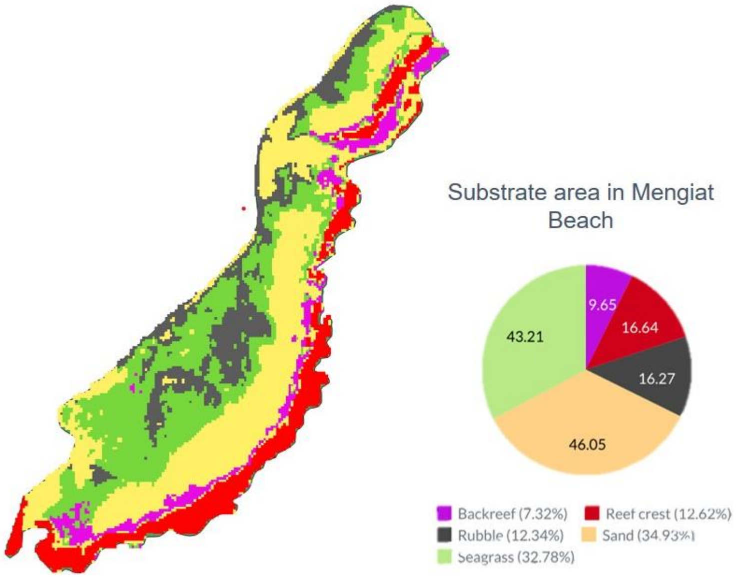

Figure 4. Mapping of substrate area cover within the study site of Mengiat Beach (map boundary follows the red delineation line in Figure 1).

The mapping model was tested for accuracy through field validation and ground truth measurements. Calculation of the model's accuracy is summarized in a confusion matrix (Table 4.) that compares the class of image classification results with the reality in the field. The model was 66.67% accurate in distinguishing between seagrass and non-seagrass cover and is therefore considered acceptable. The acceptable accuracy limit for shallow seabed habitat maps is 60% according to the Indonesian National Standard (*Standar Nasional Indonesia*) SNI 7716:2011 concerning Shallow Seabed Habitat Mapping (SNI; Prayuda, 2014).

Seagrass ecosystem health

The Seagrass Ecological Quality Index (SEQI) developed by Hernawan *et al*. (2021) was used to determine the health status of the ecosystem. SEQI calculation for the seagrass meadows of Mengiat Beach produced a value of 0.69 (Table 5.), placing it at the lower threshold of the "good" category (Table 1.). This value is nearly the same as the mean SEQI value for seagrass meadows in Indonesia, *i.e*., 0.68±0.02, based on research conducted by Hernawan *et al*. (2021) in 18 locations across the country.

Seagrass Biomass Carbon Stocks

Carbon stocks in the biomass components were calculated for each seagrass species (Figure 5A.). *Thalassodendron ciliatum* contained the highest carbon stock, with a total of 44.58 gC.m^{-2}, while *Halophila* sp. contained the lowest, with a total of 0.34 gC.m^{-2}. The pattern observed when comparing among species is similar to the pattern in dry biomass comparison (Figure 2C.). This is because there is of course a close relationship between biomass and carbon stocks, where the higher the biomass, the higher the carbon stock contained within biomass. Although *Thalassodendron ciliatum* had a lower density compared to most other seagrass species at this site, its biomass was much higher due to the characteristics of its hardened and woody rhizomes and larger size (Lanyon, 1986). This is also attributed to its status as a persistent seagrass species (Kilminster *et al*., 2015). The total carbon stocks in the seagrass biomass compartment is estimated at 102.17 gC.m^{-2}. This value is much higher than the value reported for the same area by Rahadiarta *et al*. (2018), *i.e.,* 42.88 gC.m^{-2}. Further investigation is required to explain whether this discrepancy actually implies high variability in carbon stocks, or whether it is due to technical differences in sampling and analysis.

Almost all species store more carbon in their belowground components than in their aboveground compartment, except for *Thalassia hemprichii* which exhibited larger aboveground carbon stock, amounting to 11.91 gC.m^{-2} compared to 6.79 gC.m^{-2} belowground. The higher allocation to belowground biomass is characteristic of persistent seagrass species which tend to be more resistant to disturbance because extensive root and rhizome growth enables better attachment and nutrient absorption, as well as storage of excess carbohydrates that can be used in nutrient poor conditions (Collier *et al*., 2021). However, Collier *et al*. (2021) found that several opportunistic seagrass species, including *Cymodocea rotundata* and

Table 4. Confusion matrix of cover classification model for Mengiat Beach

Class		Ground-Truth Seagrass	Ground-Truth Others	Σ	User (%)
GIS	Seagrass	11	6	17	64.71
	Others	5	11	16	31.25
Σ		16	17		
Producer Accuracy (%)		68.75	35.29		
Total Accuracy (%)			66.67		

Table 5. Calculation of SEQI (Seagrass Ecological Quality Index) from Mengiat Beach data

Parameter	Value	Component Score
Species richness (St)	5	0.56
Seagrass cover (Ct)	60.7%	0.56
Water transparency (Wt)	1.33	0.67
Macroalgae cover (Mt)	4.8%	0.95
Epiphyte cover (Et)	26.2%	0.74
	SEQI (0.2*ΣComponent score) =	0.69

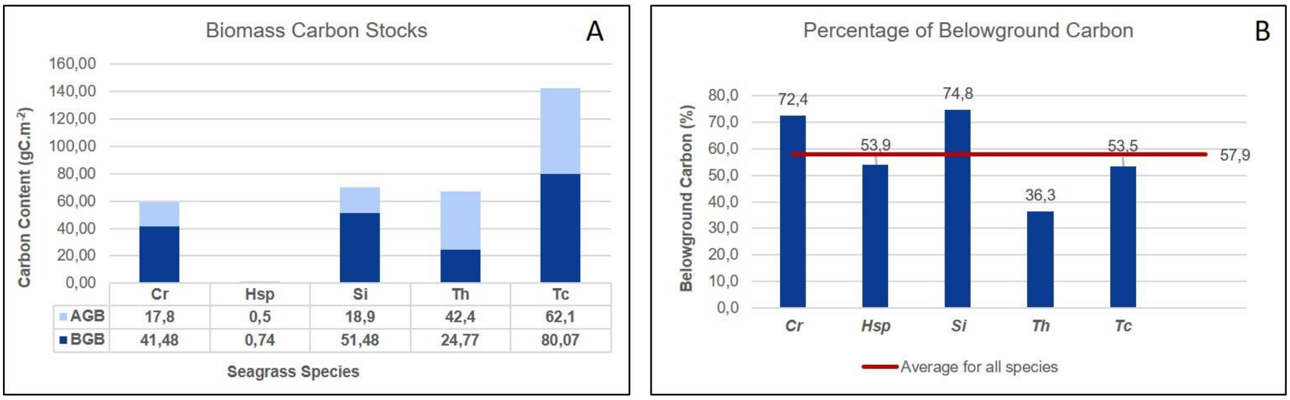

Figure 5. (A) Biomass carbon stocks of each seagrass species; (B) Percentage of belowground carbon stock relative to total biomass carbon. The red line in (B) indicates the mean value from all seagrass species. AGB= Aboveground Biomass, BGB=Belowground Biomass, Cr=*Cymodocea rotundata*, Hsp=*Halophila* sp., Si=*Syringodium isoetifolium*, Th=*Thalassia hemprichii*, Tc=*Thalassodendron ciliatum*.

Syringodium isoetifolium, may also have significant belowground biomass, which is in line with the results from Mengiat Beach. Biomass allocation in opportunistic seagrass species can be related to seagrass succession and competition. For example, *Thalassia hemprichii*, a persistent species in this study, had a belowground carbon percentage of only 36.3%. This could be attributed to the level of seagrass succession not yet reaching the climax stage and the competition for space and resources with the opportunistic seagrass species *Cymodocea rotundata* in this area, causing the low percentage of belowground biomass of persistent seagrass species (Moreira-Saporoti *et al*., 2021). The percentage of belowground carbon stocks of each seagrass species is shown in Figure 5B.

When added together, the belowground biomass compartment of seagrass at Mengiat Beach is estimated to store 59.19 gC.m^{-2}, or 57.9% of the total biomass carbon stocks. This value for belowground carbon stock is much higher than the value reported in the study by Rahadiarta *et al*. (2018). They estimated a belowground biomass carbon stock of 25.7 gC.m^{-2}, but with a belowground allocation percentage of 59.9% which is similar to the results found in this study. The difference in belowground biomass carbon stock reported in the two studies could be attributed to the timing of field sampling. Sampling in the present study was conducted in December, during the rainy season, whereas Rahadiarta *et al.* (2018) conducted their study in April, during the dry season. Similar variations have been observed in Teluk Bakau, Bintan Island where carbon stocks varied significantly over two years, *i.e.*, 452.21 gC.m^{-2} in the rainy season of 2014 and 133.71 gC.m^{-2} in the dry season of 2016 (Irawan *et al*., 2017). It is evident that seasonal changes significantly affect seagrass biomass, and these changes are influenced by a combination of environmental factors such as temperature, salinity, nutrient availability, and tidal exposure, with species-specific responses and regional variations playing significant roles (Erftemeijer and Herman, 1994; Govindasamy and Arulpriya, 2011; Govindasamy *et al*., 2013; Dahl *et al*., 2020; Metz *et al*., 2020).

Sediment carbon stocks

There was a trend of increasing carbon content with depth; however, this increase is not statistically significant (P= 0.158). See Figure 6. Therefore, it can be assumed that sediment carbon stocks tend to be homogeneous at each depth stratification and can be extrapolated to a depth of 1 meter to be compared to standards in other regions (Alongi *et al*., 2016). The amount of carbon stocks at 0-5 cm, 5-25 cm and 25-50 were respectively (10,247.92 ± 2,846.44) gC.m^{-3}, (12,816.32 ± 2,785.42) gC.m^{-3} and (16,647.38 ± 12,706.00) gC.m^{-3}. Sediment carbon content averaged over all depth layers amounted to (13,237.21 ± 7,857.15) gC.m^{-3}, or equal to (132.37 ± 7.86) MgC.ha^{-1} when taking into account carbon content to a depth of one meter. This value is higher than the mean sediment carbon stock reported from other sites across Indonesia, *i.e.*, 118.1 MgC.ha^{-1} (Alongi *et al*., 2016).

Total Ecosystem Carbon Stocks

Table 6 provides a summary of the carbon stocks in the seagrass ecosystem of Mengiat Beach, with units converted to MgC.ha^{-1}. The results show a total carbon stock of 133.39 MgC.ha^{-1}, which is higher than Indonesia's regional average of 119.52 MgC.ha^{-1} (Alongi *et al*., 2016). Most of the carbon is stored in sediment, constituting 99.24% of the total carbon stocks. This is consistent with the findings of other studies, *e.g*., Kim *et al*. (2022) also found that carbon stock in seagrass ecosystems is primarily contained in sediment due to oxygen-deprived conditions, resulting in low decomposition rates and long-term carbon accumulation. When extrapolating findings to the total seagrass area of 43.21 ha, it is estimated that the entire seagrass ecosystem at Mengiat Beach stores 5.76 Gg of organic carbon.

Further investigation is required to assess the relationship between seagrass community structure and developmental stage with carbon stocks at Mengiat Beach. Mature or enduring seagrass meadows tend to be dominated by persistent, large-sized species. Therefore, it is hypothesized that more mature meadows will exhibit higher biomass, and hence higher carbon stocks. Kumala *et al*. (2024) found that different seagrass communities in Karimunjawa Marine National Park, Indonesia, exhibited different carbon storage capacities. Meadows dominated by large-sized species such as *Enhalus acoroides* stored higher carbon stocks. The density of this species was positively correlated with total biomass carbon stocks, while its dominance was positively correlated with sediment carbon stocks and total ecosystem carbon stocks. Meanwhile, in Semujur Island, Bangka Belitung Islands province, Muliawati and Choesin (2024) found moderate positive correlation between seagrass density and cover, with carbon stocks.

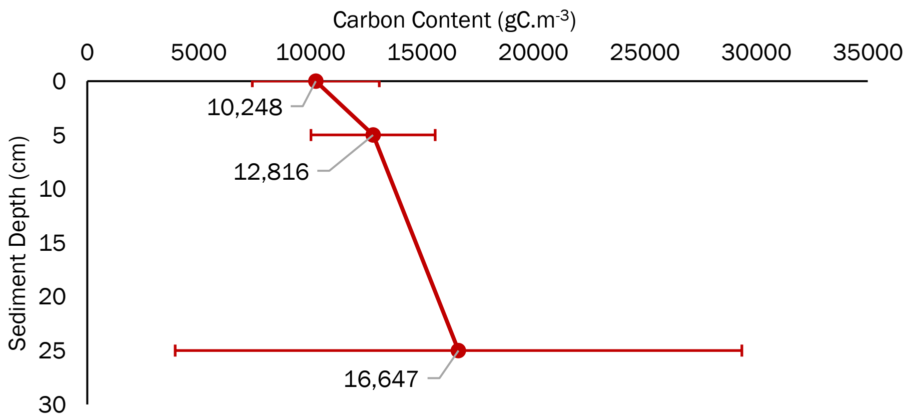

Figure 6. Mean values of sediment carbon storage at various depth stratifications. The value of 0 on the Y-axis represents the mean for 0-5cm stratum, the value of 5 indicates the mean value for 5-25 cm stratum, and the value of 25 indicates the mean for 25-50 cm stratum.

Table 6. Total carbon stocks from different compartments and their relative percentages

Compartment	Carbon Stock ($MgC.ha^{-1}$)	Percentage (%)
Sediment	132.37	99.24
Aboveground Biomass	0.43	0.32
Belowground Biomass	0.59	0.44
TOTAL	133.39	100.00

Conclusion

The seagrass meadows at Mengiat Beach, Bali, form a multispecific community consisting of at least five different seagrass species, dominated by *Cymodocea rotundata*. This meadow area is still developing towards an enduring state. The meadows overall exhibit high density (588 $ind.m^{-2}$) and good cover (60.7%). They are considered healthy, with good ecological quality, as indicated by a SEQI of 0.69. The seagrass ecosystem stores a significant amount of carbon, with 99.23% of it stored in sediment. The total carbon stock is estimated at 133.39 $MgC.ha^{-1}$, which is higher than the mean value reported from other sites in Indonesia. When extrapolated to the total seagrass area of 43.21 ha, the meadows at Mengiat Beach store a total carbon stock of 5.76 GgC. Given this magnitude of carbon storage, appropriate management is needed to prevent damage to the seagrass ecosystem that can lead to the release of carbon stocks. Further research is required to specifically identify potential disturbances and threats to the seagrass meadows in this area and formulate appropriate management decisions. The health status of seagrass meadows in this area was found to be at the lower threshold of the "good" category. Therefore, regular monitoring is needed to observe the temporal change and trends in seagrass health to promptly detect whether the ecosystem is declining. For monitoring purposes, it is recommended to use permanent plots and increase the distance between transects and the number of transects to capture the heterogeneity of the seagrass meadows at Mengiat Beach.

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