Remote Sensing-Based Assessment of Seagrass Health and Carbon Sequestration in Wakatobi National Park

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Abstract

The Wakatobi waters, part of the Wakatobi National Park, host an extensive seagrass ecosystem; however, detailed information on its exact coverage remains relatively scarce. To address this, remote sensing technology is essential for providing a comprehensive overview of the seagrass ecosystem's condition over a broad area in a relatively short time. This study focuses on analyzing the condition of seagrass through both direct measurements and remote sensing, as well as evaluating its carbon content, particularly in Wangi-Wangi Island. Conducted from January to December 2023, the research employed an exploratory approach with purposive sampling to categorize seagrass coverage as low, medium, and high. Seagrass types and total coverage were measured using 1m × 1m quadrat transects. Organic carbon content was analyzed using the Walkley and Black (WB) method, while satellite imagery from Landsat 8 (2013) and Landsat 9 (2023) was used to assess the overall coverage and distribution of seagrass. The study identified nine seagrass species, including Cymodocea serrulata, Cymodocea rotundata, Enhalus acoroides, Halodule pinifolia, Halodule uninervis, Halophila ovalis, Syringodium isoetifolium, Thalassodendron ciliatum, and Thalassia hemprichii. Seagrass conditions ranged from low (26.20%) to medium (62.50%) and high (80.48%). The seagrass area declined from 2,209.4 ha in 2013 to 2,044 ha in 2023. Average carbon content was 4.29 Mg C.ha^{-1}, with carbon stock estimates between 755,844.82 and 11,984,600.79 Mg C.ha^{-1}. The decline in seagrass coverage in Wangi-Wangi Island is attributed to environmental degradation and human activities, including coastal development. Denser seagrass areas were found to have greater carbon sequestration potential, emphasizing the ecological significance of maintaining healthy seagrass ecosystems.

Keywords: *Seagrass, Seagrass carbon stock, Seagrass present cover, Remote sensing, Wakatobi National Park.*

Introduction

Wakatobi Regency has an area of approximately 19,200 km², consisting of land of approximately 823 km² (4%) and water of approximately 18,377 km² (96%). Geographically, the island of Wakatobi is located south of the equator, stretching ± 160 km from north to south between 5°12' – 6°25' S and ±120 km from east to west between 123°20' – 124°39' E. UNESCO also designated the sea waters of Wakatobi, Indonesia, as one of the World Biosphere Reserves among the other 20 new biosphere reserves in the world (BPS-Statistics of Wakatobi Regency, 2022). The Wangi-Wangi Islands are the Main Island located in Wakatobi Regency, Southeast Sulawesi Province. According to data from the Wakatobi Statistics Agency, the Wangi-Wangi Islands have an area of 191.04 km² out of 473.62 km², or a percentage of 40.41%. There are 2 sub-districts with a total of 37 islands, a total population of 53.31% with a growth rate of 2.8%. The area of Wakatobi National Park is 1,390,000 Ha (Pusparini *et al.*, 2019).

Global warming is a phenomenon of increasing average temperatures in the atmosphere, oceans, and land. The average Earth temperature has increased by 0.74 ± 0.18°C over the past hundred years (Leu, 2021). Indonesia is part of the largest carbon emitters or the largest emitters of Greenhouse Gas (GHG). This increase in GHG emissions triggers the occurrence of sapwood warming, climate change

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and disasters such as high sea levels, extreme weather, floods, landslides, and air pollution (Patrianti *et al.*, 2020; WMO, 2024).

Efforts to reduce carbon emissions are being discussed globally. In line with the Indonesian government's efforts to reduce carbon emissions, the Government of Indonesia is targeting 142 million tons by 2024. For this reason, the Government has set a target of reducing greenhouse gases (GHG) to 31.89% with its own capabilities and 43.20% with the support of other countries in accordance with the determination of the Enhanced-Nationally Determined Contribution (E-NDC) in 2030 (Press Release, 2024).

Rising concentrations of carbon dioxide (CO_2) in the atmosphere have become a major environmental challenge due to their contribution to global warming (Forrester *et al.*, 2024). However, various efforts are being made to reduce the negative impact of CO_2 emissions, and mitigation efforts that can be made are by utilizing plants grown on land and/or seawaters to reduce carbon impact. (Shen *et al.*, 2024; Dawi *et al.,* 2025) showed that most organic carbon (99.83%) is stored in sediments, and the contribution from biomass is smaller. The ability of seagrass to absorb carbon is carried out through the process of photosynthesis. The absorbed carbon will then be stored in the form of seagrass biomass in the seagrass body. Currently, it is suspected that the concentration of carbon dioxide in the atmosphere continues to increase. The concentration of carbon dioxide gas in the atmosphere reached 407.4 ppm in 2018 (Nugraha *et al.*, 2020) Seagrass beds have a high carbon sequestration capacity even through highly productive terrestrial ecosystems (Nurdin *et al.*, 2022).

Remote sensing could provide spatial-temporal data on natural resources, including carbon dynamics in various terrestrial and coastal ecosystems (Wang *et al.*, 2023a; 2024b; Fadhlurahman *et al.,* 2024). Accurately measuring and monitoring the carbon storage potential of seagrass ecosystems is important to quantify their contribution to global carbon sequestration and develop effective carbon blue initiatives (Juncal *et al.*, 2022). However, several challenges must be overcome to ensure comprehensive, representative, consistent, and transparent seagrass data for carbon measurements (Setyanto *et al.,* 2023). This research aims to assess the potential of blue carbon stored in seagrass ecosystems within Wakatobi National Park by utilizing a remote sensing approach, specifically focusing on estimating the area, spatial distribution, and condition of seagrass meadows, as well as determining the carbon stock they contain.

Materials and Methods

This research was conducted from January - December 2023 which included field data collection in June 2023 in the waters of the Wakatobi National Park area, especially the Wangi-Wangi Islands; and data processing was carried out before determining the research location (Determination of research locations based on the representation of seagrass ecosystems based on seagrass cover conditions obtained through Landsat 9 imagery) for image data and after making observations for seagrass and carbon data. The consideration underlying the selection of the research site is that the waters of the Wangi-Wangi Islands are a conservation area of Wakatobi National Park. Geographically, Wakatobi located in south side of mark with lines the equator, northerly long to south, among 5,000 – 6,250 Paralel South (as long as ± 160 km) and unfold from West easterly among 123,340–124,640 Longitude East (as long as ± 120 km) (Figure 1).

Field sampling design

Seagrass sampling was conducted in June 2023. At each station, seagrass data were collected using a 1 m × 1 m quadrat placed randomly at 5 replicate points per station (totaling 60 quadrats). Within each quadrat, species identification, percentage cover, and biomass estimation were conducted. Seagrass species were identified morphologically following McKenzie *et al*. (2003). The biomass was measured by harvesting both aboveground (leaf) and belowground (rhizome-root) components, which were cleaned, dried at 60°C for 48 h, and weighed to determine dry weight.

Image processing and remote sensing

Landsat 8 imagery (2013) and Landsat 9 imagery (2023) were used to map seagrass distribution and detect spatial changes. Image preprocessing included radiometric, geometric, and water column corrections using the Depth Invariant Index (DII). Composite bands (RGB 432) were applied, and classification was performed using supervised pixel-based classification. Accuracy was assessed using ground-truth data, achieving >85% overall accuracy.

The image pre-processing is carried out in several stages, namely: (1) Radiometric correction is used to improve the visual quality of the image and at the same time correct the inappropriate pixel values. Radiometric correction that is often used is using the dark pixel correction method; (2) Geometric correction is the process of correcting errors and marking the characteristics of the map on an image. The main thing in geometric correction is to reposition the pixel values exactly the same so that the results obtained from the sensor recordings correspond to objects on the earth's surface (Sun *et al.*, 2023); and (3) Correction of water columns is an approach that functions to reduce the influence of depth on the mapping of shallow water bottom objects. The water column correction method is a simple image-based approach to compensate for the influence of depth variables or reduce the influence of attenuation coefficients of waters to predict the basic reflectance of waters based on the Depth Invariant Index (DII) method procedure of each spectral band pair of images used (Putra *et al.*, 2023).

Image processing is carried out in the following stages: (1) The preparation of color composite images is carried out to display color images with a resolution of 30-meters in a good contract sharpening form so that it is easy to interpret visually. Composite is done by combining 3 bands from a satellite image to produce a new image, which produces better colors that are very helpful in the object recognition process. Composite 432 is carried out because the composite is a natural color composite and is easy to interpret in general because the appearance pattern is almost the same as the actual appearance pattern; (2) Image Cutting is the final process of image pre-processing is image cropping. This image cutting aims to create an area of interest (AOI), to emphasize geospatial phenomena and discussions in the study area; (3) Classification Multispectral This approach utilizes the spectral characteristics of seagrass communities and sophisticated algorithms and classification techniques to accurately describe the area and distribution of seagrass habitats. Image classification is the process of grouping pixels into certain classes based on the brightness value (BV/ digital number) of the image. This study applies pixel based classification (Danoedoro, 2015; Carpenter *et al.* 2022; Nurdin *et al.* 2022).

Table 1. Landsat 8-9 Satellite Imagery Data used in this study

Band	Spectral Band	Wavelenght (µm)
Band 2	Blue	0.452 - 0.512
Band 3	Green	0.533 - 0.590
Band 4	Red	0.636 - 0.673
Band 5	Near-Infrared (NIR)	0.851 - 0.879

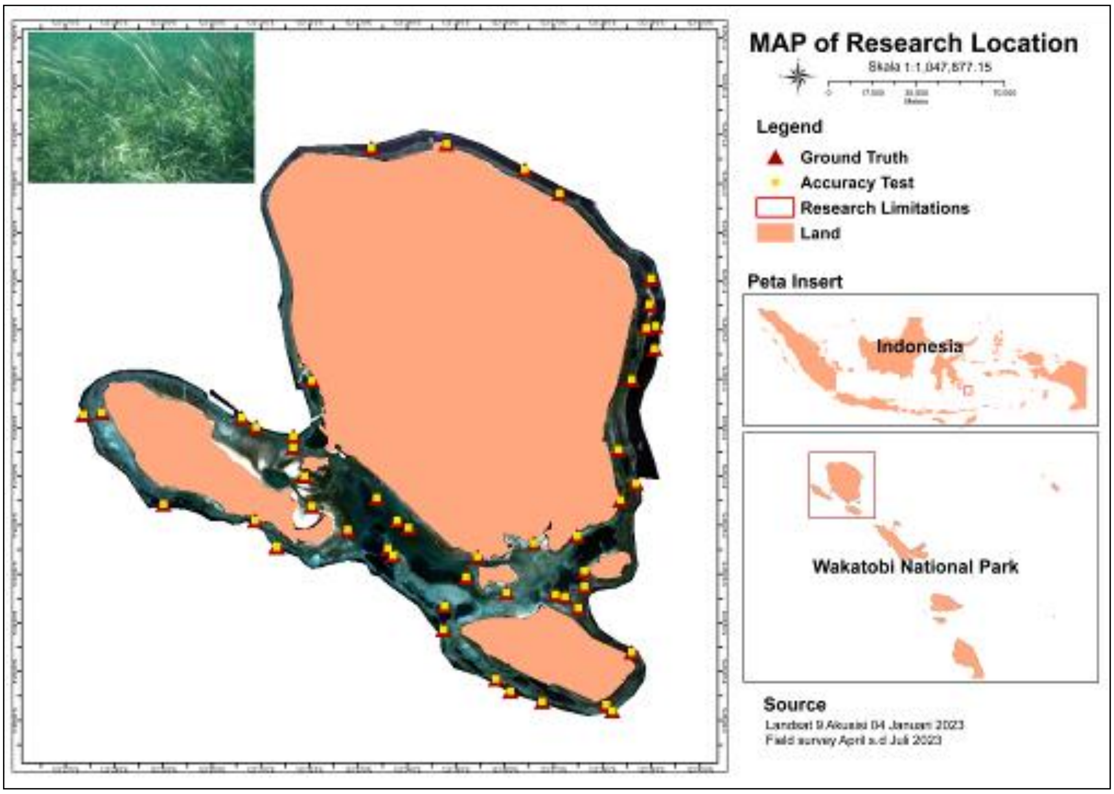

Figure 1. Research site in the area of the Wakatobi National Park, Wangi-Wangi Islands

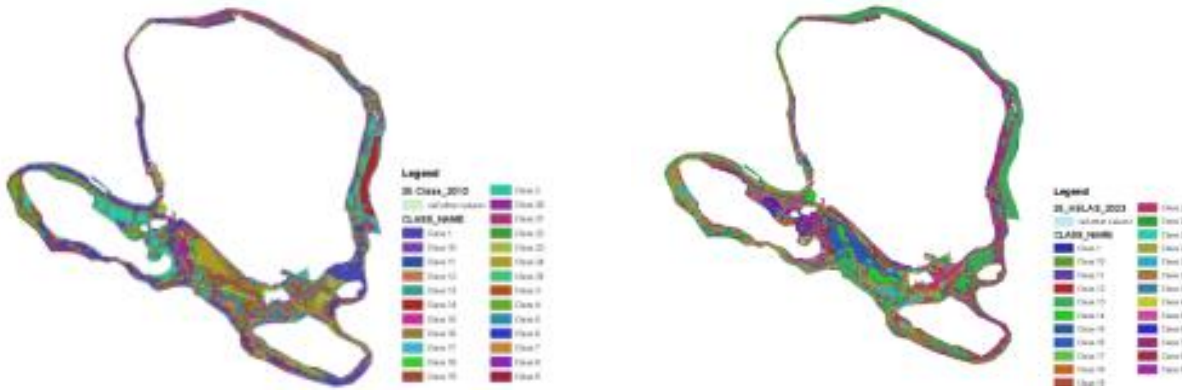

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Figure 2. Results of the Multispectral (Supervised) Classification Process of Image Data (a) Landsat Image 8 of 2013 acquired 16-11-2013, (b) Landsat Image 9 of 2023 acquired 04-01-2023

Accuracy Test is the precision and accuracy of a map in the detection and identification of an object. This accuracy test follows the Short (1982) rule which has been proposed by (Latumeten, Tubalawony and Noya, 2023) Sutanto (1999) *in* Nurdin's (2018) writing. The rigor of the analysis is made in several classes calculated by the Short method:

$$Kp = \frac{\text{The correct number of x pixels}}{\text{The correct number of x pixels + Number of pixel compositions x + Number of pixel compositions x}}$$

E*stimation of seagrass area and carbon stocks*

Total seagrass area was calculated from classified images and validated through field observation. Carbon stock per hectare ($mg.C.ha^{-1}$) was derived from biomass carbon values, and total stock (mg.C) was estimated by multiplying with the areal extent of each seagrass class. Descriptive statistics and change analysis were used to quantify temporal trends in area and carbon stock from 2013 to 2023.

Seagrass cover percent

Observation of seagrass conditions was carried out after obtaining seagrass distribution data based on the results of processing landsat 9 image data previously carried out. The observation is based on Rahmawati *et al*. (2014), with the following stages: (1) Identifying the percentage of seagrass cover by using square transect (1m x 1m) randomly based on the modified seagrass cover standard to determine the total percentage of seagrass cover conditions based on Rahmawati *et al*. (2014) in table 2. Identify seagrass species and cover based on *seagrass percentage cover* (McKenzie, Campbell and Roder, 2003) (Figure 3).

Laboratory analysis for carbon content

From the biomass samples, carbon content was analyzed using the Walkley and Black (WB) wet oxidation method. Each species was represented by 5 replicate composite samples per station (n=60 samples total). The samples were acid-digested and titrated to quantify organic carbon content. Results were expressed in $g.C.m^{-2}$. Species-specific carbon values were calculated by combining above- and belowground carbon content.

Carbon measurements were carried out in the Laboratory using the Walkley and Black Method (WB) method. This method essentially removes organic matter (oxidation) through the process of acidification then through titration counts the remaining acid after oxidizing the organic matter, this method is often said to be the wet method in the measurement of organic matter. This method is more suitable for samples that have an organic matter value of less than 6% and in addition the disposal of acidic materials must be according to procedures (Mylavarapi, 2009)

$$\text{Account: } \%C = \frac{(B - A) \times M\ FeSO4 \times 12 \times 100}{gr\ sampel \times 4000}$$

Note: A= The volume of Ferrous Sulfate solution required for sample mentitation, in mL.; B= Average Volume of Ferrous Sulfate solution required to temper two blanks, in mL; 12/4000 = milli equivalent weight of C in

Data analysis

Changes in seagrass bed area can be calculated by applying the following equation, which shows the tendency of seagrass changes that occur every year at each observation, which can be formulated as follows:

$$\Delta L = \frac{(Lt2 - Lt1)}{Lt1} \times 100\% \Delta L$$

Note: ΔL= Area change rate (%); Ltq1 = Area in the first year of observation (ha); Lt 2= : Area in the next observation year (ha).

Descriptive analysis was used to explain changes in seagrass distribution. Changes in the area of seagrass beds were detected in 2013 and 2023 in Wangi-wangi Islands National Park Area.

Seagrass biomass is calculated using equations (Azkab, 1999) *in* (Akbar *et al*., 2021)

$$B = \frac{W}{A}$$

Note: B= Biomass (gbk.m^{-2}); W= Seagrass Dry Weight (gbk); and A= Cuplikasn Area (m^2).

After obtaining the dry weight, followed by the analysis of carbon content in biomass, the carbon content can be calculated based on the formula of Fourqurean *et al*. (2014):

Carbon biomass = Dry weight (kg).$area^{-1}$ (m^2) x % C

Convert (mgC.ha^{-1})= Biomassa karbon (kgC.m^{-2}) x (mg.1000kg^{-1}) x (10.000m^2.ha^{-1})

Calculations are carried out on each type of seagrass found in one plot/square/drill. If there are three types of seagrass in one plot, then the total carbon biomass stock is the sum of all types of seagrass found in the plot, divided into upper and lower biomass. After being calculated in each plot, it is then averaged so that the total biomass in the study location is obtained in units of mgC.ha^{-1}.

After obtaining the seagrass area by analyzing the latest satellite images at the location or using global data, the value of biomass carbon stock (mgC) in the area is obtained by multiplying the value of biomass carbon stock per unit area (mgC.ha) by the known seagrass ecosystem area (ha).

Carbon stock of area A (mgC) = mgC.ha^{-1} x Seagrass ecosystem area A.

Table 2. Seagrass Percentage Category based on (Rahmawati *et al.*, 2017) (Modification of this study)

Persen Cover (%)	Seagrass Condition Criteria
0–50	Low
51 –75	Medium
76 - 100	High

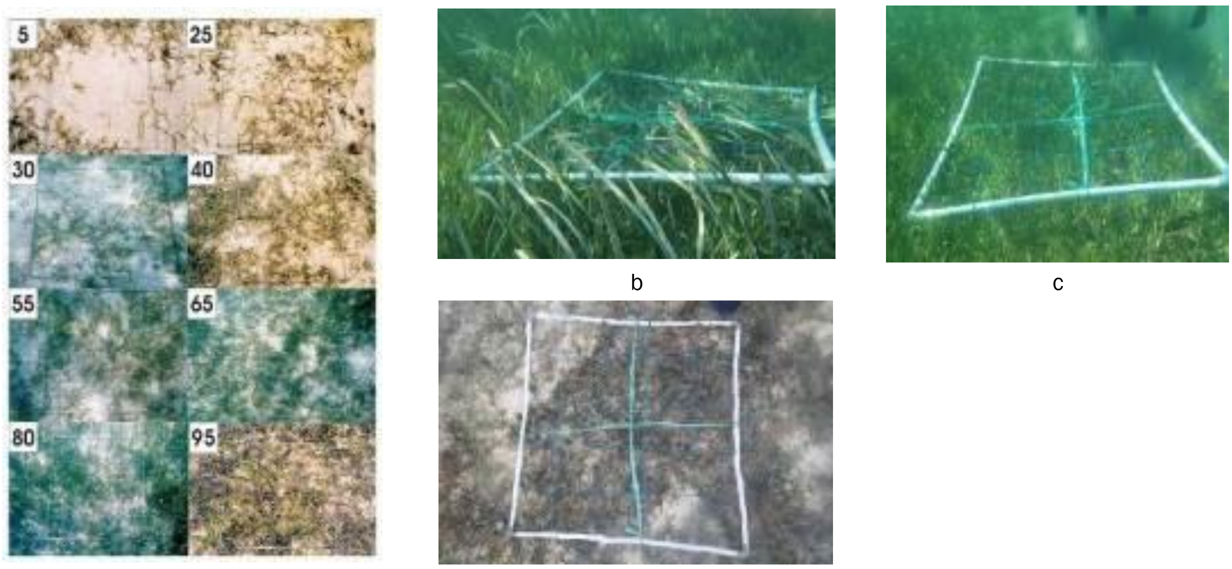

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Figure 3. Seagrass Cover Identification Guidelines (a) Seagrass *Percentage Cover* (McKenzie 2003) (b) High Conditions, (c) Medium Conditions, (d) Low Moderate Conditions

Results and Discussion

This study reveals a significant shift in seagrass cover within Wakatobi National Park, particularly in the Wangi-Wangi Islands, over a ten-year period. The total seagrass area declined from 2,209.4 ha in 2013 to 2,044 ha in 2023, resulting in a net loss of 165.4 ha (Table 3). The most substantial reduction occurred in medium-density seagrass meadows (−289.6 ha), while low-density areas also showed a decline (−43.9 ha). In contrast, high-density coverage increased by 80.3 ha (Figure 5), possibly indicating localized regeneration or spatial shifts in seagrass health.

The degradation of medium and low-density seagrass meadows may be linked to increasing anthropogenic pressures in coastal zones. Activities such as destructive fishing practices, unregulated anchoring, and coastal land-use changes are well-documented drivers of seagrass loss (Sirait *et al.,* 2022). Moreover, sedimentation from land erosion and coastal development reduces light availability, limiting photosynthesis and hampering seagrass growth (Rasmusson *et al.*, 2021; Jiang *et al.*, 2024; Zhou *et al.*, 2024). In Wakatobi, coastal construction and tourism expansion likely contribute to these impacts, particularly in nearshore habitats.

Nutrient enrichment from agricultural runoff and domestic wastewater can lead to eutrophication, promoting the overgrowth of epiphytic algae that compete with seagrasses for light and space (Gräfnings *et al.*, 2023; Adams *et al.*, 2024). These changes are often exacerbated by thermal stress from rising sea surface temperatures, which may affect seagrass physiology and species composition (Rasmusson *et al.*, 2021; Wong and Dowd, 2023). Such stressors may explain the observed shift from medium- to low-density meadows in this study.

The increase in high-density seagrass areas may reflect natural resilience or the success of local conservation interventions, such as the enforcement of marine protected areas or community-based habitat protection. Similar patterns have been reported in other regions where management practices have been improved (Turschwell *et al.*, 2021; Roca *et al.*, 2025). However, the overall net decline suggests that current conservation efforts are not yet sufficient to reverse the broader trend of degradation.

Considering the ecological functions of seagrass ecosystems—such as carbon sequestration, nursery habitat provisioning, and coastal protection, these findings underscore the urgent need for integrated, ecosystem-based management. Regular monitoring, regulation of anthropogenic activities, and active habitat restoration are recommended to enhance the long-term resilience of seagrass meadows in Wakatobi and other marine conservation areas across Indonesia. Based on the results of the analysis, the value of the seagrass cover condition presented in the following table was obtained.

Graph in Figure 5. It shows changes in the area of seagrass in hectares (ha) under various conditions at a certain time. The vertical axis (y) represents the area in hectares, while the horizontal axis (x) depicts the stages of decrease or change in area.

Based on the comparison of seagrass area in three conditions of low, medium and highseagrass (Table 5 and figure 10) shows that in 2013 the area of seagrass with medium conditions has an area of 131.6 ha, while in dense conditions there is a large increase, showing the growth or expansion of the area to 1409.5 ha, After an increase, the area decreases to 668.3 ha in the condition of seagrass with very dense cover. The results of observations in 2023 show that seagrass conditions continue to decline to reach 175.5 ha at medium cover, this value shows a significant reduction. However, in dense seagrass conditions in 2023, there will be an increase again, returning the area to 1119.9 ha, which can be caused by the recovery or expansion process. However, the area of seagrass in dense conditions decreased again to 748.6 ha.

Table 3. Area area and changes in area (ha) in several seagrass cover conditions in Wakatobi National Park Area, Wangi-Wangi Islands

Seagrass conditions	Seagrass Area (Ha) 2013	Seagrass Area (ha) 2023	Change
Low	131.6	175.5	-43.9
Medium	1409.5	1119.9	-289.6
High	668 .3	748.6	+80.3
Total	2209,4	2044	(-165,4) ha

Stick: - (decrease), + (increase)

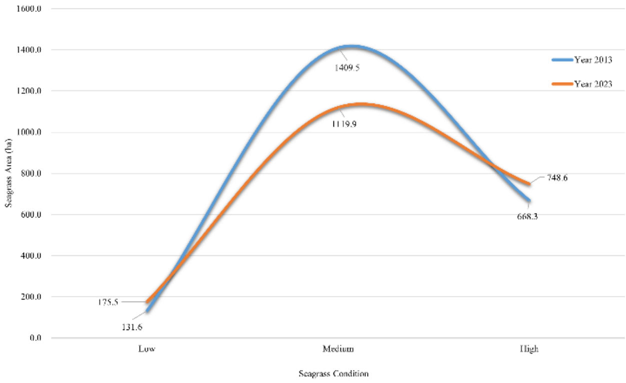

Figure 5. Comparison of seagrass area in three conditions of Low, Medium, and High cover in 2013 and 2023 in the Wakatobi National Park Area (1) Low, (2) Medium, and (3) High condition.

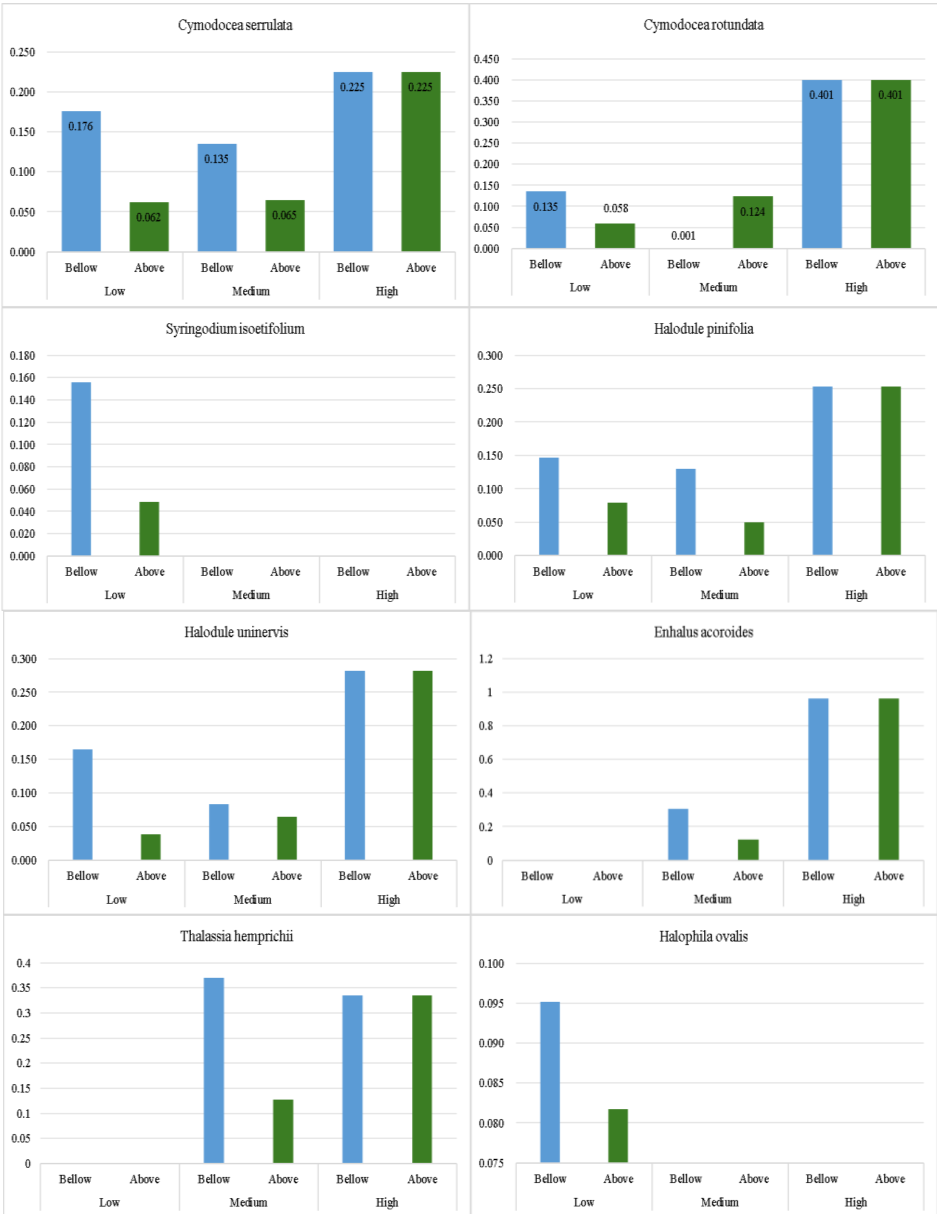

Figure 6. Amount of bellow and above biomass (gbk.m^{-2}) of seagrass at various seagrass cover conditions in the Wakatobi National Park Area, Wangi-Wangi Islands

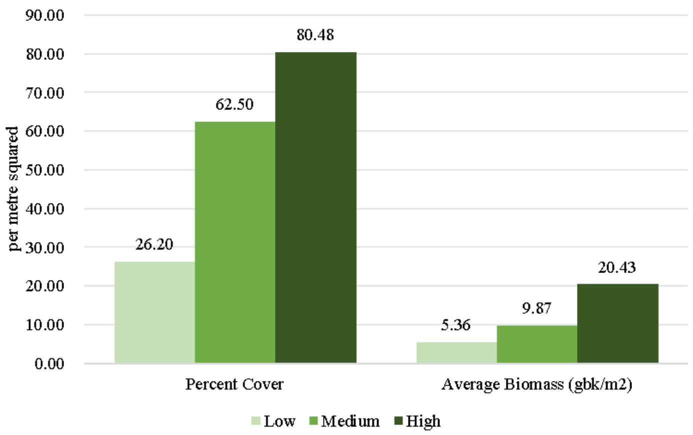

Figure 7. Total Seagrass Cover with Seagrass Biomass in the Wakatobi National Park Area, Wangi-Wangi Islands

From the results of the analysis carried out, the highest leaf biomass value in the *Enhalus acoroides* type was 0.73 gbk.m^{-2} and the lowest in the *Syringodium isoetifolium* type was 0.05 gbk.m^{-2}. Meanwhile, the highest root biomass value in *Enhalus acoroides* was 1.27 gbk.m^{-2}, and the lowest was *Halophila ovalis* 0.10 gbkm^{-2}. The season and distribution of seagrass (Kanhai, 2022) concluded that from the results of the observations made, it was obtained that several types of seagrass found in the dry season had a greater number of individuals of the type of kei than the types of seagrass found in the rainy season.

The percentage of seagrass cover ranged from 26.20% - 80.48%, with the average value of biomass ranging from 5.36 - 20.43 gbkm^{-2}. This increase shows that the denser the seagrass area, the greater the seagrass cover and biomass produced.

Estimation carbon stock

The results of the analysis of carbon content in 8 species of seagrass found (Table 4) showed that *Enhalus acoroides* had the largest carbon contribution both in leaves and roots, with leaf carbon reaching more than 5 gbk.m^{-2}. while Species such as *Cymodocea serrulata* and *Thalassia hemprichii* also store significant amounts of carbon, but still far below Enhalus acoroides. Other species such as *Halodule pinifolia* and *Halodule uninervis* have a much lower carbon storage capacity than other species. Leaves generally store more carbon than roots in most of the species shown, except for a few species where the carbon difference is quite small.

The analysis of carbon stock values among seagrass species in Wakatobi National Park (Table 4) demonstrates substantial interspecific variation in both leaf and root carbon content. Among the eight species identified, *Enhalus acoroides* exhibited the highest total carbon stock (9.1 g.m^{-2}), followed by Cymodocea serrulata (2.6 g.m^{-2}), and *Thalassia hemprichii* (2.5 g.m^{-2}). In contrast, *Syringodium isoetifolium, Halodule pinifolia,* and *Halophila ovalis* recorded the lowest total carbon values, all below 0.5 g.m^{-2}. This variation in carbon stock is largely attributable to species-specific morphological and physiological traits. *Enhalus acoroides*, the dominant large-bodied species in Indo-Pacific seagrass meadows, is characterized by thick, wide leaves and an extensive belowground rhizome-root system. These structural attributes contribute to its substantial biomass and carbon storage capacity, especially in the root compartment (3.8 g.m^{-2}), which accounts for over 40% of its total carbon pool. Similar trends have been reported in tropical seagrass ecosystems, where *E. acoroides* consistently functions as a major carbon sink due to its slow decomposition rate and long-lived tissues (Rustam *et al.*, 2021; Egea *et al.*, 2023).

Species such as *Cymodocea serrulata* and *Thalassia hemprichii* also demonstrate moderate to high carbon values, supported by their robust leaf blades and persistent root systems. These species are typically found in stable subtidal environments with moderate to high sedimentation, where conditions promote carbon accumulation in belowground biomass (Bijak *et al.*, 2023; Liu *et al.*, 2024). Their moderate productivity, combined with structural durability, allows for efficient carbon sequestration. Conversely, pioneer or fast-growing species like *Halodule pinifolia, Halophila ovalis,* and *Syringodium isoetifolium* exhibit significantly lower carbon stock values. These species are generally smaller, with narrower leaves and shallower root systems, which limit their carbon retention capacity. Additionally, their ephemeral nature and high turnover rates result in faster decomposition and reduced long-term carbon storage. The observed variability in seagrass carbon stocks highlights the importance of species composition in estimating blue carbon potential within seagrass meadows. Ecosystems dominated by large, slow-growing species such as *E. acoroides* tend to contribute disproportionately to sediment carbon accumulation and long-term carbon storage. As such, conservation strategies should prioritize the protection and restoration of these structurally complex species to enhance the carbon sink function of coastal ecosystems.

Meanwhile, the results of the analysis of carbon content in mg c.ha^{-1} units were obtained by separate measurements between upper carbon (carbon above ground level) and lower carbon (carbon below ground level) in mgC.ha^{-1} units. The average carbon stock as a whole is at 4,293.77 mgC.ha^{-1}. This data shows that carbon stocks both up and down increase along with the increasing density of environmental conditions.

Based on the results of the analysis of the accuracy test carried out, it was obtained that in 2013 it had a user accuracy value of 68%, producer accuracy 62%, overall accuracy 76%, and kappa accuracy 59%. Meanwhile, in 2023 it has a user accuracy value of 78%, producer accuracy 74%, overall accuracy 85%, and kappa accuracy 76%. This increase in accuracy from 2013 to 2023 is due to various factors. Over time, the quality of the data used is getting better, the algorithms applied are getting more sophisticated, data processing techniques are constantly evolving, and data training is becoming more representative. All of these things play a big role in producing a much more accurate and reliable classification in 2023 than in 2013. As a result, the analysis in 2023 provides a clearer and more reliable picture, reflecting a significant improvement in quality and accuracy.

Table 4. Carbon stock values of seagrass species found in Wakatobi National Park, Wangi-Wangi Islands

Spesies	Carbon Above (g.m^{-2})	Carbon Bellow (g.m^{-2})	Carbon Total (g.m^{-2})
Halodule pinifolia	0.13	0.07	0.20
Syringodium isoetifolium	0.15	0.13	0.28
Halophila ovalis	0.22	0.17	0.39
Halodule uninervis	0.84	0.63	1.47
Cymodocea rotundata	0.99	0.70	1.70
Thalassia hemprichii	1.45	1.05	2.50
Cymodocea serrulata	1.44	1.17	2.61
Enhalus acoroides	5.28	3.84	9.12

Figure 8. Seagrass Distribution Map in Wakatobi National Park Area, Wangi-Wangi Islands, Citra Landsat 8 Year 2013 Acquisition 16-11-2013 and Source of Landsat Image 9 of 2023 Acquisition 04-01-2023

Table 5. Results of Carbon Content Analysis on Varying Seagrass Conditions

Condition	Top Carbon ($mgC.ha^{-1}$)	Carbon Bottom ($mgC.ha^{-1}$)
Low	2,520.03	1,786.78
Medium	3,264.96	281.49
High	9,140.38	668.97
Total Carbon	14,925.37	10.837.24
Average	4,293.77 ($mgC.ha^{-1}$)	

Spatial analysis based on Landsat 8 (2013) and Landsat 9 (2023) imagery (Figure 8) revealed noticeable changes in the distribution patterns of seagrass meadows in the Wakatobi National Park, particularly along the coastal areas of Wangi-Wangi Island. Between 2013 and 2023, there was a marked shift in both the extent and density class of seagrass coverage. In 2013, medium- and high-density seagrass meadows were more broadly distributed along the southern and western coasts, notably in areas such as Mandati, Komala, and Wungka. By contrast, in 2023, low-density seagrass cover became increasingly dominant, especially in northern and northwestern sectors including Wanci, Mandati III, and Kapota, while some expansion of high-density patches was observed in the southeast, particularly in Liya Togo and Komala.

These spatial shifts suggest ecosystem-level responses to a combination of anthropogenic pressures and environmental changes. The contraction of medium-density meadows and their transformation into low-density areas may be attributed to intensified land-based disturbances, including coastal development, increased tourism infrastructure, and destructive fishing activities. Such activities contribute to habitat fragmentation and physical damage to seagrass beds, especially in nearshore areas where human interactions are most concentrated. Furthermore, increased sedimentation from upland erosion and runoff likely reduced water clarity, thereby inhibiting photosynthetic efficiency and seagrass productivity. Coastal zones adjacent to urban settlements (e.g., Wanci and Mandati) exhibited greater transitions toward lower-density coverage, indicating deteriorating environmental quality. Previous studies have linked reduced light penetration and turbidity to declines in seagrass biomass and cover (Harahap *et al.*, 2021; Mayoral *et al.*, 2023; Lohrer *et al.*, 2024).

Interestingly, localized increases in high-density seagrass, particularly in the southeastern coastal areas, may be a result of reduced disturbance exposure, favorable hydrographic conditions, or effective community-based management. These areas may benefit from natural protection due to geomorphological features or stronger enforcement of marine protected area regulations. Such spatial refugia have been shown to support seagrass persistence under external stress (Turschwell *et al.*, 2021; Egea *et al.*, 2024).

In addition, the observed distributional changes may reflect broader shifts in oceanographic conditions, such as sea surface temperature fluctuations, current alterations, and salinity patterns. These factors influence species composition, growth rates, and resilience of seagrass meadows. Adaptive redistribution of seagrass cover, including potential colonization of new suitable areas or retreat from degraded zones, represents a natural response to these environmental dynamics. Overall, the spatial reconfiguration of seagrass meadows in Wakatobi over the past decade underscores the vulnerability of these ecosystems to cumulative stressors. The contraction of medium-density seagrass, expansion of low-density areas, and selective gains in high-density patches emphasize the need for targeted spatial conservation planning. Integrating remote sensing with in-situ monitoring is essential for identifying degradation hotspots and prioritizing restoration or protection zones within the national park.

The identification results showed the existence of nine species of seagrass at the research site, namely *Halophila ovalis*, *Halophila pinifolia*, *Halophila uninervis*, *Enhalus acoroides*, *Thalassia hemprichii*, *Syringodium isoetifolium*, *Cymodocea rotundata*, and *Cymodocea serrulata*. This type diversity reflects the high biodiversity of seagrass ecosystems in the area, which plays an important role in supporting the productivity and stability of coastal ecosystems (Ikhsan *et al.*, 2019; Fauziah *et al.*, 2023).

The conclusion from the results presented in 2013 and 2023 was obtained that the condition of seagrass with medium and very dense cover experienced a slight recovery/increase of 43.9 ha and 80.3 ha, while in the condition of seagrass with dense cover there was a decrease of 289.6 ha, the decrease in area in the category of seagrass with dense conditions indicates a degradation or shift in

Table 6. Seagrass Carbon Conditions and Stocks in 2023

Condition	Area (ha)	Carbon Stock $mgC.ha^{-1}$	Carbon Stock $mgC.ha^{-1}$ 2023	Carbon stock estimates $tC.ha^{-1}$
Low	175.5	4,306.81	755,844.82	0,833
Medium	1,119.9	5,446.45	6,099,474.61	6,724
High	748.6	16,009.35	11,984,600.79	13,211
Total	2,044		18,839,920.22	20,767

ecosystem conditions. This decline can result from environmental stresses, such as changes in sedimentation patterns, pollution, or physical disturbances from human activities such as destructive fishing and coastal development.

This data shows that the denser the vegetation, the greater the potential for carbon storage, both at the top and bottom. This underscores the importance of dense vegetation in storing carbon in the environment, which contributes to the reduction of carbon dioxide in the atmosphere and supports climate change mitigation.

The importance of the role of seagrass beds in the Wangi-Wangi Islands, Wakatobi Regency, in mitigating climate change through carbon storage. Seagrass beds function as carbon sinks that can absorb and store carbon dioxide (CO_2) from the atmosphere, helping to reduce the effects of greenhouse gases. Sources of CO_2 emissions from human activities in coastal areas, such as industry and development, contribute to air pollution and increased carbon dioxide levels. The role of seagrass in absorbing CO_2 from the atmosphere is the main ecological function of seagrass in absorbing and storing carbon in plant tissues and marine sediments. Remote sensing technology, used to monitor and estimate carbon stocks in seagrass ecosystems. This technology allows for efficient and extensive monitoring to determine changes and potential carbon storage in seagrass beds. The recycling symbol with the image of the earth emphasizes the importance of conservation and sustainable management of seagrass, considering that seagrass not only stores carbon but also supports biodiversity and balance of coastal ecosystems. Figure 8 as a whole emphasize the critical role of seagrass in the global carbon cycle and the importance of utilizing remote sensing technology to protect these ecosystems in the context of environmental sustainability (Nurdin *et al.*, 2022; Bai *et al.*, 2023). This is consistent with the findings of various studies that show that the high density of seagrass is directly proportional to the increase in ecosystem productivity and the availability of seagrass biomass, which in pairs can support biodiversity and healthy coastal ecosystem function (Watson *et al.,* 2022).With the increase in seagrass cover, aquatic ecosystems gain additional benefits such as improved air quality, provision of habitat for fish species, and shoreline protection from erosion.

Based on the results of image data processing carried out (Figure 8), it was obtained that the total area of seagrass beds mapped reached around 2209.4 ha in 2013 and in 2023 reached around 2044 ha, with a high seagrass cover area making it important where this area plays an important role as a marine habitat as well as a carbon sink. This area with very high seagrass cover shows high carbon sequestration activity and reflects a healthy and productive ecosystem in the carbon sequestration process, but the mitigation potential in absorbing CO2 by seagrass in the photosynthetic mechanism can be lost if the degradation of the nutrient enrichment environment (eutrophication) continues to occur or the development of coastal areas increases (Rahman *et al.,* 2021; Risandi *et al.,* 2023).

Based on the results of observations on community activities in the Coastal Area of Wakatobi National Park, Wangi-wangi Islands, overall, various human activities that are not properly managed can have a negative impact on seagrass ecosystems. These activities lead to increased water turbidity, physical damage to seagrass plants, pollution of waters, and disruption of the distribution of essential nutrients that seagrass need to survive. If left unchecked, this damage to seagrass will not only affect the marine life that depends on the ecosystem, but also the important ecological functions provided by seagrass, such as coastal protection and climate change mitigation. Efforts to protect and rehabilitate seagrass ecosystems are essential to maintain ecological balance in coastal areas.

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