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Full Length Research Article

Carbon Stock and Potential for Carbon Absorption by Mangrove Forests on Maspari Island: The Outermost Small Island in South Sumatra

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ABSTRACT

Maspari Island is the only small outermost island located in the southern part of Bangka Strait, included in the coastal area of Ogan Komering Ilir Regency, South Sumatra. The island harbors a mangrove ecosystem that is believed to play a significant role in climate change mitigation through carbon storage. This study aims to identify mangrove species and measure carbon stock estimates in upper-stand biomass, lower-stand/root biomass, and sediment. Identification of mangrove species using a vegetation analysis approach. Transect plots measuring 10 m × 10 m were parallel to the coastline at 6 observation station points. The diameter of vegetation at the tree and sapling levels was measured at a height of 1.3 m from the ground surface. Carbon stock estimates were calculated using allometric equations and sediment carbon analysis methods. The results identified seven mangrove species: *Avicennia marina*, *Bruguiera sexangula*, *Ceriops tagal*, *Excoecaria agallocha*, *Rhizophora apiculata*, *Rhizophora stylosa*, and *Sonneratia alba*. Estimated carbon stocks of mangrove stands at all stations reached 3,443.42 tC/ha, with an average of 573.90 tC/ha, while carbon stocks in roots amounted to 862.96 tC/ha, with an average of 143.83 tC/ha. The total estimated carbon stock of mangrove sediment at all stations was 240.71 tC/ha, with an average of 40.12 MgC/ha. *Sonneratia alba* provided the highest carbon absorption, reaching 3,059 tC/ha for the upper stand and 697.80 tC/ha for the lower stand. Considering the contribution of the carbon storage potential in Maspari Island, this study suggests extending the investigation of the mangrove carbon fixation in other small islands in Indonesia, especially for the *S. alba* species.

1. Introduction

Climate change is one of the major global challenges of the 21st century (Feulner 2015). Increased greenhouse gas emissions in the atmosphere cause the global average temperature to continue to increase by around 2°C until 2100 (Malhi et al. 2021). This increase in global temperature triggers extreme weather changes such as heat waves, droughts and heavy rains, which impact the balance of ecosystems and human activities (Akhtar 2020). Climate change will also impact food and nutritional security in the future (Leisner 2020). Changing rainfall patterns and increasing temperatures have a negative impact on agricultural productivity (El Bilali et al. 2020).

The impacts felt are that the availability, accessibility and stability of food are threatened. Sea level rise triggered by the melting of polar ice caps and glaciers is a problem for coastal communities and results in loss of biodiversity, population displacement, and loss of local livelihoods (Kumar et al. 2021; Talukder et al. 2022). An effective and efficient mitigation strategy is needed to minimize climate change's impact. Nature-based strategies are one of the most effective ways of sequestering carbon through vegetation in forest ecosystems.

Forests, through their vegetation, have an important role in absorbing and storing blue carbon (Rahmadwiati et al. 2022). Mangrove forests offer an effective approach to reducing CO_2 concentrations in the atmosphere (Zhu and Yan 2022). Mangroves are known as the most productive coastal wetland vegetation and can store up to five times more blue carbon. Mangroves can store carbon in the form of living biomass above and below the ground surface, including leaves, stems, branches, and roots (Gómez et al. 2023), then in non-living biomass such as litter and dead wood (Choudhary et al. 2024), and in the lower layers of sediment (Rahman et al. 2021; Savari et al. 2020). Carbon is absorbed through photosynthesis, converted into carbohydrates, and stored in tree, leaf, and root biomass (Dinilhuda et al. 2020). Biomass and carbon in mangrove sediments come from collapsed litter such as leaves, twigs, roots, and tree debris accumulating and decomposing in the sediment layer. This process involves decomposing organic matter by microorganisms, which then store carbon in organic sediment (Aprilia et al. 2020; Findlay 2021).

Indonesia is a maritime country with more than 17,504 islands spread throughout the country (Basyuni et al. 2022) and the world's largest mangrove ecosystem along its coastal areas (Parthiban et al. 2021). This ecosystem contributes significantly to the absorption of global blue carbon emissions, with the highest potential in Southeast Asia (Rahman et al. 2024). One important example is on the coast of South Sumatra, which includes mangrove ecosystems such as the Air Telang Protected Forest (Eddy et al. 2021), Sembilang National Park, Banyuasin Coast (Ulqodry et al. 2020), and Tanjung Api-Api Banyuasin (Purwiyanto and Agustriani 2017). Almost all research on the carbon contribution of mangroves in Indonesia and the world is generally located on large islands such as Belitung Island, Indonesia (Henri et al. 2024), Flores Island, Indonesia (Wirabuana et al. 2025), Hainan Island, China (Jia et al. 2022), Andaman Islands, India (Ragavan et al. 2021), Panay Island, Philippines (Thompson et al. 2014), and Pohnpei Island, Micronesia (Mu et al. 2018). There are still very few studies on the carbon contribution of mangroves on small islands such as Payung Island, Indonesia (Hermialingga et al. 2023), and Tunda Island, Indonesia (Fakhrurrozi et al. 2023).

A small island is an island that has an area of less than 2,000 km^2 and a width of no more than 10 km (Republic of Indonesia 2007; UNESCO 1991). Almost all of the islands in Indonesia are categorized as very small islands. Very small islands usually have an area of no more than 100 km^2 and a width of no more than 3 km (Dijon 1984). Maspari Island is a small island in Indonesia located in the southern part of the Bangka Strait, South Sumatra (Rozirwan et al. 2020). Maspari Island has a land area of about 26 ha, where mangroves are one of the most important habitats, along with coral reefs and seagrasses. Although small in area, the mangrove vegetation growing on small islands like Maspari Island is believed to contribute to carbon storage. So far, information on mangrove species and their relationship to carbon absorption on Maspari Island has not been explored. This study is important to determine the potential for stored carbon storage so that it becomes one of the important recommendations for mangrove conservation on the outermost small islands vulnerable to degradation. This study aims to identify mangrove species and measure carbon stock estimates in upper stands, lower stands/roots, and sediments on Maspari Island, Ogan Komering Ilir (OKI) Regency, South Sumatra Province.

2. Materials and Methods

2.1. Study Area

The research location is Maspari Island, Simpang Tiga Jaya Village, Tulung Selapan District, Ogan Komering Ilir Regency, South Sumatra Province. Maspari Island has rocky, sandy, muddy beaches, high salt content, and large waves. Sampling was conducted at 6 station points with mangrove vegetation (**Fig. 1**). Sample preparation, biomass analysis and carbon stock were carried out at the Marine Oceanography Laboratory, Department of Marine Sciences, Faculty of Mathematics and Natural Sciences, Sriwijaya University.

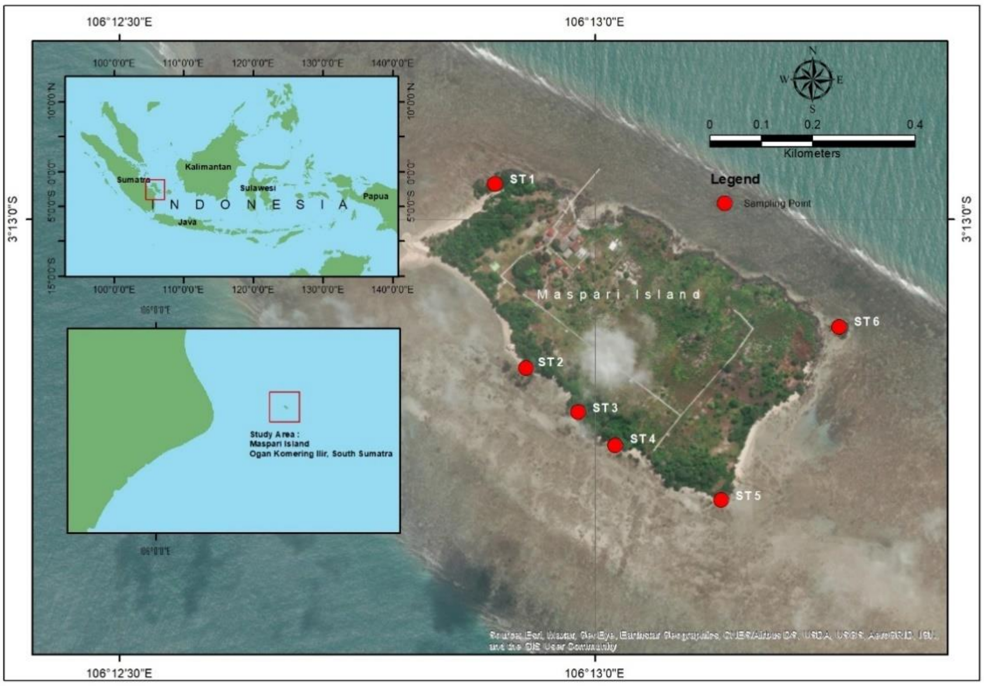


Fig. 1. Map of research location on Maspari Island.

2.2. Data Collection

2.2.1. Mangrove stand diameter measurement

Measurement of mangrove biomass and carbon stock estimates can be done using the allometric method (Abdul-Hamid et al. 2022). Measurements are made by measuring the diameter at breast height (DBH) (Indrayani et al. 2021). Allometric equations have been widely used to estimate mangrove biomass and carbon stocks in upper and lower stands (Alimbon and Manseguiao 2021; Harishma et al. 2020; Zanvo et al. 2023). The observations of mangrove vegetation samples were carried out at 6 station points based on the presence of mangroves in the island area. Mangrove stands were measured by installing a line transect parallel to the coastline. The sample plot (Plots) size was 10 m × 10 m (Ahmed et al. 2022), spreading according to the mangrove's thickness at each station.

The stand diameter was taken at breast height (DBH), 1.3 meters from the ground surface (Indrayani et al. 2021). If the tree is in a sloping area, the diameter measurement is carried out on the uphill side. Trees with sloping trunks are measured according to the natural height of the tree parallel to the trunk. Suppose there are trees that branch below a height of 1.3 m, they are counted as more than one stand. Trees with a buttress height above 1.3 m above the ground surface are measured directly at the buttress, while trees with stilt roots are measured above the stilt roots. Stands were categorized into two groups based on stem diameter: trees and saplings. Stands with stem diameters ≥ 5 cm were categorized as trees, while stands with diameters < 5 cm were categorized as saplings (Kauffman and Donato 2012). Identifying mangrove species for each plot refers to Noor et al. (2012) and Sidik et al. (2021).

2.2.2. Sediment collection

The sediment sampling process was carried out at the same station following a 10 m × 10 m transect. Mangrove sediment sampling methods follow the guidelines of Howard et al. (2014). Sediment samples were taken from each observation plot with a depth of about 10 cm using a sediment corer measuring 50 cm long and 10 cm in diameter. Sediment sampling is not done at depth intervals because the substrate conditions around the Maspari Island mangrove ecosystem tend to be muddy sand.

2.3. Data Analysis

2.3.1. Mangrove density

The density of mangrove vegetation was calculated based on the calculations of Mueller Dumbois and Ellenberg (1974), with Equation 1:

$$Ki = \frac{ni}{A} \tag{1}$$

where Ki is the density of species i, ni is the total number of stands of species i, and A is the total area of the sampling area/plot.

2.3.2. Biomass of upper and lower mangrove stands

Carbon stock measurements were taken on above-ground and below-ground biomass to estimate potential biomass and determine carbon stocks in each stand. It is important to note that each mangrove species has a different wood density. Wood density data can be referred to the Global Wood Density Database (Chave et al. 2009), and some mangrove species that have measured wood density are presented in **Table 1**. According to Fourqurean et al. (2014), stand and root biomass can be calculated using Equations 2 and 3.

$$W_{top} = 0.251 \times \rho \times (DBH)^{2.46} \tag{2}$$

$$W_{below} = 0.199\ x\ \rho^{0.899} \times (DBH)^{2.22} \tag{3}$$

where W_{top} is the biomass of the upper stand (Kg), W_{below} is understory biomass (roots) (KgC), ρ is stem density (g/cm^3), and DBH is the diameter of the stem (cm).

2.4. Analysis of Carbon Stocks in Stand Biomass

After obtaining mangrove standing biomass, carbon stock analysis was conducted on the standing biomass. According to the Intergovernmental Panel on Climate Change (2006), the concentration of carbon in organic matter is 47%. Therefore, the amount of stored carbon was calculated by multiplying 0.47 by the biomass of the mangrove (Equation 4) (Prasetyo et al. 2017).

$$C = B \times 0.47 \tag{4}$$

where C is the amount of carbon contained in biomass (kg), B is the amount of biomass in the upper mangrove stand (kg), and *47%* is the determined percentage of carbon content.

Table 1. Wood density value (ρ)

No.	Species	Wood Density (ρ)
1.	*Avicennia marina*	0.732
2.	*Bruguiera sexangula*	0.740
3.	*Excoecaria agallocha*	0.456
4.	*Rhizophora apiculata*	0.850
5.	*Rhizophora stylosa*	0.840
6.	*Sonneratia alba*	0.630
7.	*Ceriops tagal*	0.883

(Source: Chave et al. 2009)

2.5. Carbon Stock Analysis of Sediment Biomass

Carbon uptake analysis of sediments was conducted following the method outlined by Howard et al. (2014). Sediment samples were placed in aluminum cups and dried in an oven at 60°C for 48 hours. After drying, the samples were pulverized using a mortar to achieve homogeneity. Three grams of sample were taken, weighed, and placed in a porcelain crucible. Next, the sample was put into a muffle furnace and burned at 450°C for 4 hours. Calculation of carbon reserves begins with calculating soil density using Equation 5. Next, dry ignition or loss of ignition (LOI) is calculated using Equation 6. Conversion of the percentage of organic matter to the percentage of carbon is done using Equation 7. Carbon density (C) is calculated using Equation 8. Carbon content per sample thickness is estimated using Equation 9, and Soil Carbon is calculated using Equation 10:

$$BD\ (g/cm^3)\ \frac{\text{oven-dried mass (g)}}{\text{sample volume (cm}^3\text{)}} \tag{5}$$

where *BD* is the density of the soil, *oven-dried mass* is the mass of the dried sample (g), and *sample volume (cm³)* is the volume of the sample.

$$\%BO = \frac{W_o - W_t}{W_o} \times 100 \tag{6}$$

where *%BO* is the percentage of organic matter lost, *Wo* is the initial weight (3 g), and *Wt* is the final weight after combustion (g).

$$\%C = (0.415) \times \%BO + 2.89 \tag{7}$$

where *%C* is the carbon content of organic sediment material, *0.415* is the constant for converting % organic material to % organic C, and *2.89* is the organic material conversion rate.

$$Soil\ C\ Density = \frac{\%C}{100} \times BD \tag{8}$$

where *Soil C density* is carbon density, *BD* is soil density, and *%C* is the carbon content of organic sedimentary material.

$$Soil\ C\ Section = SCD \times SDI \tag{9}$$

where *SCS* is carbon content per thickness, *SCD* is Soil Carbon Density, and *SDI* is Sample Depth Interval (cm).

$$Soil\ Carbon = Soil\ C\ section \times 100 \quad (10)$$

where *soil carbon* is sediment carbon (Mg/ton), and the *soil C section* contains carbon content per thickness.

3. Results and Discussion

3.1. Mangrove Species Composition

There are seven species of mangroves found on Maspari Island, namely *Avicennia marina*, *Bruguiera sexangula*, *Ceriops tagal*, *Excoecaria agallocha*, *Rhizophora apiculata*, *Rhizophora stylosa*, and *Sonneratia alba.* The mangrove vegetation found at 6 station points had varying density values for each species (**Fig. 2**). *Rhizophora stylosa* showed the highest density at the tree and sapling levels. At the tree level, the highest density was found at Station 2, followed by Station 3, Station 4, Station 1, Station 5, and Station 6 (**Fig. 2**). At the sapling level, the highest density was found at Station 5, followed by Station 2, Station 1, Station 3, and Station 4. *Avicennia marina* and *Bruguiera sexangula* were only found at Station 1, with 33 and 67 individuals/ha tree-level densities, respectively. *Excoecaria agallocha* was found at Station 1 with a tree density of 167 individuals/ha and 50 individuals/ha of seedlings. *Rhizophora apiculata* was also found at Station 1 with a tree density of 633 individuals/ha and 183 individuals/ha of seedlings. *S. alba* was only found at the tree level, with the highest density at Station 6 (100 individuals/ha) and the lowest at Station 1 (17 individuals/ha). *Ceriops tagal* was found at Station 6 with a tree density of 1,400 individuals/ha and 100 individuals/ha seedlings.

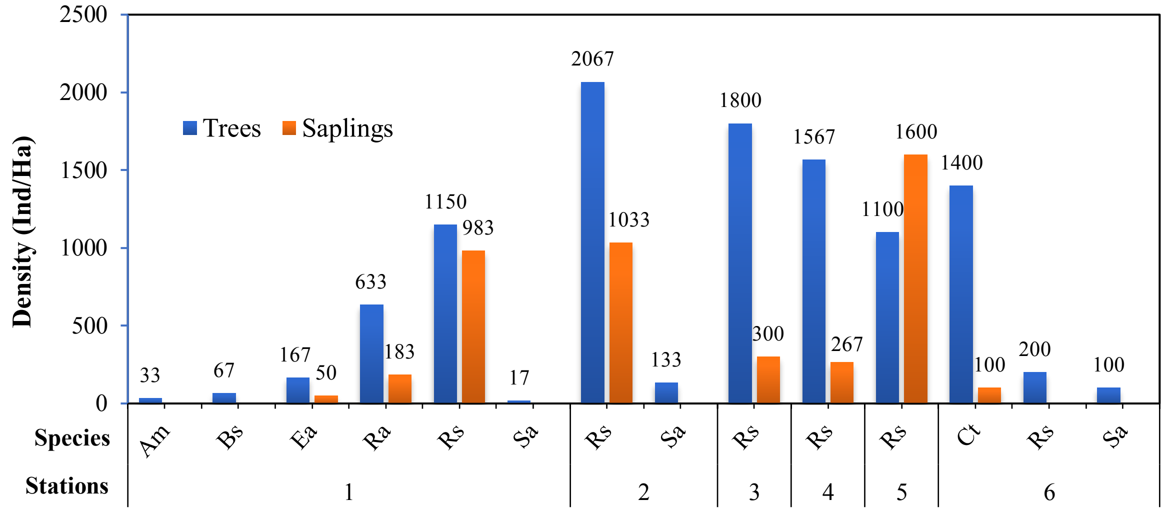


Fig. 2. Mangrove vegetation density on Maspari Island (Am : *Avicennia marina*; Bs : *Bruguiera sexangula*; Ct : *Ceriops tagal*; Ea : *Excoecaria agallocha*; Ra : *Rhizophora apiculata*; Rs : *Rhizophora stylosa*; Sa : *Sonneratia alba*).

Rhizophora stylosa has the largest individual composition compared to other species, with a percentage of up to 80%. On the coast of South Sumatra, the *Rhizophora stylosa* species is only found on Maspari Island. Maspari Island is a suitable habitat for the growth of *Rhizophora stylosa* (**Fig. 3**). *Rhizophora stylosa* can grow well in extreme coastal habitats (Akaji et al. 2024), survive in the Maspari Island environment with high salinity (Rozirwan et al. 2021) to the extreme tidal conditions. Another species, *Rhizophora apiculata*, has an individual composition of 11% and acts as a companion to *Rhizophora stylosa* in the structure of the mangrove ecosystem. *Excoecaria* *agallocha* and *Ceriops tagal* each have an individual composition of 3%. Minor species such as Sonneratia alba, *Bruguiera sexangula* and *Avicennia marina* each have an individual composition of 1%. All mangrove species are found to be habitats in supporting mangrove ecosystem services such as carbon sequestration and climate change mitigation (Jennerjahn 2020), habitat for various fishery biota (Arceo-Carranza et al. 2024), and coastal protection (Damastuti et al. 2023).

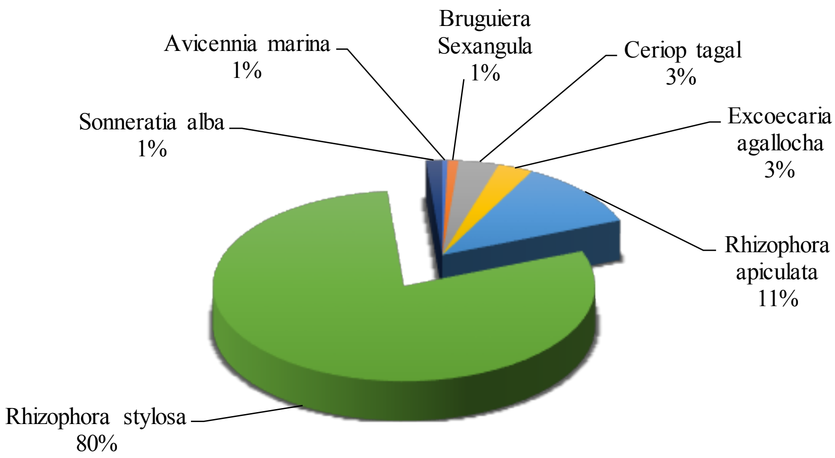


Fig. 3. Composition of mangrove species found on Maspari Island.

The diameter, above-ground biomass (AGB), and below-ground biomass (BGB) of mangroves on Maspari Island showed varying values (**Table 2**). One of the factors that determines the high biomass value of mangrove trees is diameter and age. The amount of biomass increases with tree diameter and age (Marnaek et al. 2024). Tree diameter affects biomass value. This condition can be proven at Station 2, with the largest tree diameter ranging from 1.3 cm to 260.8 cm, producing AGB (5,473.06 t/ha) and BGB (1,223.67 t/ha). In contrast, at Station 5, the small tree diameter ranging from 1.8 cm to 8.1 cm only produced AGB (34.12 t/ha) and BGB (17.82 t/ha). This study did not measure tree age directly; it was obtained from interviews with the community. According to the local community, several mangrove trees on Maspari Island are more than 50 years old, especially the *Sonneratia alba* species found at Station 2. This condition causes Station 2 to have the highest total biomass of 6,696.73 t/ha, while Station 5 shows the lowest biomass of 51.95 t/ha.

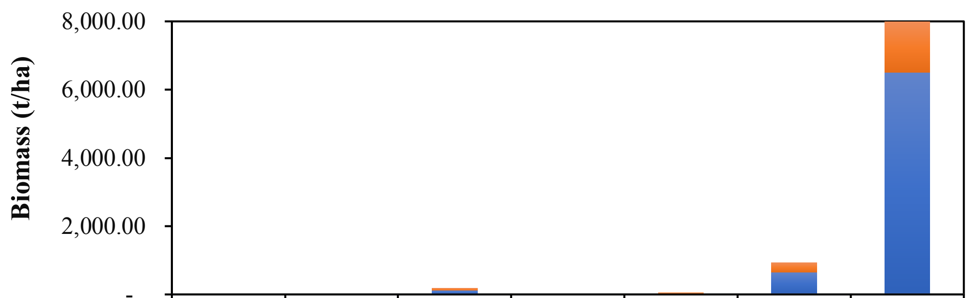
Table 2. Average above-ground biomass and below-ground biomass Maspari Island

Stations	DBH (cm)	AGB (t/ha)	BGB (t/ha)	Total Biomass (t/ha)
1	1.3–56.8	201.66	80.14	281.80
2	1.3–260.8	5,473.06	1,223.67	6,696.73
3	2.5–17.0	147.39	65.09	212.47
4	2.5–19.9	132.72	57.84	190.56
5	1.8–8.1	34.12	17.82	51.95
6	4.3–95.5	1,337.47	391.53	1,729.00
	Total	7,326.42	1,836.09	9,162.51
	Average	1,221.07	306.01	1,527.09

Total AGB at all observation stations was 7,326.42 t/ha with an average of 1,221.07 t/ha, while total BGB was 1,836.09 t/ha with an average of 306.01 t/ha. Total biomass at all stations was 9,162.51 t/ha, with an average of 1,527.09 t/ha. Overall, the total biomass reached 9,162.51 t/ha with an average of 1,527.09 t/ha. In general, BGB is higher than AGB, as in the study of Meng et al. (2021) and Mu et al. (2018); however, the results of this study produced a higher AGB compared to BGB (Hidayah et al. 2022; Panda et al. 2024; Ragavan et al. 2021; Ray et al. 2011), showing that the AGB value is greater than the BGB. The higher BGB value compared to AGB is because the mangrove roots on Maspari Island function better in adapting to the extreme conditions in the Maspari Island habitat.

The distribution of mangrove biomass on Maspari Island by mangrove species is presented in **Fig. 3**. *Sonneratia alba* dominated with the highest above-ground biomass (AGB) and lower below-ground biomass (BGB), reaching 6,510 t/ha and 1,484 t/ha, respectively, totaling 7,994 t/ha. This biomass value is higher than in Setiu Lagoon, Malaysia (Islam et al. 2022) and the Island Garden City of Samal, Davao Del Norte (Agua and Wong 2023). *Rhizophora stylosa* was the other species with significant biomass, where AGB and BGB amounted to 653.13 t/ha and 280.13 t/ha, respectively, resulting in a total of 933.26 t/ha. This biomass value is greater than that of the mangrove forest of Karawang District, West Java (Trissanti et al. 2022), Island Garden City of Samal, Davao Del Norte (Agua and Wong 2023), and mangrove forests in North Central Timor Regency, East Nusa Tenggara Province (Ledheng et al. 2022).

Other species also showed lower biomass values than *Sonneratia alba* (**Fig. 4**). *Cersiops tagal* had an AGB of 123.42 t/ha and a BGB of 52.61 t/ha. *Excoecaria agallcoha* had AGB of 5.03 t/ha and BGB of 2.37 t/ha. *Rhizophora apiculata* had AGB of 29.71 t/ha and BGB of 13.97 t/ha. *Avicennia marina* had AGB of 1.56 t/ha and BGB of 0.73 t/ha. Finally, *Bruguiera sexangula* had an AGB of 3.30 t/ha and a BGB of 1.55 t/ha. The low biomass value of this species is due to the smaller DBH compared to *Sonneratia alba* (**Table 2**).



	Am	Bs	Ct	Ea	Ra	Rs	Sa
Biomass BGB	0.73	1.55	52.61	2.37	13.97	280.13	1,484.68
Biomass AGB	1.56	3.30	123.42	5.03	29.71	653.13	6,510.27

Species

Fig. 4. Biomass of mangrove upper and lower stands on Maspari Island (Am : *Avicennia marina*; Bs : *Bruguiera sexangula*; Ct : *Ceriops tagal*; Ea : *Excoecaria agallocha*; Ra : *Rhizophora apiculata*; Rs : *Rhizophora stylosa*; Sa : *Sonneratia alba*).

3.2. Carbon Stock Estimation of Mangrove Above-Ground Carbon and Below-Ground Carbon

Carbon stock estimates showed significant variation between stations (**Table 3**). As with biomass, AGC carbon stocks tend to be higher at each station than BGC carbon stocks. These results indicate that carbon on Maspari Island is stored more in the upper part of the mangrove, such as stems, twigs and leaves. In addition, carbon stored below (roots) is lower because mangrove roots on Maspari Island function more to adapt to conditions on Maspari Island, which have a sandy substrate, extreme tides and high salinity. The total carbon stock of the upper stand reached 3,443.42 tC/ha with an average of 573.90 tC/ha, while the total carbon stock of the lower stand was 862.96 tC/ha with an average of 143.83 tC/ha. Overall, the total carbon stock at all stations was 4,306.36 tC/ha, with an average of 717.73 tC/ha. Station 2 recorded the highest carbon stock of 3,147.46 tC/ha, while Station 5 showed the lowest carbon stock, totaling 24.42 tC/ha.

Table 3. Estimation of above-ground and below-ground carbon stocks on Maspar Island

Stations	DBH (cm)	AGC (tC/ha)	BGC (tC/ha)	Total Carbon Stock (tC/ha)
1	1.3–56.8	94.78	37.67	132.45
2	1.3–260.8	2,572.34	575.12	3,147.46
3	2.5–17.0	69.27	30.59	99.86
4	2.5–19.9	62.38	27.18	89.56
5	1.8–8.1	16.04	8.38	24.42
6	4.3–95.5	628.61	184.02	812.63
	Total	3,443.42	862.96	4,306.38
	Average	573.90	143.83	717.73

The carbon stock estimates of each mangrove species on Maspari Island show different values based on DBH (**Table 4**). *Sonneratia alba* has a higher carbon storage capacity compared to other species. *Sonneratia alba* with DBH 8.9–260.8 cm stores the highest carbon stock, reaching 3,059.83 tC/ha (AGC) and 697.80 tC/ha (BGC). As a comparison, *Rhizophora stylosa* with DBH 1.3–60.6 stores carbon stock of 306.97 tC/ha (AGC) and 131.66 tC/ha (BGC). *Ceriops tagal* with DBH 4.3–23.9 cm stores carbon stock of 58.01 tC/ha (AGC) and 24.73 tC/ha (BGC). *Rhizophora apiculata* with DBH 2.4–17.1 cm stores carbon stock of 13.94 tC/ha (AGC) and 6.55 tC/ha (BGC). *Excoecaria agallocha* with DBH 3.2–18.3 cm stores carbon stock of 2.43 tC/ha (AGC) and 1.14 tC/ha (BGC). While *Avicennia marina* with DBH size 8.8–10.2 cm stores lower carbon stock of 0.74 tC/ha (AGC) and 0.35 tC/ha (BGC).

Table 4. Estimation of above-ground and below-ground carbon stocks by mangrove species

Species	DBH (cm)	AGC (tC/ha)	BGC (tC/ha)
A. marina	8.8–10.2	0.74	0.35
B. sexangula	5.6–10.8	1.55	0.73
C. tagal	4.3–23.9	58.01	24.73
E. agallocha	3.2–18.3	2.43	1.14
R. apiculata	2.4–17.1	13.94	6.55
R. stylosa	1.3–60.6	306.97	131.66
S. alba	8.9–260.8	3,059.83	697.80
	Average	**491.9**	**123.3**

The diameter size influences the relationship between biomass and carbon stock in mangroves at Breast Height (DBH). The greater the value of the tree DBH, the greater the value of biomass and carbon stock produced (Islam et al. 2022). These conditions are suitable and support the large diameter of the Sonneratia alba mangrove, which can store large amounts of carbon. The same results were found in the study (Tupan and Lailossa 2019), which states that the carbon absorption of Sonneratia alba stored above ground is greater than that of below ground, and high carbon storage is supported by tree biomass and diameter.

3.3. Organic Matter and Carbon Stock Estimation of Mangrove Sediment on Maspari Island

Organic carbon in mangrove ecosystems is significantly stored in soils, accounting for over two-thirds of the ecosystem's total carbon stock (Sasmito et al. 2020). Organic carbon in mangrove ecosystems is stored significantly in the soil, reaching over two-thirds of the total ecosystem carbon stock (Sasmito et al. 2020; Zimmer and Helfer 2021). Mangrove litter, microphytobenthos, and phytoplankton are the main contributors to organic carbon in mangrove sediments (Ogawa et al. 2021). These three sources significantly provide carbon-rich organic matter to aquatic ecosystems. Leaves, twigs, and other vegetative parts of deciduous mangroves contribute substantially to the carbon content of sediments, while microphytobenthos and phytoplankton add carbon through photosynthesis and decomposition. Estimates of total carbon stocks in mangrove sediments on Maspari Island are presented in **Table 5**.

Table 5. Total estimated mangrove sediment carbon stock on Maspari Island

Stations	Soil Density (g/cm³)	Organic Material	Organic Carbon	Carbon Density (g/cm³)	Sedimentary Carbon
1	0.710	5.10	5.01	0.036	36
2	0.816	5.33	5.10	0.042	42
3	0.842	4.01	4.55	0.038	38
4	0.965	1.70	3.60	0.034	34
5	0.890	4.24	4.65	0.041	41
6	0.708	9.97	7.03	0.050	50
Average		5.06	4.99	0.04	40.12
Total					241

The organic matter and organic carbon values in the sediments of Maspari Island showed significant variations (**Fig. 6**). Station 6 recorded the highest values with 9.97% for organic matter and 7.03% for organic carbon, respectively, while Station 4 had the lowest values of 1.70% for organic matter and 3.60% for organic carbon. Overall, organic matter in the sediments of Maspari Island ranged from 1.70% to 9.97%, with an average of 5.06% across stations. Meanwhile, organic carbon ranged from 3.60% to 7.03%, averaging 4.99%. Organic matter and organic carbon on Maspari Island have lower values compared to research results on other islands, such as Payung Island, Banyuasin, with an average organic matter of 8.69% and organic carbon of 5.04% (Hermialingga et al. 2020). The low amount of decomposed mangrove litter can cause the low organic matter and organic carbon content on Maspari Island. Litter that falls from mangrove trees, such as leaves and twigs, plays an important role as the main source of organic carbon in the mangrove ecosystem (Chen et al. 2023).

The total estimated carbon stock in mangrove sediments from the six research stations reached 240.71 tonsC/ha, with an average of 40.12 tonsC/ha (**Fig. 7**). This value is greater than in the study by Emrinelson and Warningsih (2024). Carbon stocks in mangrove sediments on Maspari Island can reach up to 50 tonsC/ha, while Station 4 showed the lowest carbon stock value of 34 tonsC/ha. Factors such as soil content, density, depth, and spatial variation of soils play an important role in the differences in carbon stocks (Donato et al. 2011). Sampling depth greatly influences carbon stock estimation. Based on IPCC and UNESCO, as mentioned (Nwankwo et al. 2023), about one-third of the total organic carbon in mangrove sediments is located at depths of 1–2 meters, while the upper 0–15 cm is the most significant area for carbon loss or accumulation in sediments. This study only measured to a depth of 10 cm, which resulted in a lower carbon estimate. Other studies suggest that high organic content can be found at depths between 0.5 m and more than 3 m, which certainly affects the amount of carbon stock (Donato et al. 2011).

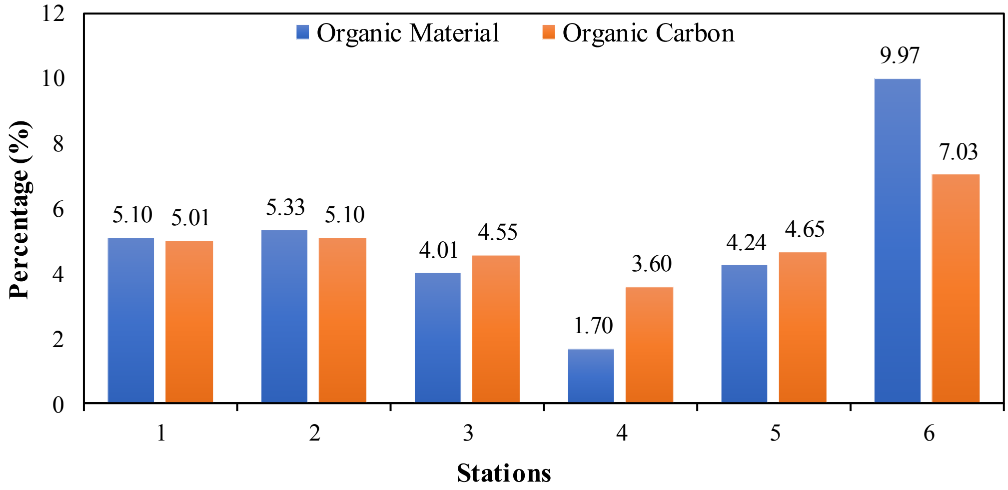


Fig. 6. Organic matter and organic carbon in mangrove sediments.

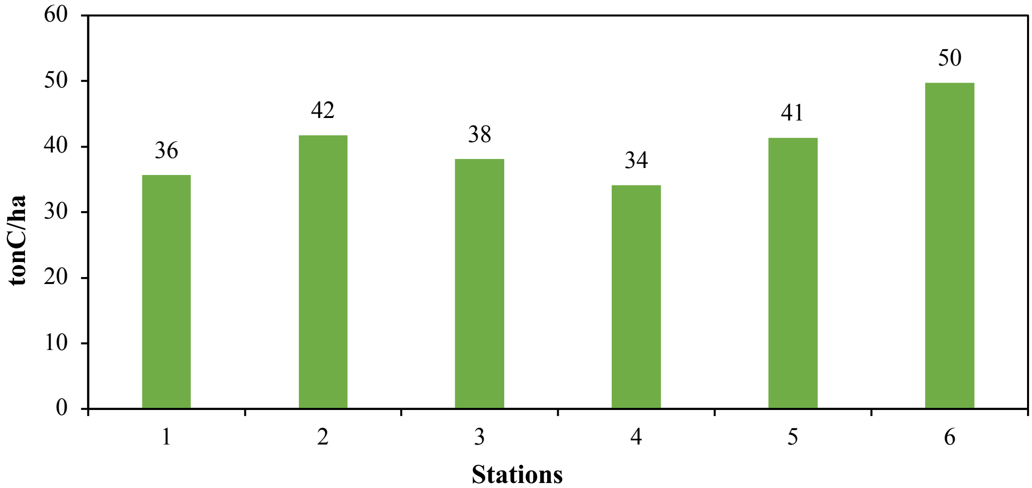


Fig. 7. Average mangrove sediment carbon estimate.

3.4. Organic Matter and Carbon Stock Estimation of Mangrove Sediment on Maspari Island

Table 6 provides a detailed analysis of the total and average carbon stocks of all stations on Maspari Island, focusing on three main components: carbon stored in the upper stand, lower stand, and sediment. The results showed that all stations' estimated average carbon stock was 757.85 tC/ha. The average carbon stored in the upper stand was 573.90 tC/ha, the lower stand was 143.83 tC/ha, and the sediment was 40.12 tC/ha.

Station 2 showed a total dominant carbon stock value reaching 3189.22 tC/ha, with upper stand carbon stock of 2,572.34 tC/ha, a lower stand of 575.12 tC/ha, and sediment of 42 tC/ha (**Table 6**). This dominance is influenced by the *Sonneratia alba* species which has a large biomass and can store more carbon (Zulhalifah et al. 2021). *Sonneratia alba* grows in habitats with muddy sandy substrates (Soe-Win and Ni- Win 2021) and is tolerant of extreme tides (Nguyen et al. 2020) and high salinity conditions (Chen et al. 2011). The suitable conditions on Maspari Island make

Sonneratia alba grow well, produce large biomass, and contribute a greater total carbon stock than other species. The carbon absorption capacity of mangroves is greatly influenced by the height, diameter and density of mangroves in an ecosystem (Harishma et al. 2020; Zaman et al. 2023).

Table 6. Total estimated carbon stock and average carbon across stations

Stations	AGC (tC/ha)	BGC (tC/ha	Sediment (tC/ha)	Total (tC/ha)
1	94.78	37.67	36	168.09
2	2,572.34	575.12	42	3,189.22
3	69.27	30.59	38	137.98
4	62.38	27.18	34	123.66
5	16.04	8.38	41	65.78
6	628.61	184.02	50	862.37
Average	573.90	143.83	40.12	757.85

Based on **Table 5**, the average total value of carbon stocks at each station in this study is greater than the results in mangrove ecosystems in Kerala, southwest coast of India of 139.82 t/ha (Harishma et al. 2020), research in Payung Island, South Sumatra of 221.68 t/ha (Hermialingga et al. 2023), and research in a tropical lagoon ecosystem in Setiu, Malaysia of 261.45 t/ha (Islam et al. 2022). Standing carbon has the largest proportion in the total carbon stock, which means that stands have an important role in carbon sequestration and storage in the Maspari Island ecosystem. Although the contribution of carbon from roots and sediments is relatively smaller than that of the stands, they still play an important role in long-term carbon storage. The complex root system of mangroves can trap organic matter and detritus, allowing long-term carbon storage in the soil (Alongi 2012). Understanding the distribution and storage of carbon in different components of mangrove ecosystems is essential for conservation and environmental management strategies, especially in climate change mitigation. Mangroves are important in storing blue carbon (Zhu and Yan 2022). Effective management can maximize the role of mangrove ecosystems in the global carbon cycle and enhance the ecosystem services they offer, including carbon sequestration and coastal protection.

4. Conclusions

In conclusion, Maspari Island is a habitat for seven mangrove species, namely *Avicennia marina*, *Bruguiera sexangula*, *Ceriops tagal*, *Excoecaria agallocha*, *Rhizophora apiculata*, *Rhizophora stylosa*, and *Sonneratia alba*. The biomass of mangrove upper stands at all research stations reached 7,326.43 tonsC/ha, with an average of 1,221.07 tonsC/ha, while the biomass of lower stands was recorded at 1,836.08 tonsC/ha, with an average of 306.01 tonsC/ha. Estimated carbon stocks of mangrove stands at all stations reached 3,443.42 tonsC/ha, with an average of 573.90 tonsC/ha, while carbon stocks in roots amounted to 862.96 tonsC/ha, with an average of 143.83 tonsC/ha. In addition, the total estimated carbon stock in mangrove sediments at all stations was 240.71 tonsC/ha, with an average of 40.12 MgC/ha. The results of this study emphasize the importance of conserving mangrove ecosystems on small islands, as small islands such as Maspari Island can contribute significant carbon stocks.

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Author Contributions

T.Z.U.: Conceptualization, Methodology, Supervision, Data Curation, Writing – Original Draft Preparation, Writing – Review and Editing; M.R. and R.Ap.: Conceptualization, Investigation, Data Curation, Data Analysis, Writing – Review and Editing; M., S., and M.H.: Writing – Review and Editing, Visualization, Supervision; W.A.E.P. and R.Ar.: Data Curation, Writing – Original Draft Preparation.

Conflict of Interest

The authors declare no conflict of interest.

Declaration of Generative AI and AI-Assisted Technologies in the Manuscript Preparation

During the preparation of this work, the authors used ChatGPT to smartly enhance the clarity of the writing, making it easy for the readers to understand. After using this tool/service, the authors reviewed and edited the content as needed and took full responsibility for the publication's content.

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