

Diversity, carbon stock and economic value of the mangrove ecosystem in Wakatobi Biosphere Reserve, Indonesia

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Abstract. Manan A, Sudia LB, Hasani UO, Kete SCR, Gandri L, Yasin A, Agusrinal, Isabela. 2025. Diversity, carbon stock and economic value of the mangrove ecosystem in Wakatobi Biosphere Reserve, Indonesia. *Biodiversitas* 26: 1095-1104. Mangrove ecosystems significantly contribute to climate change mitigation through the absorption and storage of carbon. This research evaluates the diversity, carbon stock, and economic valuation of mangrove ecosystems within the Wakatobi Biosphere Reserve. Data collection occurred at 11 stations distributed among four primary islands: Kaledupa, Wangi-Wangi, Tomia, and Binongko. Diameter at Breast Height (DBH) measurements were utilized to estimate biomass and carbon storage, employing species-specific allometric equations. Economic valuation utilized carbon trading data from the Indonesia Stock Exchange (IDX Carbon) as of 3 January 2025, alongside the Social Cost of Carbon (SCC) and Voluntary Market (VM) prices. The mangrove ecosystem of the Wakatobi Biosphere Reserve covers an area of 10,994 hectares and is in excellent ecological condition. The Shannon-Wiener Diversity Index values for tree and pole strata demonstrate moderate diversity (1-3), with Kaledupa and Binongko classified as moderate, whereas Wangi-Wangi and Tomia are categorized as low (<1). The evenness score indicates a high classification for tree strata (>0,6), with the exception of Wangi-Wangi, which is classified as medium (0,4-0,6). Wangi-Wangi Island is classified as low for splinter strata (<0,4), whereas Tomia, Kaledupa, and Binongko Islands are classified as medium. The composition of mangrove species differed across islands, with *Sonneratia alba*, *Rhizophora mucronata*, *Bruguiera gymnorrhiza*, and *Ceriops tagal* identified as the most prevalent species and significant contributors to carbon sequestration. The total carbon stock was estimated at 329,82.06 tons, with Kaledupa Island exhibiting the highest stock at 317,226.51 tons, while Binongko Island recorded the lowest at 2,053.8 tons. The economic valuation of carbon storage indicates significant potential: IDR 18,763,377,420 or USD 1,159,307 (IDX Carbon), IDR 266,390,582,055 or USD 16,459,103 (SCC), and IDR 43,155,274,293 or USD 2,666,375 (VM), underscoring the financial importance of mangrove conservation. This signifies a potential for revenue generation in the Wakatobi region, offering a hopeful prospect for the future. This study highlights the ecological and economic significance of mangroves and establishes a basis for sustainable conservation and management strategies aimed at improving the resilience of the Wakatobi Biosphere Reserve.

Keywords: Blue carbon, carbon stock, economic valuation, mangrove diversity, Wakatobi Biosphere Reserve

INTRODUCTION

The rise in global temperatures, driven by higher levels of greenhouse gases in the atmosphere, including carbon dioxide (CO₂), methane (CH₄), and nitrous oxide (N₂O), poses a significant threat to the survival of life on our planet (Laihonen et al. 2024). Over the past 220 years, global CO₂ levels have risen from 283 to 419 parts per million (ppm), while CH₄ levels have escalated from 750 to 1925 parts per billion (ppb), and N₂O levels have grown from 273 to 336 ppb (He et al. 2024). Carbon dioxide is the primary contributor to greenhouse gases (Carong et al. 2024; Ibrahim et al. 2024), leading to rising air temperatures and an increase in the frequency, duration, and intensity of extreme weather events (Psistaki et al. 2024). Apart from that, forest degradation contributes significantly to the increase in greenhouse gases. This situation is highly unfavorable. So, at COP 21, the UN set up the United Nations Framework Convention on Climate Change (UNFCCC), which is a set

of rules meant to keep the rise in global temperature to no more than 2°C, with 1.5°C being the best goal by 2012 (UNFCCC 2020). Rabbi and Kovács (2024) say that one way to reach these global goals would be to use plant photosynthesis to remove CO₂ from the air. This is a natural way to lower greenhouse gas levels.

Mangroves are capable of storing and absorbing significant quantities of carbon in above-ground and below-ground biomass, as well as soil organic carbon (Basyuni et al. 2024; Bernardino et al. 2024). The average soil carbon stock is 1,819.31 tonnes/ha, and the soil absorbs 1,074.99 tonnes/ha (Handoyo et al. 2020). In Indonesia, they store 313.52 tons per hectare, which is four times more than tropical forests, swamps, and seagrass ecosystems (Cusack et al. 2018; Dinilhuda et al. 2020; Banerjee et al. 2021).

Stand variables, such as diameter, density, and species composition, influence carbon stocks and mangrove absorption rates (Wang et al. 2013; Ahmed and Kamruzzaman 2021). The *Rhizophora mucronata* species demonstrates a carbon

storage and absorption capacity of 19.94 tons C/ha and 73.13 tons CO₂/ha, whereas the *Nypa fruticans* species exhibits a carbon storage and absorption capacity of 21.82 tons C/ha and 80.02 tons CO₂/ha (Rudianto et al. 2019; Nwankwo et al. 2023).

Mangroves may store and sequester significant amounts of carbon in both above- and below-ground biomass, as well as soil organic carbon (Basyuni et al. 2024; Bernardino et al. 2024). The average soil carbon stock is 1,819.31 tons/ha, while the soil absorbs 1,074.99 tons/ha (Handoyo et al. 2020). Mangroves in Indonesia have an average carbon storage capacity of 313.52 tons per hectare, which is four times that of tropical forests, swamps, and seagrass habitats (Cusack et al. 2018; Dinilhuda et al. 2020; Banerjee et al. 2021). Stand factors like diameter, density, and species composition influence mangrove carbon stock and absorption rate (Wang et al. 2013; Ahmed and Kamruzzaman 2021). The *R. mucronata* species had a carbon storage and absorption capacity of 19.94 tons C/ha and 73.13 tons CO₂/ha, but the *N. fruticans* species had a capacity of 21.82 tons C/ha and 80.02 tons CO₂/ha (Rudianto et al. 2019; Nwankwo et al. 2023). Previous research has demonstrated that mangrove carbon sequestration is controlled by species composition, environmental circumstances, and forest structure (Komiya et al. 2005; Alongi et al. 2016).

Wakatobi received official recognition as a world biosphere reserve at the 18th International Conference of the Man and the Biosphere (MAB) Program of UNESCO, which took place in Paris. This conference acknowledges Wakatobi as an area characterized by a unique and ecologically important environment. The Wakatobi Biosphere Reserve is located in the center of the world's coral triangle, recognized for its unparalleled marine biodiversity. This 50,000-ha area is the subject of global initiatives aimed at preserving marine biodiversity (Pet-Soede and Erdmann 2003). Mangrove forests serve as essential habitats in shallow marine waters and represent a significant component of the ecosystem in this region (Clifton et al. 2013).

The mangrove forests of Wakatobi span 1,088.14 hectares across four primary islands: Wangi-Wangi, Kaledupa, Tomia, and Binongko (BPDAS Sampara 2022). The mangrove

ecosystem in this area boasts a wealth of biodiversity. It offers a range of ecological advantages, such as safeguarding against coastal erosion and serving as a habitat for various species and carbon stock. Wakatobi's mangrove ecology is currently under threat from mangrove forest exploitation, coastal development, abrasion, and marine pollution (Clifton et al. 2013). Increased sedimentation and habitat fragmentation are also observed in other mangrove-rich locations (Duke et al. 2007; Polidoro et al. 2010). If these issues are not addressed, Wakatobi mangroves will struggle to maintain their status as carbon sinks and biodiversity centers.

Mangrove ecosystems absorb and store carbon, which is critical to reducing greenhouse gas emissions. The decline in mangrove area and quality is accelerating, endangering the ability of the Wakatobi Biosphere Reserve to fulfill global promises to reduce carbon emissions. As a result, it is critical to perform a thorough analysis of the mangrove ecosystem, including an assessment of variety, carbon supply, and mangrove economic worth. The purpose of this project is to characterize mangrove diversity, quantify carbon stocks, and compute the economic worth of mangrove carbon under various carbon trading frameworks in the Wakatobi Biosphere Reserve. This study combines ecological and economic analyses to present a complete picture of the Wakatobi mangrove ecosystem. This study's findings help to inform both local conservation strategies and global climate mitigation efforts. By addressing this gap, policymakers and conservationists can gain actionable knowledge to guarantee that Wakatobi mangrove forests are preserved for ecological and economic advantages.

MATERIALS AND METHODS

Study area

The research examined the mangrove ecosystem in the Wakatobi Biosphere Area, Southeast Sulawesi, Indonesia, which consists of four main islands: Wangi-Wangi, Kaledupa, Tomia, and Binongko (Figure 1). It was conducted from June to September 2024.

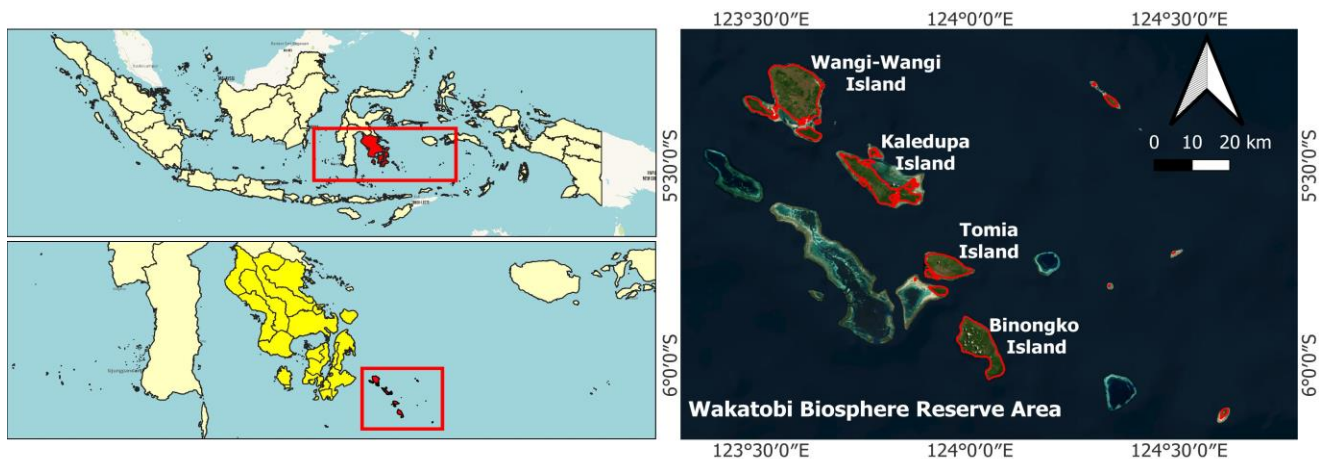


Figure 1. Location of Wakatobi Biosphere Area, Southeast Sulawesi, Indonesia

Table 1. Allometric equations of several types of mangroves

Mangrove species	Allometric method	Reference
<i>Avicennia alba</i>	$B = 0.251 \times \rho \times D^{2.46}$ ($\rho = 0.506$)	Komiyama et al. (2005)
<i>Avicennia marina</i>	$B = 0.1848 \times D^{2.3524}$	Dharmawan and Siregar (2008)
<i>Bruguiera gymnorhiza</i>	$B = 0.0754 \times D^{2.505}$	Kauffman and Donato (2012)
<i>Rhizophora apiculata</i>	$B = 0.043 \times D^{2.63}$	Kauffman and Donato (2012)
<i>Rhizophora mucronata</i>	$B = 0.1466 \times D^{2.3136}$	Dharmawan (2010)
<i>Sonneratia alba</i>	$B = 0.3841 \times \rho \times D^{2.101}$ ($\rho = 0.078$)	Kauffman and Donato (2012)

Notes: B: Biomass (kg); D: DBH (cm); ρ : Wood density (g/m^3)

Data analysis

Diversity index of mangrove species

Observation points are distributed across Kaledupa Island, totaling up to 11, with 5 stations located there and 2 stations each on Wangi-Wangi, Tomia, and Binongko Islands. The difference in the number of stations can be attributed to the considerably larger mangrove area present on Kaledupa Island compared to the other three islands. The observation area measures 10 m by 10 m. Field observations were conducted to gather vegetation data on each plot. The collected data encompassed various mangrove species, along with measurements of diameter, height, and individual counts across all growth strata. This included trees (DBH >20 cm), poles (DBH 10-19 cm), saplings (DBH <10 cm and height >1.5 m), and seedlings (height <1.5 m). The stem diameter is measured at a height of 130 cm from the ground level.

We use the following formula to quantitatively determine the density of each individual plant.

$$\text{Density (D)} = \frac{\text{Number of Individuals of a species}}{\text{Area of sample area}}$$

$$\text{Relative Density (RD)} = \frac{\text{Density of a species}}{\text{Total density of all species}} \times 100\%$$

$$\text{Frequency (F)} = \frac{\text{Number of Plots where a species is found}}{\text{Total number of plots}}$$

$$\text{Relative Frequency (RF)} = \frac{\text{Frequency of a species}}{\text{Frequency of all species}} \times 100\%$$

$$\text{Dominance (D)} = \frac{\text{Total basal area of a species}}{\text{Area of sampling area}}$$

$$\text{Basal Area} = \frac{(d)^2}{4} \times 3.14$$

$$\text{Relative Dominance (RD)} = \frac{\text{Dominance of one type}}{\text{Dominance of all types}} \times 100\%$$

$$\text{Importance Value Index (IVI)} = D + Rf + Rd \text{ (Krebs 1989)}$$

$$\text{Shannon-Wiener Diversity Index, } H' = - \sum_{i=1}^s \left(\frac{n_i}{N} \right) \ln \left(\frac{n_i}{N} \right)$$

Where:

H' : Diversity of species

n_i : The population size of a species

N : The total number of species

Biomass measurement

Biomass measurements were carried out in a non-destructive manner and later analyzed using allometric equations derived from previous studies that employed destructive methods. This investigation utilizes the allometric

equations outlined in Table 1. Measurements of biomass were carried out in the right and left subplots of each stand. DBH measurements were carried out solely on trees that had a diameter greater than 5 cm. The circumference of the trunk was measured and subsequently converted into diameter utilizing the following equation:

$$D = \frac{K}{\pi} \text{ (Simon 2007)}$$

Calculation of carbon stock and carbon sequestration

The measurements of carbon storage are converted into carbon content values. The carbon storage capacity in trees aligns with SNI 7724:2011, which is quantified at 0.47. The carbon content value is subsequently utilized to determine the carbon absorption value, following the findings of Banuwa et al. (2019).

$$C = \text{Biomass} \times 0.478 \times \text{Carbon Sequestration CO}_2 = \frac{\text{Mr CO}_2}{\text{Ar C}} \times \text{Carbon}$$

Where:

C : Carbon

0.47 : Conversion factor

Mr CO₂ : Relative molecular mass (44)

Ar C : Relative atomic mass (12)

The economic value of carbon

The carbon pricing estimate is based on data from the Indonesia Stock Exchange (IDX Carbon) for Friday, 3 January 2025, when trades closed at IDR 57,000 per TonCO_{2e}. In addition, various instruments are utilized, such as the Environmental Defense Fund's social cost of carbon of USD 50 per ton of CO_{2e} and the voluntary market price of USD 8.1 per ton of CO_{2e} (Hamrick and Gallant 2018). The exchange rate is set to USD 1 = IDR 16,185.

RESULTS AND DISCUSSION

Mangrove ecosystem

The mangrove forests in the Wakatobi Biosphere Reserve consist of four families: Avicenniaceae, Meliaceae, Rhizophoraceae, and Sonneratiaceae. Furthermore, a total of seven species have been identified, which include *Avicennia marina* (Forssk.) Vierh, *Bruguiera gymnorhiza* (L.) Lam., *Ceriops decandra* (Griff.) Ding Hou, *Ceriops tagal* (Perr.) C.B.Rob, *Rhizophora apiculata* Blume, *Rhizophora mucronata*

Lam., and *Sonneratia alba* Sm. The Meliaceae family is unique to Wangi-Wangi Island, while other families are found throughout all the islands. The Rhizophoraceae family dominates the mangrove forests in this region. Wangi-Wangi Island has six species from four families; Kaledupa Island and Tomia Island have seven species from three families. Binongko Island has six species from three groups (Table 2). RD (Relative Density) was dominated by *S. alba*, while RF (Relative Frequency) was dominated by *R. apiculata*.

The analysis of mangrove vegetation on Wangi-Wangi Island, using parameters such as Relative Density (RD), Relative Frequency (RF), Relative Dominance (RD), and Importance Value Index (IVI), revealed that the species *B. gymnorrhiza* had the highest relative dominance and importance value index among the tree strata. In the pole, sapling, and seedling strata, *R. apiculata* dominated other species. This suggests that the *R. apiculata* species is important in maintaining the stability of the mangrove community in the pole, sapling, and seedling layers. In contrast, the *X. granatum* species is only found in the tree and pole layers, highlighting regeneration difficulties. This could be due to either natural or human influences (Table 3).

The comprehensive analysis of mangrove vegetation on Kaledupa Island has revealed insightful findings. Within the tree, pole, and sapling strata, the species *R. mucronata* has emerged as the most dominant, with the highest relative density, relative frequency, relative dominance, and importance value compared to other species. In the seedling strata, the *Ceriops tagal* species exhibited the highest relative density and importance value. The data indicates that within the tree, pole, and sapling strata, the *R. mucronata* species exhibits the most extensive growth distribution, the highest population density, and the greatest average stem diameter. The importance value parameter, which integrates relative frequency, relative density, and relative dominance values, indicates that the *R. mucronata* species holds the highest importance value overall, with the exception of the seedling strata, where *C. tagal* is the dominant species (Table 3).

The analysis of mangrove vegetation on Tomia Island indicates that in the tree strata, *B. gymnorrhiza* stands out as the predominant species in comparison to others, although *R. apiculata* showed similar values in RD and RF, *B. gymnorrhiza* had higher Rd values, indicating an even distribution of this species in the study area. Within the pole, sapling, and seedling strata, the species *C. tagal* demonstrates the highest importance value index (Table 4). This suggests that among the three growth strata, the *C. tagal* species exhibits a higher degree of adaptability to the environment than other species.

The findings from the vegetation analysis conducted on Binongko Island indicate that within the tree growth strata, the species *S. alba* exhibits the highest relative density, relative frequency, relative dominance, and importance value index. The findings indicate that the *S. alba* species exhibits the highest population density, the most extensive growth distribution, and the greatest coverage area. In the pole, sapling, and seedling strata, the *R. mucronata* species exhibits greater dominance compared to other species (Table 4).

The Diversity Index and Evenness Index (E) of mangrove species

The H Value (Shannon-Wiener Species Diversity Index) and E (Species Evenness Index) represent the species diversity of the mangrove community. The Wakatobi Biosphere Reserve Area classifies mangrove diversity in the tree and pole layers as medium (1-3). The sapling and seedling strata classify Kaledupa and Binongko Islands as medium and Wangi-Wangi and Tomia Islands as low (<1). Overall, the mangrove diversity value is scored modestly (1.25). The evenness value indicates that the tree strata receive a high rating (>6), while only Wangi-Wangi Island receives a medium rating (0.4-0.6). Wangi-Wangi Island has low sapling strata (<0.4), while Tomia Island, Kaledupa, and Binongko Islands have medium-class sapling strata (high). Tomia Island is the sole low-level island in the seedling strata. The study discovered that the mangrove vegetation on Wangi-Wangi, Tomia, and Kaledupa Islands has the highest species diversity and evenness among tree layers. Kaledupa Island has the greatest diversity and evenness of species in the poles (Figure 2). This suggests that mangrove plants in the tree layers of Wangi-Wangi, Tomia, and Binongko Islands face less competition than plants in other strata. On Kaledupa Island, the pole stratum mangrove has a balanced distribution of individuals among species, ensuring that no single species dominates the others.

Many different kinds of mangrove species can be found in the Wakatobi Biosphere Reserve, but not in Baluran National Park, Situbondo, East Java (Hariyanto et al. 2019), Papua Province (Rumbino et al. 2024), Palopo City (Sakaria and Polapa 2024), North Maluku Province (Najamuddin et al. 2024), or Bunaken National Park (Schaduw et al. 2024). However, it is lower than in Rote Ndao, East Nusa Tenggara (Fakhrurrozi et al. 2024), Lubuk Damar Coast, Seruway, Aceh Tamiang (Darmarini et al. 2022), Gili Sulat, East Lombok (Diniyatushoaliha et al. 2024), Ngurah Rai National Park, and Nusa Lembongan in Bali (Wijaya et al. 2024), and Alas Purwo National Park (Rijal et al. 2024).

Carbon stock

The significance of mangrove vegetation's biomass carbon stock stands out as a crucial element in evaluating the role of mangrove ecosystems in addressing climate change challenges. The analysis reveals that the Wakatobi Biosphere Reserve exhibits the biomass and carbon absorption capacities of mangrove forests at 15 kg and 25.30 kg, respectively, with an overall carbon stock of 252.99 kg/m² or 2,529.89 tons/ha. Kaledupa Island exhibits significant carbon absorption capacity and carbon stock, ranging from 2.55 to 3.55 kg, with an average of 315.62 tons/ha. It also demonstrates a higher DBH value, between 3.16 and 7.83 cm, in comparison to Wangi-Wangi Island (3.41-7.96 cm), Tomia (2.07-7.03 cm), and Binongko (1.07-2.19 cm), as shown in Table 5. The findings indicate that Kaledupa Island boasts a robust mangrove ecosystem with significant potential for carbon conservation. In contrast, Wangi-Wangi Island exhibits a slow vegetation growth rate, Tomia Island presents a mix of young and old trees, and Binongko Island is characterized by young vegetation and low regeneration, all of which necessitate rehabilitation efforts to enhance carbon stocks.

Table 2. Composition of mangrove species in the Wakatobi Biosphere Reserve, Southeast Sulawesi, Indonesia

Family	Species	Wangi-Wangi	Kaledupa	Tomia	Binongko
Avicenniaceae	<i>Avicennia marina</i> (Forssk.) Vierh.	+	+	+	+
Meliaceae	<i>Xylocarpus granatum</i> J. Koenig	+	-	-	-
Rhizophoraceae	<i>Bruguiera gymnorhiza</i> (L.) Lam.	+	+	+	-
	<i>Ceriops decandra</i> (Griff.) Ding Hou	-	+	+	+
	<i>Ceriops tagal</i> (Perr.) C.B.Rob.	-	+	+	+
	<i>Rhizophora apiculata</i> Blume	+	+	+	+
	<i>Rhizophora mucronata</i> Lam.	+	+	+	+
Sonneratiaceae	<i>Sonneratia alba</i> Sm.	+	+	+	+

Notes: +: Found; -: Not found

Table 3. The relative density, frequency, dominance, and importance value index of mangrove vegetation on Wangi-Wangi and Kaledupa Island, Wakatobi Biosphere Reserve, Southeast Sulawesi, Indonesia

Strata	No	Species	Wangi-Wangi Island				Kaledupa Island			
			RD (%)	RF (%)	Rd (%)	IVI (%)	RD (%)	RF (%)	Rd (%)	IVI (%)
Tree	1	<i>Avicennia marina</i>	16.67	11.76	11.57	40.00	N/A	N/A	N/A	N/A
	2	<i>Bruguiera gymnorhiza</i>	16.67*	17.65	32.34	66.66	23.81	22.22	45.51	88.10
	3	<i>Rhizophora apiculata</i>	20.83	23.53	16.25	60.62	9.52	11.11	54.40	28.46
	4	<i>Rhizophora mucronata</i>	12.50	17.65	10.16	40.31	52.38*	50.00	132.96	110.21
	5	<i>Sonneratia alba</i>	25.00	17.65	23.89	66.53	9.52	11.11	41.82	60.03
	6	<i>Xylocarpus granatum</i>	8.33	11.76	5.78	25.88	N/A	N/A	N/A	N/A
	7	<i>Ceriops decandra</i>	N/A	N/A	N/A	N/A	4.76	5.56	25.31	13.20
Pole	1	<i>Avicennia marina</i>	11.76	9.52	8.74	30.03	1.75	2.86	1.59	6.20
	2	<i>Bruguiera gymnorhiza</i>	23.53	19.05	30.23	72.81	17.54	20.00	24.92	62.46
	3	<i>Rhizophora apiculata</i>	32.35*	33.33	19.64	85.32	14.04	14.29	10.45	38.77
	4	<i>Rhizophora mucronata</i>	20.59	23.81	25.60	69.99	40.35*	31.43	40.88	112.66
	5	<i>Sonneratia alba</i>	8.82	9.52	14.44	32.79	1.75	2.86	0.92	5.53
	6	<i>Xylocarpus granatum</i>	2.94	4.76	1.35	9.06	N/A	N/A	N/A	N/A
	7	<i>Ceriops decandra</i>	N/A	N/A	N/A	N/A	8.77	11.43	8.72	28.92
Sapling	8	<i>Ceriops tagal</i>	N/A	N/A	N/A	N/A	15.79	17.14	12.52	45.45
	1	<i>Avicennia marina</i>	N/A	N/A	N/A	N/A	1.18	3.85	N/A	5.03
	2	<i>Bruguiera gymnorhiza</i>	1.13	4.65	N/A	5.78	6.16	15.38	N/A	21.55
	3	<i>Rhizophora apiculata</i>	95.11*	79.07	N/A	174.18	12.09	17.31	N/A	29.39
	4	<i>Rhizophora mucronata</i>	3.76	16.28	N/A	20.04	32.70*	25.96	N/A	58.66
	5	<i>Sonneratia alba</i>	N/A	N/A	N/A	N/A	1.66	2.88	N/A	4.54
	6	<i>Ceriops decandra</i>	N/A	N/A	N/A	N/A	24.17	18.27	N/A	42.44
Seedling	7	<i>Ceriops tagal</i>	N/A	N/A	N/A	N/A	22.04	16.35	N/A	38.38
	1	<i>Avicennia marina</i>	N/A	N/A	N/A	N/A	0.94	3.37	N/A	4.31
	2	<i>Bruguiera gymnorhiza</i>	9.43	13.33	N/A	22.77	2.11	13.48	N/A	15.59
	3	<i>Rhizophora apiculata</i>	67.92*	60.00	N/A	127.92	4.30	8.99	N/A	13.29
	4	<i>Rhizophora mucronata</i>	22.64	26.67	N/A	49.31	18.92	29.21	N/A	48.13
	5	<i>Sonneratia alba</i>	9.43	13.33	N/A	22.77	1.02	4.49	N/A	5.51
	6	<i>Ceriops decandra</i>	N/A	N/A	N/A	N/A	33.15	19.10	N/A	52.25
	7	<i>Ceriops tagal</i>	N/A	N/A	N/A	N/A	39.56*	21.35	N/A	60.91

Note: *species with the highest IVI

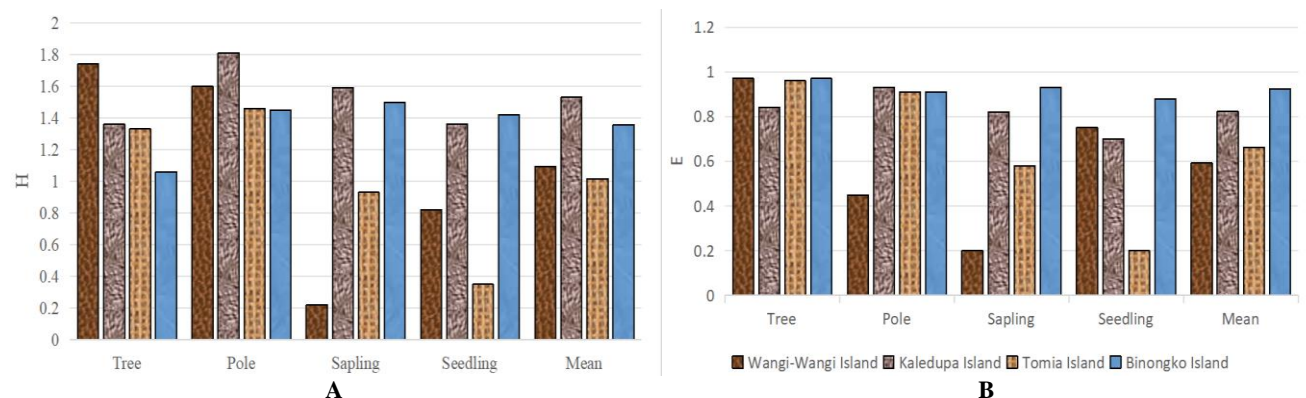


Figure 2. A. Diversity Index; and B. Evenness Index of mangrove vegetation species at various growth strata

Table 4. The relative density, frequency, dominance, and importance value index of mangrove vegetation on Tomia and Binongko Island, Wakatobi Biosphere Reserve, Southeast Sulawesi, Indonesia

Strata	No	Species	Tomia Island				Binongko Island			
			RD (%)	RF (%)	Rd (%)	IVI (%)	RD (%)	RF (%)	Rd (%)	IVI (%)
Tree	1	<i>Avicennia marina</i>	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
	2	<i>Bruguiera gymnorhiza</i>	33.33*	33.33	39.36	106.02	26.67	30.43	29.15	86.25
	3	<i>Rhizophora apiculata</i>	33.33	33.33	31.86	98.53	N/A	N/A	N/A	N/A
	4	<i>Rhizophora mucronata</i>	16.67	16.67	12.24	45.57	26.67	30.43	18.66	75.77
	5	<i>Sonneratia alba</i>	16.67	16.67	16.54	49.87	46.67*	39.13	52.19	137.98
Pole	1	<i>Avicennia marina</i>	15.00	20.00	11.31	46.31	15.22	20.00	12.33	47.55
	2	<i>Bruguiera gymnorhiza</i>	25.00	26.67	36.52	88.18	13.04	25.00	19.78	57.82
	3	<i>Rhizophora apiculata</i>	10.00	13.33	9.09	32.43	8.70	15.00	6.95	30.65
	4	<i>Rhizophora mucronata</i>	N/A	N/A	N/A	N/A	41.30*	15.00	33.35	89.66
	5	<i>Sonneratia alba</i>	10.00	13.33	11.20	34.53	21.74	25.00	27.58	74.32
Sapling	6	<i>Ceriops tagal</i>	40.00*	26.67	31.88	98.55	N/A	N/A	N/A	N/A
	1	<i>Avicennia marina</i>	14.29	22.22	N/A	36.51	12.12	14.71	N/A	26.83
	2	<i>Bruguiera gymnorhiza</i>	3.30	7.41	N/A	10.70	10.61	17.65	N/A	28.25
	3	<i>Rhizophora apiculata</i>	8.79	7.41	N/A	16.20	16.67	20.59	N/A	37.25
	4	<i>Rhizophora mucronata</i>	N/A	N/A	N/A	N/A	36.36*	26.47	N/A	62.83
	5	<i>Sonneratia alba</i>	N/A	N/A	N/A	N/A	24.24	20.59	N/A	44.83
	6	<i>Ceriops decandra</i>	2.20	3.70	N/A	5.90	N/A	N/A	N/A	N/A
Seedling	7	<i>Ceriops tagal</i>	71.43*	59.26	N/A	130.69	N/A	N/A	N/A	N/A
	1	<i>Avicennia marina</i>	47.34	46.15	N/A	93.49	11.95	14.86	N/A	26.82
	2	<i>Bruguiera gymnorhiza</i>	17.75	42.31	N/A	60.06	9.26	14.86	N/A	24.12
	3	<i>Rhizophora apiculata</i>	88.76	73.08	N/A	161.83	10.77	13.51	N/A	24.29
	4	<i>Rhizophora mucronata</i>	N/A	N/A	N/A	N/A	43.60*	37.84	N/A	81.44
	5	<i>Sonneratia alba</i>	11.24	26.92	N/A	38.17	24.41	18.92	N/A	43.33
	6	<i>Ceriops decandra</i>	47.34	30.77	N/A	78.11	N/A	N/A	N/A	N/A
	7	<i>Ceriops tagal</i>	239.05*	76.92	N/A	315.98	N/A	N/A	N/A	N/A

Note: *species with the highest IVI

Table 5. DBH, biomass, and carbon stocks in the Wakatobi Biosphere Reserve, Southeast Sulawesi, Indonesia

Island	Station	DBH (cm)	Biomass (kg)	Carbon (kg)	Carbon sequestration (kg)	Carbon stock	
						kg/m ²	Ton/Ha
Wangi-Wangi	1	3.41	0.30	0.14	0.50	4.98	49.84
	2	7.96	0.50	0.23	0.85	8.46	84.59
Kaledupa	3	4.40	1.88	0.86	3.17	31.68	316.84
	4	4.40	1.88	0.86	3.17	31.68	316.84
	5	5.26	1.98	0.91	3.35	33.46	334.58
	6	3.16	2.10	0.97	3.55	35.48	354.82
	7	7.83	1.51	0.70	2.55	25.50	255.04
Tomia	8	2.07	0.85	0.39	1.44	14.38	143.83
	9	7.03	1.83	0.84	3.08	30.84	308.39
Binongko	10	2.19	1.55	0.71	2.61	26.10	261.03
	11	1.07	0.62	0.28	1.04	10.41	104.09
Total		48.77	15.00	6.90	25.30	252.99	2529.89

The analysis revealed that the average carbon storage and stock of mangroves in the Wakatobi Biosphere Reserve Area is 791.51 tons/ha, equating to a total of 329,182.06 tons for the area. The highest carbon stock was identified on Kaledupa Island (315.62 ha/ha or 317,226.51 tons/area), Tomia Island (226.11 tons/ha or 6,145.78 tons/area), Wangi-Wangi Island (67.22 ha/ha or 3,755.97 tons/area), and Binongko Island (182.56 tons/ha or 2,053.80 tons/area) (Table 6). The carbon value on Kaledupa Island was lower than the findings in the Musi River, which reported 393.59 tons/ha (Farahisa et al. 2021) and 634.54 tons/ha (Imran et al. 2022). However, it was higher than the measurements from

Kemujan Island-Karimun Jawa at 91.31 tons/ha (Cahyaningrum et al. 2014) and the Kema Area of North Sulawesi at 133.76 tons/ha (Kapel et al. 2017). Variations in carbon values are shaped by factors such as vegetation density and tree size, including tree height and diameter (Augusto and Boča 2022). Additionally, the carbon stock of a region is significantly affected by the extent of mangrove areas.

The economic value of mangrove carbon

The estimated price of mangrove carbon within the Wakatobi Biosphere Reserve is derived from carbon trading information sourced from the Indonesia Stock Exchange

(IDX Carbon). On Friday, 3 January 2025, carbon trading concluded at IDR 57,000 per TonCO_{2e}. The IDX Carbon market price, Social Cost of Carbon (SCC), and Voluntary Market (VM) indicate that the carbon price in the Wakatobi Biosphere Reserve stands at IDR 18,763,377,420 or USD 1,159,307, IDR 266,390,582,055 or USD 16,459,103, and IDR 43,155,274,293 or 2,666,375, respectively. Kaledupa Island made significant contributions amounting to IDR 18,081,911,070 or USD 1,117,202 (IDX Carbon), IDR 256,715,553,218 or USD 15,861,326 (SCC), and IDR 41,587,919,621 or USD 2,569,535 (VC), while Binongko Island recorded the lowest contributions at IDR 117,066,600 or USD 7,233, IDR 16,620,376,50 or USD 102,690, and IDR 269,250,099 or USD 16,636 (Table 7). The carbon stock and the extent of mangrove areas play a crucial role in determining the contribution of each island.

The SSC exhibits the highest cost among the economic instruments, amounting to IDR 266,390,582,055 or USD 16,459,103 (Table 6). SSC reflects the community's willingness to invest in preventing the harm associated with increased carbon emissions (Rennert et al. 2021), while the voluntary market price arises from a collective aspiration to reduce carbon emissions (Farahisah et al. 2021). Mangroves' economic value as carbon absorbers has also been studied in several other regions in Indonesia, including IDR 509,599,619,024 or USD 31,279,224.62 on the North Coast of Cawan Island, Indragiri (Emrinelson and Warningsih 2024), and IDR 135,663,899,478.30 or USD 832,705,015.00 in Bintan District (Arkham et al. 2024). This demonstrates that mangroves provide environmental services as big carbon absorbers and have a significant economic value.

Discussion

The diversity of mangrove species in the Wakatobi Biosphere Reserve Area is assessed using the Shannon-Wiener diversity index and the evenness index. The findings of the study indicated that the overall diversity value was 1.25, categorizing it within the moderate class. The findings indicate that the mangrove ecosystem exhibits a considerable diversity of species, with several dominant ones present. However, it's important to note that numerous other species also play a crucial role in shaping the ecosystem's composition. The evenness value stands at 0.75, categorized as high, which suggests a balanced, diverse, and healthy vegetation structure within the ecosystem. This reflects the presence of complex interactions among species that contribute to ecosystem stability and enhance carbon absorption capacity.

The carbon stock value is theoretically positively correlated with tree biomass. The analysis of carbon stocks in mangrove biomass within the Wakatobi Biosphere Reserve indicates a significant correlation between carbon stocks and biomass (Table 7). The study's results indicated that each hectare of land stored carbon at a rate of 2,529.89 tons/ha, with an average of 791.51 tons/ha represented as living biomass. This value represents a significant finding due to the high number of species (Wardle 2016) and the density of mangroves (Adotey et al. 2022), which enhance the capacity for carbon storage and absorption.

The biomass value of plant material is influenced by tree diameter; larger diameters correlate with increased biomass production potential (Ati et al. 2014; Kepel et al. 2017; Dutcă and Mcroberts 2024). The process of photosynthesis enables plants to produce carbon dioxide, which is converted into organic carbon and stored in the biomass of trees. As the age of the stand increases, the carbon reserves accumulate, and the absorption of carbon dioxide from the atmosphere persists (Kepel et al. 2017; Carnell et al. 2022). Furthermore, factors such as soil conditions (Harefa et al. 2022), nutrient availability (Alongi et al. 2016), water salinity (Amanda et al. 2021), climate conditions (Alongi 2022), types of disturbances and their intensity (Zakaria et al. 2018), and management systems, including conservation and restoration efforts (Liu et al. 2018), positively influence carbon storage and absorption.

Soil, nutrients, and salinity significantly influence the growth of mangrove vegetation and biomass. Mangrove vegetation struggles to thrive in high salinity environments, as these conditions require greater energy expenditure to maintain water balance and ion concentration, detracting from growth and primary production. In contrast, at low salinity, energy is more effectively utilized for growth and primary production (Supriyantini et al. 2018).

Table 6. Total carbon stock in the Wakatobi Biosphere Reserve Area, Southeast Sulawesi, Indonesia

Island	Area (Ha)	Diversity value		Carbon stock (Ton)	
		H'	E'	Average	Total area
Wangi-Wangi	55.88	1.10	0.59	67.22	3,755.97
Kaledupa	1,005.09	1.53	0.82	315.62	317,226.51
Tomia	27.18	1.02	0.66	226.11	6,145.78
Binongko	11.25	1.36	0.92	182.56	2,053.80
Mean		1.25	0.75		
Total	1,099.40			791.51	329,182.06

Table 7. The economic value of mangrove carbon in the Wakatobi Biosphere Reserve Area, Southeast Sulawesi, Indonesia

Islands	Carbon stock (TonCO _{2e})	IDX carbon (IDR 57,000/TonCO _{2e})		Social cost of carbon (\$50/TonCO _{2e})		Voluntary market (\$8.1/TonCO _{2e})	
		IDR	USD	IDR	USD	IDR	USD
Kaledupa	317,226.51	18,081,911,070	1,117,202	256,715,553,218	15,861,326	41,587,919,621	2,569,535
Tomia	6,145.78	350,309,460	21,644	4,973,472,465	307,289	805,702,539	49,781
Binongko	2,053.8	117,066,600	7,233	1,662,037,650	102,690	269,250,099	16,636
Total	329,182.06	18,763,377,420	1,159,307	266,390,582,055	16,459,103	43,155,274,293	2,666,375

Climate factors such as rainfall and temperature can enhance carbon storage by boosting primary productivity, which in turn influences mangrove growth and biomass. This leads to increased organic matter input from litter and roots in mangrove sediments (Wang et al. 2021). The age of a plant shows a positive relationship with both its carbon storage value and the rate at which it accumulates carbon.

Management systems for mangrove ecosystems can enhance carbon absorption in them. Nonetheless, activities carried out by humans, including logging, infrastructure development, and the conversion of land for aquaculture in the vicinity of mangrove forests, can significantly harm vegetation. This, in turn, diminishes the forest's ability to store and absorb carbon (Harishma et al. 2020; Amanda et al. 2021; Zakaria et al. 2021; Islam et al. 2022). Furthermore, natural phenomena like storms, tsunamis, and rising sea levels can lead to erosion and harm to mangrove roots and stems, ultimately diminishing the biomass of the vegetation (Zakaria et al. 2021). The damage to vegetation not only removes current carbon storage but also interferes with the future carbon absorption process (Hilmi et al. 2021). The capacity of mangrove forests to absorb carbon and regulate carbon dioxide levels in the atmosphere is significantly affected, leading to detrimental consequences for climate change mitigation efforts.

Indonesia has committed to reducing carbon emissions by 31.89% and 43.20% in its efforts to address climate change by 2030 under unconditional and conditional mitigation scenarios (KLHK 2022). The forestry sector, recognized as the primary source of emissions, is projected to account for as much as 60% of the overall reduction target (Arifanti et al. 2021). The Long-Term Strategy for Low Carbon and Climate Resilience (LTS-LCCR) 2050 is designed to achieve the Nationally Determined Contribution (NDC) target for the forestry sector through the prevention of deforestation and degradation, as well as the restoration of mangrove forests. Mangrove forests constitute around 2.6% of Indonesia's overall forest area. Yet, they play a crucial role in mitigating emissions from the forestry and other sectors, contributing to a reduction of 6.5% (497 TonCO₂e) and 3.9% (834 TonCO₂e) by 2030, respectively (Arifanti et al. 2021). The protection and restoration of mangroves are essential not only for addressing climate change but also for providing economic advantages.

The Wakatobi Biosphere Reserve has a high economic value of carbon, with potential values of IDR 18,763,377,420 or USD 1,159,307 (IDXCarbon), IDR 266,390,582,055 or USD 16,459,103 (SSC), and IDR 43,155,274,293 or USD 2,666,375 (CV). The findings indicate that the mangrove ecosystem, recognized for its significant carbon absorption capabilities, also possesses considerable economic value (Table 7). The significant economic potential can serve as an extra avenue for local revenue generation in Wakatobi Regency. Moreover, Wakatobi features a wide array of coral reefs and seagrass beds that play a crucial role in carbon absorption and storage, often referred to as blue carbon. With sustainable management of blue carbon, the economic potential of Wakatobi Regency could significantly increase, in addition

to the tourism sector, which has been the primary source of local revenue to date.

In conclusion, this study emphasizes the ecological and economic value of the Wakatobi mangrove ecosystem, which spans 10,994 hectares and contains a diverse species composition. *Sonneratia alba*, *Rhizophora mucronata*, *Bruguiera gymnorrhiza*, and *Ceriops tagal* contribute significantly to carbon storage. The estimated carbon stock is 329,182,06 tons, with the largest at Kaledupa (317,226,51 tons) and the lowest at Binongko (2,053.8 tons). Economic value ranges from IDR 18,763,377,420 or USD 1,159,307 (IDX Carbon) to IDR 266,390,582,055 or USD 16,459,103 (SCC). Future research should look into the role of coral reefs and seagrass in blue carbon storage, and combining carbon trading policies with community-based conservation can boost sustainability and regional income.

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