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Adaptive Capacity of Mangrove Ecosystems on Mare Island Tidore Islands City

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ABSTRACT

Adaptive capacity refers to the ability of mangrove ecosystems to respond and adjust to environmental changes, whether driven by natural processes or anthropogenic influences. Mare Island, one of the small islands within the Tidore Islands City region, has been designated as a marine conservation area. However, to date, no specific research has been conducted to assess the adaptive capacity of coastal ecosystems, particularly mangrove ecosystems, in this area. Therefore, this study is essential for evaluating the adaptive capacity of mangroves as part of a sustainable ecosystem management strategy. The primary objective of this research was to quantify and analyze the adaptive capacity of the mangrove ecosystem on Mare Island, Tidore Islands City. Data collection on mangrove ecosystems was conducted through field surveys using the line transect method combined with quadrat sampling techniques and Geographic Information System (GIS) analysis. The assessment of mangrove adaptive capacity was carried out by measuring key parameters that influence the resilience and sustainability of the ecosystem. These parameters include the Mangrove Dimension Index, Average Mangrove Width, Mangrove Zonation, Tree Density, Number of Genera, Substrate Type, and the Proximity of Mangrove Ecosystems to Human Activities. Based on the assessment of seven key parameters, the overall adaptive capacity of the mangrove ecosystem was recorded at 0.504, classifying it as "Moderate." These findings suggest that the mangrove ecosystem has limited capacity to respond to external pressures, including anthropogenic activities and environmental changes. Additionally, the relatively low adaptive capacity highlights the vulnerability of mangrove ecosystems in coastal areas, particularly on small islands, emphasizing their critical condition and the urgent need for conservation efforts.

INTRODUCTION

Mangroves that thrive in the coastal areas of small islands have an important role in providing a variety of ecosystem services that support human well-being. However, its sustainability is increasingly threatened by human activities and the impact of climate change. As a highly productive coastal ecosystem, mangroves contribute to maintaining a balance between humans and the environment and support various crucial ecosystem services **(Neogi *et al*., 2017)**.

One of the main aspects that determines the sustainability of this ecosystem is adaptive capacity, which is the ability of mangrove ecosystems to adapt to environmental changes, both caused by natural and anthropogenic factors. Factors that contribute to the adaptive capacity of mangroves include the level of sedimentation, the ability to absorb and accumulate organic matter, and the hydrological and geomorphological dynamics that support their survival **(Alongi, 2015)**. Mangroves are highly resistant to environmental changes, including salinity fluctuations, temperature variations, and sea level rise. Research shows that these ecosystems can withstand sea level rise by utilizing sedimentation mechanisms and root biomass production that help maintain substrate stability **(Neogi *et al*., 2017)**.

The response of mangroves to climate change depends heavily on their capacity to maintain ecological balance through increased sedimentation and biomass accumulation. However, uncontrolled human activities, such as land conversion for aquaculture, timber exploitation, and urbanization, can reduce this adaptive capacity. Increasing external pressures have the potential to accelerate the degradation of mangroves, reduce their ability to absorb carbon, and weaken the function of their ecosystem in protecting coastlines from abrasion and natural disasters **(Alongi, 2015)**.

Mangroves also have a very important ecological and economic role in coastal areas and on small islands. One of its main functions is as a natural fortress that protects coastal areas from the impact of disasters such as hurricanes, high waves, and tsunamis, thus reducing risks to coastal communities **(Subur *et al*., 2022)**. In addition, complex mangrove root systems help resist erosion and stabilize coastlines, thus contributing to maintaining the sustainability of coastal ecosystems and protecting infrastructure and settlements from abrasion **(Suharno & Saraswati, 2020)**. Mangrove ecosystems are also important habitats for various species of flora and fauna, including some that are endangered. In addition, mangroves have high economic value because they provide biological resources such as fish, shellfish, and wood, as well as opening new opportunities in the ecotourism and recreation sectors, which have a positive economic impact on coastal communities **(Alappatt, 2008)**.

Mare Island, which is within the administrative area of the city of Tidore Islands, has been designated as a conservation area. However, until now there has been no specific study that discusses the adaptive capacity of mangrove ecosystems in the region. Therefore, this study was conducted to calculate the adaptive capacity of mangrove ecosystems on Mare Island, Tidore Islands City, to support sustainable management strategies.

MATERIALS AND METHODS

1. Place and time of research

This research was carried out in Mare Island, Tidore Islands City. The research implementation time was 8 months from May to December 2024.

2. Data collection

Data collection on mangrove ecosystems was generally carried out directly at the research site using the line transect method with a square sampling technique and GIS analysis. The measurement of the adaptive capacity of the mangrove ecosystem was carried out by measuring the parameters assumed to affect the high and low capacity of the ecosystem. The data analyzed include the mangrove dimension index; mangrove thickness (km); and the distance of the ecosystem from human activities (km), measured and analyzed using GIS; mangrove zoning; density (trees/ha); number of genera, measured and calculated using a combination of line transect and quadrat techniques; substrate type, observed directly in the research location.

Mangrove Adaptive Capacity was assessed using 7 parameters consisting of: (1) Mangrove dimension index (MgDI), weighted 5; (2) average mangrove thickness (km), weighted 5; (3) mangrove zonation, weighted 5; (4) Tree density/ hectare, weighted 3; (5) number of genera, weighted 3; (6) substrate type, weighted 1; (7) distance of mangrove ecosystem from human activities, weighted 1. All these parameters were classified into 5 categories with an ordinal scale, namely "very low (1), low (2), medium (3), high (4), and very high (5)". The maximum value of all the above parameters was 115 (N_{max}: 115). The maximum value was obtained by multiplying the weight of each parameter by the highest scale/ score value.

3. Data analysis

The mangrove dimension index (MgDI) was calculated using the equation of **Subur (2012)** as follows:

$$\mathrm{MgDI} = \sum \left[\frac{NL}{SL}\right] + \sum \left[\frac{NP}{SP}\right]$$

Where:

MgID : Mangrove dimension index
NL : The total sum of all the values of the thickness dimension segment
SL : Total number of thickness dimension segments
NP : Total sum of all dimension segment values length
SP : Total sum of length dimension segments

The MgID was in the range between 0.0-2.0, and was classified into five categories, namely "Very Low (0.0≤MgDI≤0.4)"; "Low (0.4≤MgDI≤0.8)"; "Medium (0.8≤MgDI≤1.2)"; "High (0.2≤MgDI≤0.6)", and "Very high" (1.6≤ MgDI≤ 2.0)".

The measurement of the adaptive capacity of mangrove ecosystems (ACMg) was calculated using the equation of **Subur (2012)** as follows:

$$ACMg = \sum \left[\frac{N_i}{N_{max}}\right] x100\%$$

Where:
ACMg : Adaptive capacity of mangrove
Ni : Total value of parameter measurement results
N_{max} : Maximum value.

The adaptive capacity of mangroves (ACMg) was in the range between 0.0-1.0, and it was classified into five categories, namely "Very Low (0.0≤ACMg≤0.2)"; "Low (0.2≤ACMg≤0.4) "; "Medium (0.4≤ACMg≤0.6)"; "High 0.6≤ACMg≤0.8", and "Very high" (0.8≤ACMg≤1.0".

RESULTS

1. Mangrove dimension index

The results of the analysis of mangrove dimensions obtained on Mare Island, Tidore City, Islands obtained a Dimension Index value of 0.094 which shows that the vertical and horizontal distribution of mangroves is classified as "very low". The distribution of mangroves in Mare Island can be seen in Fig. (1) and Table (1).

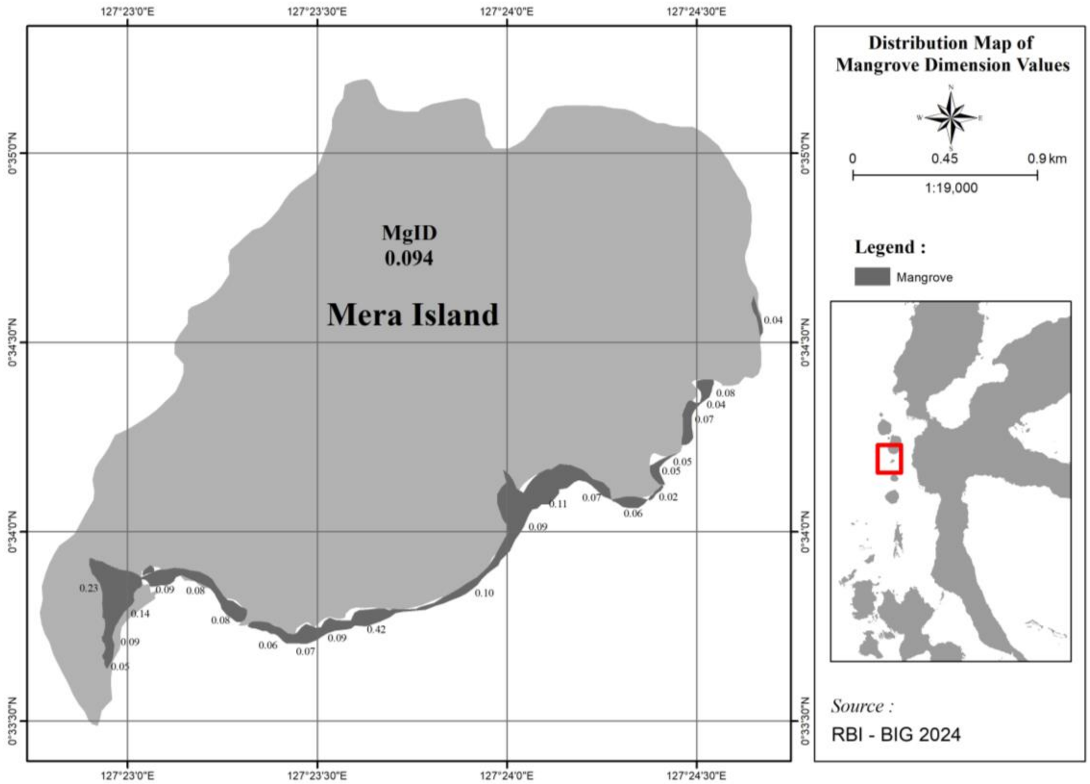

Fig. 1. Distribution of mangrove dimension values for Mare Island

Table 1. Results of vertical and horizontal dimension measurements of mangroves on Mare Island

No.	Vertical (m)	Vertical dimension value	Horizontal (m)	Horizontal dimension value
1	19.63	0.02	194.49	0.02
2	63.85	0.07	77.55	0.01
3	28.655	0.03	51.72	0.01
4	46.485	0.05	213.6	0.02
5	32.195	0.04	75.79	0.01
6	39.03	0.04	101.16	0.01
7	9.77	0.01	98.11	0.01
8	36.095	0.04	179.2	0.02
9	48.855	0.05	192.14	0.02
10	72.8	0.08	299.28	0.03
11	69.93	0.07	217.13	0.02
12	34.885	0.04	710.83	0.06
13	37.635	0.4	199.88	0.02

14	53.825	0.06	192.67	0.02
15	51.325	0.06	111.92	0.01
16	37.48	0.04	238.53	0.02
17	55.065	0.06	136.43	0.02
18	44.865	0.05	294.82	0.03
19	63.33	0.07	138.6	0.02
20	209.09	0.21	174.62	0.02
21	116.78	0.12	133.79	0.02
22	61.345	0.07	193.05	0.02
23	35.72	0.04	46.95	0.01
Total:		**1.726**		**0.45**
Length (m)			**4.272.26**	

Table (1) shows that the average vertical growth of mangroves ranged from 9.77 to 209.09 meters toward the sea, with a measured length of about 4.272.26 meters along the southern coast of Mare Island.

2. Mangrove thickness

The results of the analysis of the thickness of mangroves on Mere Island showed that the average thickness was 39.64 meters and was classified as "very low". This is due to the limited distribution of substrates, thus limiting the growth of mangroves.

3. Mangrove zoning

The zone formed in the mangrove forest community on Mare Island is *Rhizophora* which is classified as having a "high" adaptive capacity, or high adaptability. Mangrove ecosystems, found in tropical and subtropical coastal regions, are renowned for their unique adaptations and important ecological roles. These dynamic habitats exhibit different zoning patterns, with species groups varying along the gradient from the zone towards the sea to the land **(Alappatt, 2008; Ginantra *et al*., 2020; Sreelekshmi *et al*., 2020)**.

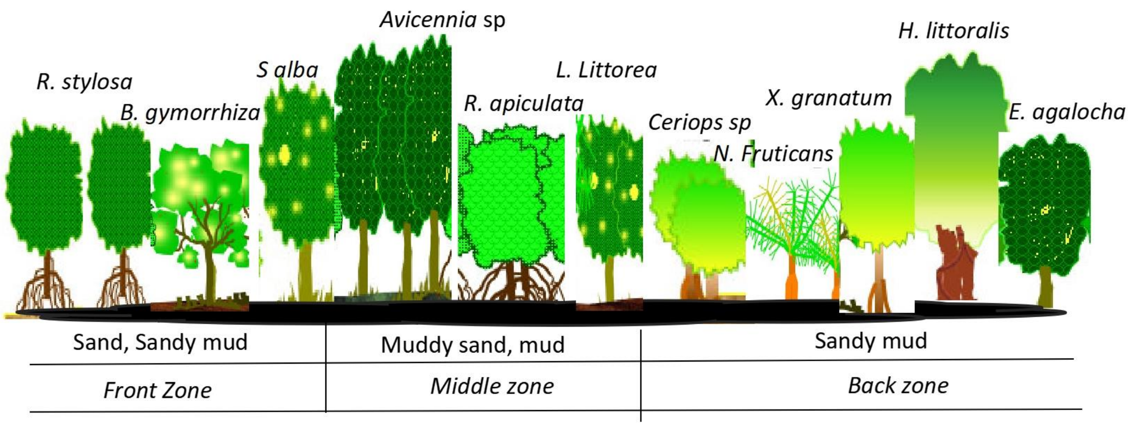

Fig. 2. Mangrove zoning on Mare Island

The image above shows that the zonation formed in the front zone is dominated by *Rhizophora stylosa* associated with Sonneratia alba, and the middle zone is dominated by *Avicennia* sp. associated with *Rhizoporha apicullata*; in addition, the back zone is dominated by Ceriops sp. associated with *Nypa fruticans*, *Heritiera littoralis*, and *Excoecaria agallocha*.

4. Tree density

The results of the calculation of the density of mangrove trees on Mare Island ranged from 330-660 trees per hectare, classified as having a "Medium" density. This condition occurs because the residents on the island have an awareness to protect mangroves as natural fortresses against wave activities and sea currents that previously eroded the coastline so that aberration occurred. According to **Ginantra *et al*. (2020)**, mangrove forests are highly productive ecosystems and provide important services for coastal communities, including shoreline protection, carbon sequestration, and nursery habitats for various marine organisms.

5. Number of genera

The results of this study found as many as 10 genera from 8 mangrove families in Mare Island and classified as "high", consisting of the genus *Rhizophora*, *Bruguiera*, *Ceriops*, *Sonneratia*, *Xylocarpus*, *Avicennia*, *Heritiera*, *Lumnitzera*, *Nypa*, *Exocoecaria*, and found as many as 13 species (Table 2).

Table 2. Mangrove species found on Mare Island

Family	No.	Genus	Species	Name	
				Indonesia	Local
Rhizophoraceae	1.	*Rhizophora*	*Rhizophora apiculata*	Bakau kacang	Halaro
	2.		*Rhizophora stylosa*	Bakau	Halaro puha
	3.	*Bruguiera*	*Bruguiera gymnorrhiza*	Tanjang merah	Dau
	4.	*Ceriops*	*Ceriops decandra*	Tengar	Ting
	5.		*Ceriops tagal*	Tengar	Ting
Sonneratiaceae	6.	*Sonneratia*	*Sonneratia alba*	Pedada	Posi-posi
Meliaceae	7.	*Xylocarpus*	*Xylocarpus granatum*	Kira-Kira	Tanga
Avicenniaceae	8.	*Avicennia*	*Avicennia officinalis*	Api-api	Wika-wika
	9.		*Avicennia marina*	Api-api	Wika-wika
Sterculiaceae	10.	*Heritiera*	*Heritiera littoralis*	Dungun	Rum
Combretaceae	11.	*Lumnitzera*	*Lumnitzera littorea*	Teruntum	Tawabi
Arecaceae	12.	*Nypa*	*Nypa fruticans*	Nipah	Bobo
Euphorbiaceae	13.	*Exocoecaria*	*Exocoecaria agalocha*	Kayun wuta	Bolo

6. Substrate type

The results of the study showed that the types of substrates overgrown with mangroves on Mare Island varied but with a limited area, so that 13 species from 10 genera and 8 families were found. As an island with a very small size (micro), the number of these species is quite high (Table 1).

7. Distance of mangrove ecosystems from human settlements

The results of measuring the distance between residential areas and mangrove ecosystems on Mare Island are around 0 – 1km.

8. Adaptive capacity of mangroves in Mare Island

Based on the analysis of seven parameters to assess the adaptive capacity of mangroves, the results of the analysis of the adaptive capacity of mangroves on Mare Island obtained a value of 0.504, classified as "Moderate".

DISCUSSION

The results of the analysis of mangrove dimensions for Mare Island, Tidore Islands City, obtained a dimension index value of 0.094, which shows that the vertical and horizontal distribution of mangroves is classified as "very low". This is because mangroves on Mare Island are only found in the southern part of the island which is relatively protected from waves and currents and the existence of barrier coral reefs, so that the substrate as a medium for mangrove growth can be maintained and mangroves can grow well. Meanwhile, in other parts of Mare Island, it is quite open so that wave & current activities cause no deposition of the underlying substrate that is possible for mangrove growth. The substrate is the core of the ecosystem and is the foundation for all mangrove communities to thrive **(Menéndez *et al*., 2020; Suharno & Saraswati, 2020)**.

Mangrove growth vertically affects the ability of mangrove ecosystems to protect coastlines from erosion, natural disasters, and provide diverse habitats. Meanwhile, the horizontal distribution of mangroves supports ecological sustainability and increases ecosystem resilience to environmental fragmentation and pressure. These dimensions together affect the adaptive capacity of mangroves, especially on small islands that are more vulnerable to the impacts of climate change and human activities **(Duke *et al*., 2020)**.

Mangrove tree density plays an important role in increasing the adaptive capacity of mangrove ecosystems in coastal areas, especially on small islands. This adaptive capacity refers to the ability of mangroves to respond and adapt to environmental changes, including climate change, sea level rise, as well as anthropogenic pressures such as land conversion and pollution **(Alongi, 2012; Subur, 2012)**.

The diversity of mangrove species on small islands is extraordinary, with some regions having 38 different species, including associated mangroves **(Alappatt, 2008)**. This is an evidence of the remarkable adaptability and resilience of coastal ecosystems, which face a unique set of environmental stresses, such as tidal inundation and frequent salinity conditions **(Triest *et al.*, 2021)**.

Mangrove forests in small islands not only store rich biodiversity but also provide important ecosystem services, including coastal protection, carbon sequestration, and nutrient cycling **(Alongi, 2015; Rahman & Mahmud, 2018)**. These services are critical to the overall health and environmental resilience of these vulnerable islands **(Dabalà *et al*., 2023)**.

Understanding the diversity of mangrove species on small islands is essential for effective conservation and management **(Dabala *et al*., 2023)**. By becoming familiar with the unique adaptations and ecological roles of these species, we can develop targeted strategies to safeguard these critically valuable ecosystems, ensuring their survival and the preservation of the biodiversity they support **(Alappatt, 2008)**. One of the key factors that is getting more attention is the role of substrate diversity in the growth and development of mangroves **(Loughland *et al*., 2020)**. Mangroves thrive in a variety of substrates, ranging from muddy sediments to sandy and coarse-grained soils. The composition and heterogeneity of substrates can have a significant impact on the growth, distribution, and resilience of mangrove communities **(Dewiyanti *et al*., 2021)**. Substrates with a higher diversity of particle size and organic matter content can provide a more favorable environment for the formation and growth of mangrove seedlings **(Krauss *et al*., 2008; Auni *et al.*, 2020; Dewiyanti *et al.*, 2021)**.

The availability of diverse substrates can also facilitate the spread of mangroves by providing a variety of microhabitats suitable for different species and life stages **(Krauss & Allen, 2003Auni *et al*., 2020; Dewiyanti *et al.*, 2021)**.

Several studies have explored the relationship between substrate diversity and mangrove dynamics. For example, a study in tropical estuaries found that areas with fine-grained and coarse-grained sediment mixtures favored greater diversity and productivity of mangroves compared to more homogeneous substrate conditions **(Lee *et al*., 2014)**. Similarly, research in mangrove forests in Southeast Asia revealed that heterogeneous substrates, characterized by a mixture of mud, sand, and organic matter, are associated with greater resilience of mangroves to sea level rise **(Winterwerp *et al*., 2020)**. According to **Hamilton *et al*. (2023**) and **Gajre *et al*. (2024)**, the greater resilience of mangroves to sea-level rise is likely due to the increased capacity of diverse substrates to trap sediments and facilitate elevation gains, allowing mangrove forests to offset sea level rise.

Substrate diversity can also play an important role in the formation and early development of mangrove seedlings, which is an important life stage for these ecosystems. Mangroves thrive in a variety of tidal environments, from muddy estuaries to coral sandy beaches **(Krauss *et al.*, 2008)**.

One of the factors that may have a significant impact on the health and resilience of mangrove ecosystems is the proximity of residential areas to these critical habitats **(Osorio *et al.*, 2016)**.

The distance between residential areas and mangrove forests can have a big impact on the condition and function of the mangrove ecosystem. Mangrove forests located close to human settlements are more susceptible to direct disturbances, such as encroachment, resource extraction, and pollution **(Alongi, 2002; Prakash & Chauhan, 2017)**. As residential areas expand, mangrove habitats can become increasingly fragmented and isolated, reducing mangroves' ability to provide important ecosystem services and support the diverse species that depend on them **(Lee *et al*., 2014; Kelleway *et al.*, 2017)**. On the other hand, mangrove forests located far from residential areas may be less vulnerable to direct human impacts, so mangrove forests can thrive and maintain their ecological integrity **(Lee *et al.*, 2014; Suharno & Saraswati, 2020)**. The proximity of human settlements to mangrove forests can have far-reaching consequences on the balance of mangrove ecosystems (**Lee *et al*., 2014)**.

This condition shows that mangrove ecosystems have limitations in responding to external pressures, both from human activities and environmental changes. In addition, the low adaptive capacity indicates that mangrove ecosystems in coastal areas, especially on small islands, are in critical condition and are at high risk. Efforts to increase vegetation density, improve hydrology, and protect mangrove habitats from human interference are essential to increase their adaptive capacity and maintain the function of these ecosystems in the face of environmental changes.

Mangroves with low adaptive capacity tend to be more vulnerable to sea level rise. When mangroves' ability to capture sediment and expand root areas is disrupted, these ecosystems are unable to adapt quickly to changes in coastlines. This can cause mangrove ecosystems to be submerged in seawater or eliminated by abrasion, which can ultimately destroy these habitats **(Gilman *et al*., 2008)**.

CONCLUSION

Analysis of seven parameters to assess the adaptive capacity of mangroves on Mare Island obtained a value of 0.504, classified as "Moderate". This condition shows that mangrove ecosystems have limitations in responding to external pressures, both from human activities and environmental changes.

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