Original Research Article

Recruitment index as a novel approach to assessing the resilience of natural mangrove ecosystems: A case study on the coast of West Muna Regency

Abstract

This study aims to determine the resilience of mangrove ecosystems with a recruitment index approach on the coast of West Muna Regency. The recruitment index in mangrove ecosystems reflects the comparison between the number of newly established mangrove seedlings and saplings and the number of mature mangroves. The research method used quadrant transects (10 x 10 m^2). Analysis of the resilience index is based on the recruitment index (RI) with the equation RI = Ln ((0.7 x DSd/DT.)+ (DSp/DT)). The results showed that the mangrove ecosystem in all stations had a high resilience with an RI value of 1.43 for station I, 1.38 for station II, 1.07 for station III, and 1.05 for station IV. Meanwhile, mangrove species with very high resilience categories are *B. gymnorrhiza* (RI = 1.70) and *B. cylindrica* (RI = 1.63). In comparison, the resilience of *S. alba* (RI = 0.90) and *R. stylosa* (RI = 1.22) is classified as medium and high resilience, respectively. Based on the RI value, the mangrove ecosystem on the coast of West Muna Regency is in the high resilience category (RI = 1.25 ± 0.20). It indicates that the mangrove ecosystem on the coast of West Muna Regency has good regeneration and growth abilities, so it can recover even when under ecological pressure.

Keywords: Mangrove ecosystem, mangrove management, recruitment index, resilience.

Introduction

Mangrove ecosystems play an essential role in marine life (Nordhaus et al., 2006) and coastal communities by provisioning various ecosystem services (Owuor et al., 2019; Handayani et al., 2020). Some essential services of mangrove ecosystems include the providing of biodiversity (Sievers et al., 2023; Rahman et al., 2024a), carbon sequestration (Choudhary et al., 2024; Rahman et al., 2024b), coastal protection (Damastuti et al., 2023; Morris et al., 2023; van Hespen et al., 2023; Anu et al., 2024), wind and wave storm breakers (Sunkur et al., 2023; Rahman et al., 2024c), as well as providers of firewood, honey, fruit, fooder, and traditional medicine (Nyangoko et al., 2022).

The availability of mangrove ecosystem services triggers socio-ecological interactions that cause the degradation of mangrove ecosystems, such as declining density, species diversity, and mangrove area (Rahman et al., 2020a). However, mangrove ecosystems can maintain ecological conditions or renew themselves after being pressured by anthropogenic activities formed in these ecological social interactions. The ability to recover is known as resilience (Holling, 1973). Resilience is the ability of environmental systems to cope with disturbances and changes and return to stable conditions or adapt to new situations (Holling et al., 2002). Studies on the resilience of mangrove ecosystems that have been reported analyze the level of resilience based on ecological pressures caused by several factors, such as sea level rise (Yulianti et al., 2013) and storm waves (Lagomasino et al., 2021). The determination of the level of resilience in the study refers to several ecological aspects, especially the density, thickness, and diversity of species (Irwansyah et al., 2023).

One aspect that needs to be understood in the mangrove ecosystem resilience study is the ability of ecosystems to renew and maintain existing mangrove plant populations. It can be measured through the recruitment index, which is one of the indicators of the health of the mangrove ecosystem. The recruitment index in mangrove ecosystems can compare the number of newly grown mangrove plants (seedlings) and mangrove saplings with the number of adult mangroves (Rahman et al., 2019). The availability of seedlings and their ratio to mangrove density represents the ability of mangroves to be resistant and resilient to ecological disturbances such as marine debris inputs, changes in water quality, timber, land conversion, and other environmental stresses. In addition, it can also indicate the resilience of mangrove ecosystems, especially in ecological aspects.

Research on the recruitment index concerning the resilience of mangrove ecosystems has rarely been conducted. This research can help evaluate mangrove ecosystems' health and ability to maintain existing mangrove plant populations. In addition, the results of this study can also be the basis for formulating appropriate management strategies to reduce damage to mangrove ecosystems and increase the resilience capacity of mangrove ecosystems in the future. The research could also provide deeper insights into ways to improve the health of mangrove ecosystems and prevent further damage. For example, by improving environmental quality, reducing human pressure on ecosystems, or protecting critical mangrove areas, as Rahman et al. (2020a) reported.

Materials and Methods

Description of Study Area

This research was conducted in the mangrove ecosystem of West Muna Regency, encompassing four district as study stations: Maginti District (Station I), Tiworo Tengah District (Station II), Tiworo Kepulauan District (Station III), and Sawerigadi District (Station IV) (Figure 1). The selected stations, based on their mangrove area, represent the mangrove ecosystem along the coast of West Muna Regency, with a varying sizes of 372.73 ha at station I, 534.31 ha at station II, 1033.04 ha at station III, and 286.65 ha at station IV.

The dominant mangrove species in the mangrove ecosystem along the coast of West Muna Regency are *B. cylindrica, B. gymnorrhiza, R. apiculata, R. mucronata, R. stylosa,* and *S. alba* (Rahman et al., 2020b). The species has been degraded due to its use as timber, residential areas, and aquaculture from 2014 to 2017 (Rahman et al., 2020a).

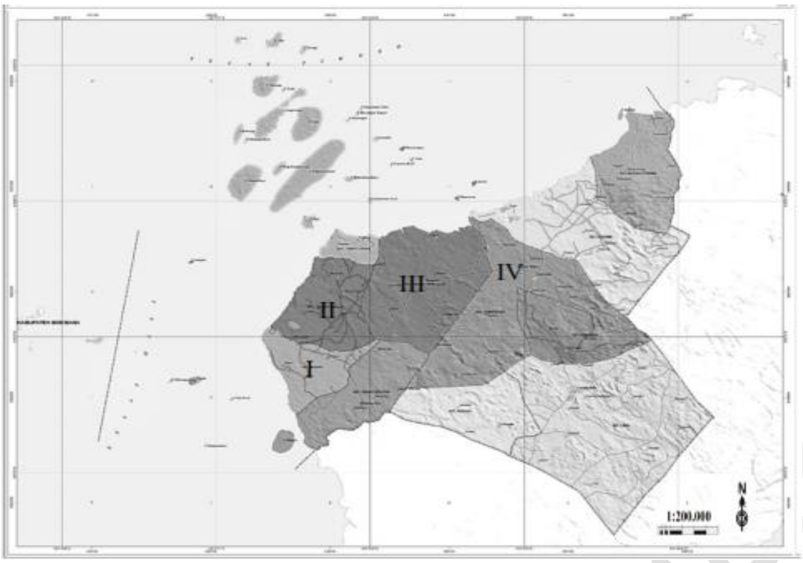

Figure 1. Location map of the West Muna Regency with four studied stations

Sampling Methods

Mangrove ecosystem data was collected using a quadrant plot measuring 10 x 10 m^2, placed by random sampling. The number of quadrants at each location adjusts to the area and condition of the mangrove ecosystem so that 300 quadrants are obtained with a distribution of 60 at station I, 90 at station II, 110 at station III, and 40 at station IV.

Data was collected by counting the number of mangrove stands in all categories. Species identification was carried out based on the morphological characteristics of mangroves, including roots, leaves, flowers, and fruits, as referred to in the manual according to Noor et al. (2006) and Bengen et al. (2022).

The mangrove vegetation structure was observed across three categories: trees, saplings, and seedlings. Each category is classified based on diameter size: D = 1-3 cm for seedlings, D = 3-5 cm for saplings, and D > 5 cm for the tree category. The classification of D > 5 cm as trees is based on observations showing that mangroves can reproduce at this diameter, particularly for the Rhizophora types (**Figure 2**).

Figure 2. Rhizophora mangroves (D ≥ 5 cm) produce propagules as a source of new individuals

Data Analysis

Mangrove Density

Mangrove density in each type of stand was analyzed regarding the equation according to Bengen et al. (2022), namely as follows:

$$D = \frac{\Sigma\, Ni}{A} \quad (1)$$

Where D is mangrove density (stands/ha), Ni is the number of mangroves of each type found in the plot (stands), and A is the area of the plot (ha).

The mangrove density status is classified into five categories according to the criteria by Rahman et al. (2019) as in Table 1 below:

Table 1. The classification of mangrove density status (Rahman et al. 2019)

Density (stands/ha)	Criteria
<500	Very rare
>500 – 1000	Rare
>1000 – 1500	Medium
>1500 – 2000	Dense
>2000	Very dense

Mangrove Resilience and Recruitment Index

The recruitment index in mangrove ecosystems can refer to the comparison between the number of newly growing mangrove plants (seedlings) and mangrove seedlings (saplings) to the number of mature mangroves (Rahman et al. 2019).

Ecologically, each mangrove seedling has a 60 – 80% survival potential or an average of 70% to grow into saplings until they reach a tree type (Bengen et al. 2022). Based on this, the mangrove ecosystem recruitment index can be formulated as follows:

$$RI = \mathrm{Ln}\ ((0.7\ x\ \frac{DSd}{DT}) + (\frac{DSp}{DT})) \qquad (2)$$

Where:

RI = value is the recruitment index

0.7 = the average value of the probability that mangrove seedlings can live to reach tree size (Bengen et al., 2022).

DT = the density of mangroves in the tree category with DT ≠ 0 (stands/ha)

DSd = the density of mangroves in the seedling category (stands/ha)

DSp = the density of mangroves in the sapling category (stands/ha).

Either of DSd and DSp can be equal to zero but not for both.

The criteria for resilience and management actions are based on the value of the Mangrove Recruitment Index (RI.), namely (1) Very low resilience (RI ≤ 0): in this condition, management of the mangrove ecosystem is with complete protection. Efforts to improve mangrove conditions are rehabilitation based on a modification of ecological conditions according to the ability of mangrove species to live; (2) Low resilience (0 <RI ≤ 0.5): In this condition, the management of the mangrove ecosystem is conservation and rehabilitation. Rehabilitation efforts can be carried out in the original habitat according to its natural conditions in the ecosystem; (3) Moderate resilience (0.5 <RI ≤ 1.0): in this condition, mangrove management is conservation with particular uses such as ecotourism or fruit utilization so that mangroves can remain sustainable; (4) High resilience (1.0 <RI ≤ 1.5): in this condition, mangrove management is conservation with limited use. Limited use means that under certain conditions, mangroves can be cut down in small quantities to fulfill the need for wood; (5) Very high resilience (RI > 1.5): in this condition, mangrove management is conservation with medium utilization. Medium utilization means that under certain conditions, the mangrove ecosystem can be converted into aquaculture areas or other areas with a maximum area of 20% of the total ecosystem area (Table 2).

Table 2. Resilience criteria and management actions based on Recruitment Index (RI) values.

R.I. Value	Criteria of Resilience	Management Strategy
$RI \leq 0$	Very low resilience	Protection and rehabilitation
$0 < RI \leq 0.5$	Low resilience	Conservation and rehabilitation
$0.5 < RI \leq 1.0$	Medium resilience	Conservation with a special activity
$1.0 < RI \leq 1.5$	High resilience	Conservation with low utilization
$RI > 1.5$	Very high resilience	Conservation with medium utilization

Result and Discussions

Mangrove Density

Six dominant species were identified in the mangrove ecosystem along the coast of West Muna Regency, including *B. cylindrica*, *B. gymnorrhiza*, *R. apiculata*, *R. mucronata*, *R.*

stylosa, and *S. alba*, consistent with the findings of Rahman et al. (2020). These species dominate across all mangrove categories: trees, saplings, and seedlings. Tree density ranges from 617 to 829 stands/ha, with the highest density observed in Maginti District (829 stands/ha) and Sawerigadi District (808 stands/ha), while the lowest was recorded at stations II and III (617 and 688 stands/ha, respectively) (Table 3).

In the sapling category, the highest density was found in Tiworo Tengah District (1393 stands/ha), while the lowest was at station III (1011 stands/ha). For seedlings, the highest density was recorded in Maginti District (3155 stands/ha) and the lowest in Tiworo Kepulauan District (1421 stands/ha). *S. alba* exhibited the highest tree density (299 stands/ha), while *B. gymnorrhiza* had the lowest (31 stands/ha). In the sapling category, *R. stylosa* had the highest density (433 stands/ha), and *B. cylindrica* the lowest (97 stands/ha). In the seedling category, *R. stylosa* recorded the highest density (736 stands/ha), while *B. cylindrica* had the lowest (37 stands/ha).

According to Ilman et al. (2016) and Arifanti et al. (2021), the low density of mangrove ecosystems is primarily due to land conversion for ponds, settlements, and infrastructure, such as docks and roads. Similarly, Rahman et al. (2020) reported that the degradation of mangrove forests in West Muna Regency, particularly at stations I to IV, is driven by land conversion for aquaculture and residential purposes, as well as infrastructure development.

Table 3. Mangrove density on the coast of West Muna Regency

	Station I			**Station II**			**Station III**			**Station IV**		
Species	D.T.	DSp	DSd	DT	DSp	DSd	DT	DSp	DSd	DT	DSp	DSd
B. cylindrica	43	97	330	38	108	166	34	113	67	57	138	37
B. gymnorrhiza	105	178	467	59	201	133	34	167	154	31	123	87
R. apiculate	180	250	667	106	221	267	144	198	224	75	223	179
R. mucronata	120	143	543	74	163	189	121	133	216	65	227	155
R. stylosa	225	367	736	178	433	427	137	167	312	281	381	584
S. alba	156	233	412	162	267	315	218	233	448	299	133	512
Total	**829**	**1268**	**3155**	**617**	**1393**	**1497**	**688**	**1011**	**1421**	**808**	**1225**	**1554**

Recruitment Index

The highest mangrove species recruitment index (RI) at each station was dominated by *Bruguiera cylindrica* and *Bruguiera gymnorrhiza* species, while the lowest was dominated by *Sonneratia alba*. This disparity is driven by both reproductive processes and biological factors between *Bruguiera* and *Sonneratia* species. *Bruguiera* reproduces through propagules, which are partially developed seedlings that detach from the parent tree, giving them a biological advantage in terms of survival and faster growth upon reaching a suitable substrate. In contrast, *Sonneratia* reproduces through round-shaped fruits, which are more vulnerable to environmental conditions and require specific conditions to germinate. These biological factors, such as differences in dispersal methods and growth success rates, contribute to the variation in resilience and regeneration between these two species (Hogarth, 2007). According to Bengen et al. (2022), the propagules of Bruguiera mangroves, when they fall into the ecosystem areas, are more likely to grow naturally because they easily embed in the mud sediments, which are the typical habitat for these mangroves. Conversely, the fruit of Sonneratia species disperses more quickly due to the current and wave patterns found in the ecosystem area. This rapid dispersal is also related to the presence of Sonneratia species in open zones that directly face ocean currents and waves (Bengen et al., 2022).

The highest RI values were at stations I and II, namely *B. cylindrica*, with respective values of 2.03 and 1.77). The highest RI at stations III and IV was *B. gymnorrhiza*, with R.I. values of 2.09 and 1.78, respectively (Figure 3). The lowest R.I. values at stations I, II, and IV were *S. alba*, namely RI = 1.21 at station I, RI = 1.10 at station II, and RI = 0.50 at station IV. The lowest R.I. at station III were *R. mucronata* and *R. apiculata*, with R.I.s of 0.85 and 0.90, respectively (Figure 3).

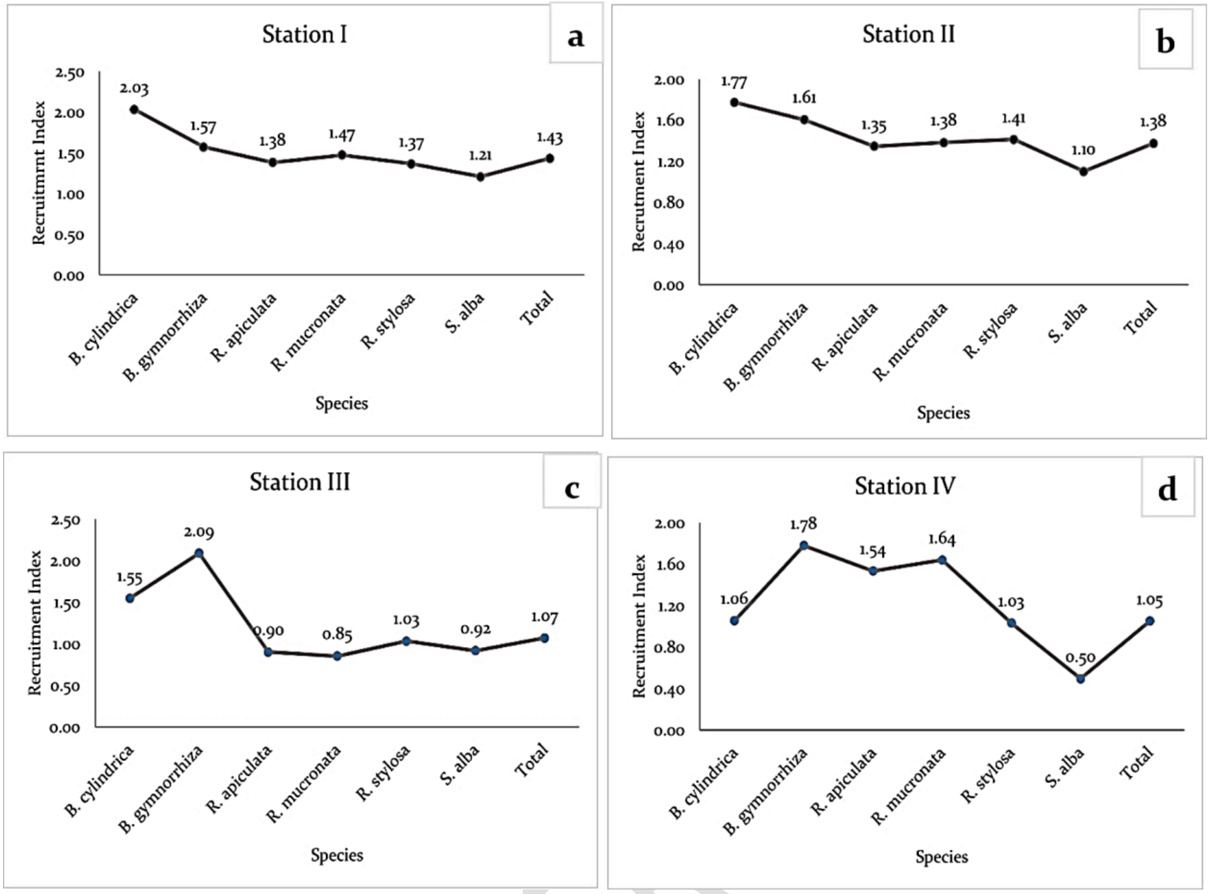

Figure 3. Mangrove species recruitment index at each station along the coast of West Muna Regency

Figure 3 also shows that the highest RI. values for total mangrove forests were found at Maginti district (station I) and Tiworo Tengah district (station II), with values of 1.43 and 1.38. At the same time, stations III and IV were the lowest, with RI values of 1.07 and 1.05, respectively. Meanwhile, the highest RI values for mangrove species on the coast of West Muna Regency were *B. gymnorrhiza* and *B. cylindrica*, with RI = 1.70 and RI = 1.63, respectively. In comparison, the lowest were *S. alba* (RI = 0.90) and R. stylosa (RI = 1.22) (Figure 4).

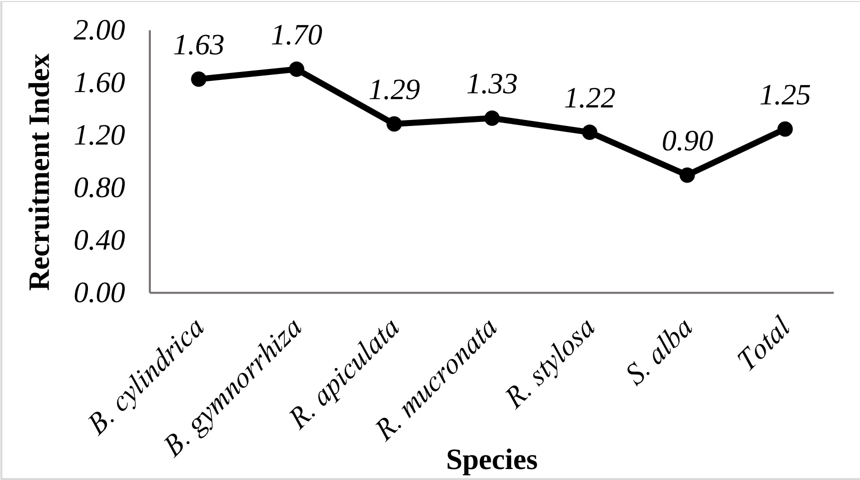

Figure 4. Recruitment Index of mangrove species on the coast of West Muna Regency

An RI of 1.25 in ecological terms indicates the relative success of a species in regenerating and establishing new individuals (seedlings, saplings, or trees) in a specific habitat. A value of RI = 1.25 suggests that the species is relatively stable in its recruitment process, meaning it is successfully producing and sustaining new growth at a rate that allows it to maintain its population under the given environmental conditions.

When compared to other ecosystems, the meaning of an RI of 1.25 can vary:

- In healthy or undisturbed ecosystems, an RI of 1.25 would generally be considered moderate, reflecting adequate species recruitment but perhaps lower resilience compared to species with higher RI values (e.g., 2.0 or higher).
- In stressed or degraded ecosystems, where recruitment is often low due to factors like habitat destruction or pollution, an RI of 1.25 could indicate relatively good resilience and adaptation, as many species may exhibit lower values in such environments.

Ultimately, an RI of 1.25 indicates a species that is regenerating at a steady pace but may not be as competitive or resilient as other species with higher RI values, especially in fluctuating or adverse environmental conditions.

Mangrove Resilience

Mangrove ecosystem resilience is a form of adaptation to various disturbances outside the ecosystem. Disruption to mangrove ecosystems can occur due to human intervention, such as land conversion, and natural disturbances, such as climate change and sea level rise (Alongi 2008; Yulianti et al. 2013; Barik & Gouda 2024).

Based on the RI. value, the mangrove ecosystem on the coast of West Muna Regency is in the high resilience category (RI = 1.25 ± 0.20) (Table 3). The resilience value is based on each stand category's total density (Table 2). The findings indicate that the mangrove ecosystem on the coast of West Muna Regency has good regeneration and growth abilities, so it can recover even when under ecological pressure.

The resilience criteria also indicate that mangroves must be managed wisely, namely conservation-based management with limited use. According to Rahman et al. (2020), the coastal communities of West Muna Regency still often use mangroves as firewood and building materials in residential areas in the mangrove ecosystem area. Conservation-based management with limited use is still included in the criteria for a sustainable management mechanism because it maintains ecological sustainability, supports economic life, and harmonizes the social life of coastal communities in mangrove ecosystem areas or between communities and government stakeholders. Yulianda (2007) states that conservation does not mean complete protection; instead, it uses ecosystems wisely to form a balance between social and ecological systems.

Ali et al. (2020) reported that good social-ecological interactions in managing mangrove ecosystems could achieve sustainable management. Mangroves provide ecosystem services to support people's lives. At the same time, humans as a social system will protect mangrove ecosystems for the sustainability of mangrove ecosystem services by providing direct and indirect economic benefits (Handayani et al. 2020; Nazar et al. 2021).

Table 4. Resilience criteria and management strategies for mangrove ecosystems in the coastal areas of West Muna Regency

Locations	RI value	Criteria	Management Strategy
Station I	1.43	High resilience	Conservation with low utilization
Station II	1.38	High resilience	Conservation with low utilization
Station III	1.07	High resilience	Conservation with low utilization
Station IV	1.05	High resilience	Conservation with low utilization
Total	1.25±0.20	High resilience	Conservation with low utilization

Although this study focuses specifically on the coastal areas of West Muna Regency, the findings offer valuable insights for mangrove conservation efforts on a broader scale. Our results illustrate how the resilience of mangrove species in this region can inform conservation strategies in other locations with similar ecosystem conditions. For instance, species showing high resilience could be prioritized for protection and restoration efforts in areas facing similar threats.

Additionally, it is important to consider whether the observed resilience aligns with global trends or is specific to this region. Comparing our findings with data from mangrove ecosystems worldwide can provide further context on whether the resilience patterns are part of a broader global trend or represent local adaptations. By expanding the discussion of these findings, we aim to contribute more significantly to the global understanding of mangrove ecosystem resilience and inform more effective conservation strategies across various locations.

Conclusion

The findings revealed that the mangrove ecosystems at all stations exhibited high resilience, with RI values of 1.43 for station I, 1.38 for station II, 1.07 for station III, and 1.05 for station IV. *Bruguiera gymnorrhiza* (RI = 1.70) and *Bruguiera cylindrica* (RI = 1.63) demonstrated very high resilience among the mangrove species. In contrast, *Sonneratia alba* (RI = 0.90) were categorized as having medium resilience. Overall, the mangrove ecosystem along the coast of West Muna Regency falls into the high resilience category, with an average RI value of 1.25 ± 0.20. This indicates that the mangrove ecosystem in this region has strong regeneration and growth capabilities, enabling it to recover effectively even under socio-ecological pressure.

While this study focuses on West Muna Regency, the findings offer valuable insights for broader mangrove conservation efforts. The resilience observed in local mangrove species can guide conservation strategies in similar ecosystems elsewhere. Comparing these results with global data will help determine if the resilience patterns are region-specific or part of a larger trend. This expanded perspective will contribute to more effective global conservation strategies for mangrove ecosystems.

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