# THE CONDITION OF MANGROVES IN NORTH MALUKU DUE TO THE INFLUENCE OF CLIMATE CHANGE

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***Abstract:*** *Mangrove environments in North Maluku are essential ecologically, as they sustain coastal productivity, act as developmental areas for sea life, and shield coastlines from water based impacts. Yet, constant climate shifts, marked by increasing sea levels, rising temperatures, changing rainfall amounts, and different salt levels, have increased stress on the stability of mangrove ecology. This research assesses the ecological health of mangrove forests in several areas of North Maluku, focusing on elements such as structural makeup, variety of species, successful sapling growth, condition of the tree cover, and signs of ecosystem stress. On-site data collection was performed using ecological methods such as transect-quadrant sampling, identifying zones, and assessing regeneration potential. The findings reveal considerable structural variations among the areas studies, with some showing lower seedling numbers, canopy decline, and changes in the main species present. Rising sea levels, severe tidal occurrences, coastal wear, and inconsistent salt content were identified as key climate-related factors negatively impacting mangrove health. Although these risks exist, several locations demonstrate ecological strength through natural re establishment and consistent regeneration rates. This study underscores the pressing requirement for management approaches that adapt to climate change, projects aimed at restoration, and conservation efforts driven by the community to guarantee the lasting sustainability of mangrove environments in North Maluku.*

***Keywords:*** **mangrove ecology; climate change; North Maluku; coastal ecosystems; ecological resilience; species composition**

## 1. INTRODUCTION

Mangrove environments stand out as some of the most fruitful and environmentally vital shore based habitats found in warm areas. Throughout Indonesia, mangrove forests blanket extensive zones and support varied life forms, fish populations, carbon capture, and defense of the shoreline. North Maluku, which sits in the eastern portion of Indonesia, is home to a wide array of mangrove types, largely consisting of *Rhizophora*, *Avicennia*, *Bruguiera*, and *Sonneratia*. These environments are being threatened more and more by shifts in the world's climate, which appear as rising sea levels, climbing temperatures, severe weather, and changes in water patterns [1], [2].

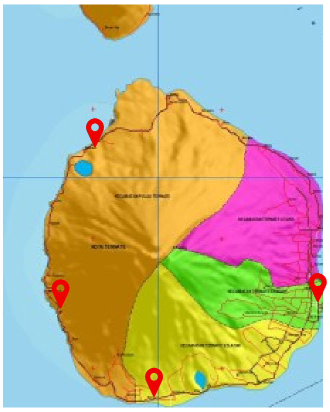
Mangrove ecosystems face various effects from climate change through mechanisms such as physiological strain, altered salt concentration patterns, lower rates of new mangrove growth, and greater land loss [3]. Although prior research has looked into mangrove decline due to human-caused factors, investigations into ecological changes caused by climate in this area are still scarce[4]. It is crucial to know the ecological state of mangroves when considering climate-related stresses to inform effective conservation strategies and policies for long-term sustainability [5], [6].

The purpose of this research is to determine the state of mangrove environments in North Maluku, achieved through the assessment of species makeup, structural characteristics, regeneration situation, and evident effects tied to climate change. The results offer fundamental data that will be helpful when creating protective plans that can withstand climate change effects.

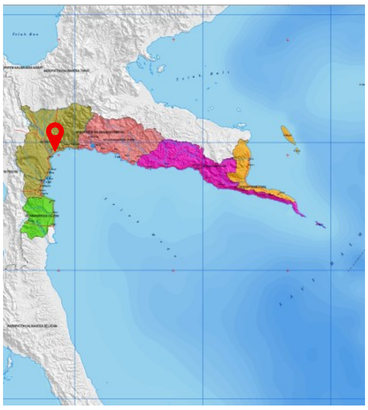
## 2. METHOD

This research was conducted across selected mangrove sites in North Maluku Province, including Ternate city, West Halmahera regency, South Halmahera regency, and Central Halmahera regency. These sites represent varied geomorphological settings, tidal exposure, and climate vulnerability, allowing a comparative ecological assessment.

North Maluku



Ternate Island Map;
Site: Gambesi Village, Kastela Village, Takome Village, Mangga dua Village



Central Halmahera regency Map;
Site: Nusliku Village

South Halmahera Map;
Site: Panambuang Village, Amasing Village, Foya Village

West Halmahera Map:
Site: Talaga Village, Tuada Village

Figure 1. Site location in 4 regency of North Maluku

A purposive sampling approach was used to select representative mangrove stands. Ecological sampling followed standard transect–quadrant methods: Transect lines were established perpendicular to the coastline, covering landward to seaward zones; Quadrants (10 m × 10 m) were used for tree-level vegetation data; Sub-quadrants (5 m × 5 m) recorded saplings; and Smaller quadrants (1 m × 1 m) recorded seedlings .

The following ecological variables were assessed: Species composition and diversity: Shannon–Wiener Index (H'). Structural attributes: tree density, basal area, tree height, and diameter at breast height (DBH), Regeneration capacity: density of seedlings and saplings, Zonation patterns: distribution of species across tidal gradients, Canopy condition: canopy closure, defoliation levels, chlorosis, and signs of dieback, Environmental indicators: salinity, temperature, substrate characteristics, tidal influence.

Climate impact indicators were evaluated through: shoreline retreat and erosion levels, tidal inundation frequency, sediment deposition changes, observed shifts in species zones, extreme weather event history (community-based documentation).

Data analysis was conducted using a combination of quantitative ecological indices, structural metrics, and climate-related stress assessments to comprehensively evaluate the ecological condition of mangrove ecosystems in North Maluku. Several analytical approaches were employed:

a) Vegetation Structure and Composition Analysis, were: Tree Density (ind/ha), calculated by converting the number of individuals in each 10 m × 10 m quadrant to per-hectare density.

b) Diversity and Community Ecology Metrics, were: Shannon–Wiener Diversity Index (H'), Pielou's Evenness Index (J'), Simpson's Dominance Index (D).

c) Ecosystem Resilience Assessment, Resilience was analyzed using qualitative ecological indicators (per Alongi, 2008): natural recolonization ability, species redundancy (multiple species fulfilling similar ecological functions), resistance to salinity fluctuations, observed recovery after disturbances.

## 3. RESULTS AND DISCUSSION

### 4.1. Vegetation Structure

According to the data of vegetation structure, the mangrove community shows a clear dominance pattern, moderate species richness, and an uneven distribution of ecological roles among species.

*Rhizophora apiculata* is the most dominant species in the stand. It present the greatest number of individuals (N = 45) and density (300 ind/ha), it also records the highest Relative Frequency (FR = 22.5%), Relative Density (DR = 28.0%), and Relative Dominance (KR = 25.4%). Consequently, it achieves the highest Importance Value Index (IVI = 75.9%). This indicates that *R. apiculata* plays a key structural and functional role in the mangrove ecosystem, strongly influencing canopy formation, spatial occupation, and overall stand stability.

Secondly, *Rhizophora mucronata* is the second most important species, with an IVI of 61.6%. Although its individual number (N = 32) and density (213 ind/ha) are lower than *R. apiculata*, it still contributes substantially to stand dominance (KR = 18.0%) and density (DR = 24.2%). The co-dominance of these two *Rhizophora* species suggests favorable environmental conditions for this genus, such as stable substrates and regular tidal inundation.

The Third, *Bruguiera gymnorrhiza* occupies an intermediate position within the community. With an IVI of 43.4%, this species shows moderate frequency, density, and dominance values. Its presence indicates a transitional ecological role, contributing to species diversity and structural complexity but not exerting strong dominance over the stand.

Fourth, *Avicennia marina* and *Sonneratia alba* exhibit relatively low IVI values (31.5% and 31.9%, respectively), reflecting their minor contribution to the overall stand structure. Their lower densities and dominance values suggest that these species are either less competitive under the prevailing site conditions or are limited to specific microhabitats within the mangrove area. However, their presence remains ecologically important, as they enhance functional diversity and may serve as pioneer or stress-tolerant species.

Table 1. Mangrove Vegetation Structure Based on Growth Category

| Species | Growth class | Individuals Number (N) | Density (ind/ha) | FR (%) | DR (%) | KR (%) | IVI (%) |
|---|---|---|---|---|---|---|---|
| ***Rhizophora apiculata*** | Tree | 45 | 300 | 22.5 | 28.0 | 25.4 | 75.9 |
| ***Rhizophora mucronata*** | Tree | 32 | 213 | 19.4 | 24.2 | 18.0 | 61.6 |
| ***Bruguiera gymnorrhiza*** | Tree | 18 | 120 | 14.8 | 16.5 | 12.1 | 43.4 |
| ***Avicennia marina*** | Tree | 10 | 67 | 12.4 | 10.8 | 8.3 | 31.5 |
| ***Sonneratia alba*** | Tree | 12 | 80 | 10.9 | 12.0 | 9.0 | 31.9 |

Information:
FR= Frequency; DR= Dominance; KR= Diversity index; IVI= Importance Value Index

Overall, the mangrove stand is characterized by a dominance of *Rhizophora* species, particularly *R. apiculata*, indicating a structurally stable but compositionally uneven community. Such a pattern is typical of mangrove ecosystems subjected to relatively uniform environmental conditions, where a few well-adapted species dominate, while others persist at lower abundance, contributing to resilience and ecological balance.

### 4.2. Diameter and Height Structure

*Rhizophora mucronata* exhibits the highest average DBH (16.1 cm) and the widest DBH interval (7–31 cm), indicating a population composed of both younger and well-developed individuals. This wide diameter range, together with the highest average height (12.2 m) and maximum height (18.0 m), suggests that *R. mucronata* is among the most structurally mature species in the stand and plays a major role in forming the upper canopy layer.

*Rhizophora apiculata* also demonstrates strong growth performance, with an average DBH of 14.2 cm and a DBH range of 5–28 cm. Its average height (10.4 m) and maximum height (16.5 m) indicate a well-established population with good vertical development. Although slightly smaller in stature than *R. mucronata*, *R. apiculata* contributes substantially to canopy continuity and stand density.

*Bruguiera gymnorrhiza* shows moderate growth characteristics, with an average DBH of 12.4 cm and a DBH interval of 4–23 cm. The average height of 9.8 m and maximum height of 14.4 m suggest that this species occupies the mid-canopy layer. Its structural attributes indicate stable growth but relatively lower competitiveness compared to the dominant *Rhizophora* species.

*Sonneratia alba* presents an interesting growth pattern, with a moderate average DBH (11.2 cm) but relatively high vertical development, as reflected by an average height of 11.1 m and a maximum height of 15.1 m. This indicates a tendency toward height growth rather than diameter expansion, which is typical for species adapted to open, more exposed coastal environments.

*Avicennia marina* records the smallest average DBH (10.3 cm) and a narrower DBH interval (3–18 cm), coupled with the lowest average height (8.9 m) and a moderate maximum height (13.2 m). These values suggest a younger or less developed population structure, or growth constraints imposed by site conditions such as salinity or substrate instability.

Table 2. Mangrove Tree Diameter and Height Structure

| Jenis | Average DBH (cm) | DBH Intervals (cm) | Average High (m) | Max height (m) |
|---|---|---|---|---|
| ***Rhizophora apiculata*** | 14.2 | 5–28 | 10.4 | 16.5 |
| ***Rhizophora mucronata*** | 16.1 | 7–31 | 12.2 | 18.0 |
| ***Bruguiera gymnorrhiza*** | 12.4 | 4–23 | 9.8 | 14.4 |
| ***Avicennia marina*** | 10.3 | 3–18 | 8.9 | 13.2 |
| ***Sonneratia alba*** | 11.2 | 4–20 | 11.1 | 15.1 |

Overall, the DBH and height structure indicates a heterogeneous but stable mangrove stand, dominated by *Rhizophora mucronata* and *Rhizophora apiculata* as the main canopy-forming species. The presence of wide DBH ranges across species reflects continuous regeneration and long-term stand development, while differences in height and diameter growth strategies highlight species-specific adaptations to local environmental conditions.

### 4.3. Diversity, Evenness, and Dominance

The diversity indices indicate clear spatial variation in mangrove community structure among the four sampling stations, reflecting differences in species richness, distribution evenness, and dominance patterns.

Station 4 (South Halmahera regency) shows the highest ecological complexity among all stations. With the greatest species richness (S = 7) and the highest total number of individuals (N = 194), this station also records the highest Shannon–Wiener diversity index (H′ = 1.95) and evenness value (E = 0.78). The low dominance index (C = 0.19) indicates that no single species overwhelmingly controls the community. These values suggest a relatively stable and well-balanced mangrove ecosystem with high resilience to environmental disturbances.

Station 1 (west halmhaera regency) ranks second in terms of diversity, with six species (S = 6) and 178 individuals. The Shannon diversity index (H′ = 1.82) and evenness (E = 0.73) indicate a moderately high diversity with a fairly uniform distribution of individuals among species. The relatively low dominance value (C = 0.21) further suggests a stable community structure, although slightly more influenced by dominant species compared to Station 4.

Station 2 (central halmahera regency) exhibits moderate diversity characteristics. Despite having fewer species (S = 5) and individuals (N = 156) than Station 1, it shows a slightly higher evenness (E = 0.75), indicating a more balanced distribution of individuals among species. However, the lower diversity index (H′ = 1.67) and higher dominance value (C = 0.24) imply that community structure is influenced by a limited number of relatively dominant species.

Station 3 (Ternate city) displays the lowest diversity and the strongest dominance pattern. With only four species (S = 4) and 140 individuals, it records the lowest Shannon diversity index (H′ = 1.44) and relatively low evenness (E = 0.72), while showing the highest dominance index (C = 0.32). This indicates that one or two species strongly dominate the community, reducing overall diversity. Such a pattern may reflect environmental stress, habitat simplification, or anthropogenic pressures in the area.

Table 3. Diversity, Evenness, and Dominance Index

| Station | S | N | H' | E | C |
|---|---|---|---|---|---|
| **Station 1 (west halmahera regency)** | 6 | 178 | 1.82 | 0.73 | 0.21 |
| **Station 2 (centra halmahera regency)** | 5 | 156 | 1.67 | 0.75 | 0.24 |

| | | | | | |
|---|---|---|---|---|---|
| **Station 3 (Ternate city)** | 4 | 140 | 1.44 | 0.72 | 0.32 |
| **Station 4 (south halmahera regency)** | 7 | 194 | 1.95 | 0.78 | 0.19 |

Information:
S= Simpson index; N= Number of individuals; H'=Shannon-Wienner index; E=Evenness; C= Dominance Index

In summary, the mangrove ecosystems across the stations range from highly diverse and stable (south halmahera regency) to less diverse and more dominance-driven (Ternate city). The results suggest that higher species richness and evenness are associated with lower dominance and greater ecological stability, highlighting Station 4 (south halmahera regency) as the most ecologically balanced mangrove habitat among the surveyed locations.

### 4.4. Importance Value Index (IVI)

The Importance Value Index (IVI) and its components, Relative Dominance (KR), Relative Frequency (FR), and Relative Density (DR), clearly describe the ecological role and dominance hierarchy of mangrove species within the study area.

*Rhizophora apiculata* is the most ecologically dominant species, with the highest IVI value (75.9%). This dominance is consistently supported by the highest relative density (DR = 28.0%), high relative dominance (KR = 25.4%), and the highest relative frequency (FR = 22.5%). These results indicate that *R. apiculata* is widely distributed, occurs in high abundance, and contributes substantially to stand basal area, making it the primary structural and functional species in the mangrove ecosystem.

*Rhizophora mucronata* ranks second in ecological importance, with an IVI of 61.6%. Its relatively high DR (24.2%) and FR (19.4%) demonstrate strong population abundance and wide spatial distribution, while its KR value (18.0%) reflects significant contribution to canopy structure. Together with *R. apiculata*, this species forms the core of the mangrove stand, indicating favorable site conditions for the genus *Rhizophora.*

*Bruguiera gymnorrhiza* occupies an intermediate position, with an IVI of 43.4%. Moderate values of KR (12.1%), FR (14.8%), and DR (16.5%) suggest that this species contributes meaningfully to community structure but does not dominate the ecosystem. Its presence enhances species diversity and adds structural heterogeneity to the stand.

*Sonneratia alba* and *Avicennia marina* show relatively low IVI values, at 31.9% and 31.5%, respectively. Both species exhibit lower dominance, frequency, and density compared to the *Rhizophora* species. This indicates a more limited ecological role, likely confined to specific microhabitats or environmental niches within the mangrove area. Nevertheless, these species remain ecologically important, particularly in terms of functional diversity, coastal protection, and adaptation to environmental stressors.

Table 4. IVI Mangrove Vegetation

| Species | KR (%) | FR (%) | DR (%) | IVI (%) |
|---|---|---|---|---|
| ***Rhizophora apiculata*** | 25.4 | 22.5 | 28.0 | 75.9 |
| ***Rhizophora mucronata*** | 18.0 | 19.4 | 24.2 | 61.6 |
| ***Bruguiera gymnorrhiza*** | 12.1 | 14.8 | 16.5 | 43.4 |
| ***Avicennia marina*** | 8.3 | 12.4 | 10.8 | 31.5 |
| ***Sonneratia alba*** | 9.0 | 10.9 | 12.0 | 31.9 |

Information:
KR= Density relative; FR= Frequency relative; DR= Dominance relative; IVI= Importance Value Index

Overall, the IVI analysis reveals a mangrove community strongly dominated by *Rhizophora apiculata* and *Rhizophora mucronata*, with other species playing supporting roles. This dominance pattern suggests a relatively stable but uneven community structure, typical of mangrove ecosystems where a few well-adapted species exert strong control over space and resources while maintaining ecosystem resilience through species complementarity.

**4.5. Environtmental Conditions**

The environmental parameters measured across the four stations indicate that the mangrove habitats generally fall within optimal ecological thresholds, supporting favorable conditions for mangrove growth and sustainability, with some spatial variation among sites.

Salinity values range from 22‰ (Station 4) to 30‰ (Station 2), all of which fall within the optimal tolerance range for mangroves (20–35‰). Station 2 exhibits the highest salinity, suggesting stronger marine influence, while Station 4 shows comparatively lower salinity, likely reflecting greater freshwater input. These variations are typical of mangrove ecosystems and do not indicate salinity stress.

Water temperature across all stations varies narrowly between 28.8°C and 30.1°C, remaining well within the optimal range of 26–32°C. This thermal stability supports physiological processes such as photosynthesis, respiration, and nutrient uptake, indicating no temperature-related constraints on mangrove growth at any station.

Soil pH values range from 6.5 to 7.1, indicating slightly acidic to neutral conditions. All stations fall within the optimal pH range (6–8) for mangrove soils, which favors nutrient availability and microbial activity. Station 3 shows the lowest pH (6.5), but this value remains suitable and does not suggest soil acidity stress.

Soil organic carbon (C-organic) content ranges from 2.5% (S3) to 3.4% (S4), exceeding the minimum threshold of 2.0% at all stations. Higher organic carbon content at Station 4 indicates better soil fertility and higher litter accumulation, which enhances nutrient cycling and sediment stability. Station 3, while still adequate, shows comparatively lower organic matter, possibly reflecting reduced litter input or higher decomposition rates.

Total nitrogen (N-total) values vary between 0.12% and 0.21%, all exceeding the minimum requirement of ≥0.1%. Station 4 again shows the highest nitrogen content (0.21%), suggesting more fertile substrate conditions, while Station 3 records the lowest value (0.12%), which may slightly limit productivity but remains within acceptable ecological limits.

Maximum tidal height ranges from 155 cm to 180 cm, indicating strong tidal influence across all stations. Station 2 experiences the highest tidal amplitude, which may enhance sediment deposition and nutrient exchange but also increase physical stress. Conversely, Station 4 shows the lowest maximum tide, which may contribute to more stable substrate conditions and higher organic matter accumulation.

Table 5. Environtmental Parameters

| Parameter | S1 | S2 | S3 | S4 | Optimal tresholds |
|---|---|---|---|---|---|
| **Salinity (‰)** | 26 | 30 | 28 | 22 | 20–35 |
| **Temperature (°C)** | 29.5 | 30.1 | 29.0 | 28.8 | 26–32 |
| **pH soil** | 6.8 | 7.1 | 6.5 | 6.9 | 6–8 |
| **C organic (%)** | 3.1 | 2.8 | 2.5 | 3.4 | ≥2.0 |
| **N-total (%)** | 0.19 | 0.15 | 0.12 | 0.21 | ≥0.1 |
| **Max Tide(cm)** | 160 | 180 | 170 | 155 | – |

Information:
S1 = station 1; S2= Station 2; S3= Station 3; S4= Station 4

Overall, the environmental conditions across all stations are conducive to mangrove growth and ecosystem stability. Station 4 consistently exhibits the most favorable soil fertility indicators (higher organic carbon and nitrogen), which aligns with higher species richness and diversity observed in biological analyses. In contrast, Station 3 shows relatively lower soil fertility and higher dominance patterns, suggesting that subtle environmental differences may influence mangrove community structure and diversity across the study area.

### 4.6. Indicators of Climate Change Impacts

The ecological indicators derived from field observations reveal clear signals of climate change impacts on mangrove ecosystems, affecting regeneration capacity, structural stability, and species composition [7].

The high seedling mortality observed along the open coast indicates increasing physiological stress during the early growth stages of mangroves. Elevated salinity levels and higher temperatures reduce seedling survival by disrupting water uptake and metabolic processes. This trend suggests that climate-induced changes are weakening natural regeneration, particularly in exposed coastal zones.

Shoreline erosion, evidenced by abrasion in the East Obi area, reflects the influence of sea-level rise and increased wave energy. Continuous erosion not only leads to the loss of mangrove habitat but also destabilizes root systems, increasing the vulnerability of mature stands to collapse and further shoreline retreat.
A shift in species composition, marked by the increasing dominance of *Avicennia* species, indicates an adaptive response to changing environmental conditions. *Avicennia* species are known for their higher tolerance to salinity fluctuations and exposed conditions, suggesting that climate-driven salinity stress is reshaping the mangrove community toward more stress-tolerant species at the expense of less adaptable taxa.

Substrate degradation, characterized by a decline in soil organic matter, points to reduced litter input and altered decomposition dynamics. This condition weakens sediment structure, lowers nutrient availability, and diminishes the capacity of mangrove soils to store carbon, thereby reducing overall ecosystem functioning and resilience. The observed 15–25% decrease in mangrove stand density is a strong indicator of hydrological disturbances, such as altered tidal regimes and increased inundation frequency. Reduced density reflects both increased mortality and limited recruitment, leading to simplified stand structure and lower ecological complexity.

Table 6. Impact of Climate Change

| Ecological indicators | Field observation | Indications of Climate change |
|---|---|---|
| **Seedling mortality increases** | High on the open coast | Salinity and temperature stress |
| **Shoreline erosion** | Abrasion in the East Obi | Sea-level rise |
| **Shift in species composition** | *Avicennia* species increase | Salinity adaptation |
| **Substrate degradation** | Decrease in organic matter | Decrease in litter input |
| **Decreased density** | Density drops by 15–25% | Hydrological disturbances |

Overall, these indicators collectively demonstrate that climate change is exerting multidimensional pressure on mangrove ecosystems, affecting regeneration, species composition, and habitat stability. If these trends persist, the long-term resilience of mangrove forests will be compromised, underscoring the need for adaptive management strategies, including restoration of hydrological connectivity, protection of vulnerable shorelines, and enhancement of natural regeneration processes.

# 4. DISCUSSION

The results of this study demonstrate that mangrove ecosystems across the observed stations are already experiencing measurable ecological responses that are strongly associated with climate change–related stressors. The integration of vegetation structure, diversity indices, environmental parameters, and field-based ecological indicators provides a comprehensive understanding of how climate variability and sea-level dynamics are reshaping mangrove communities.

**1. Climate Change as a Driver of Structural Degradation**

The observed increase in seedling mortality, particularly along open coastal areas, represents one of the earliest and most sensitive indicators of climate change impacts on mangroves [8]. Elevated salinity and rising temperatures directly affect osmotic balance and physiological performance in seedlings, reducing survival rates during critical establishment phases [9]. This condition constrains natural regeneration and threatens long-term stand persistence, especially in areas lacking adequate freshwater input or sediment accretion. Shoreline erosion, documented as active abrasion in East Obi, further reinforces the role of sea-level rise and increased hydrodynamic energy as dominant physical stressors. Persistent erosion leads to habitat loss, undermines root anchorage, and accelerates stand retreat [10]. These processes not only reduce mangrove area but also disrupt sediment dynamics essential for vertical accretion, a key mechanism by which mangroves adapt to rising sea levels.

**2. Shifts in Species Composition and Adaptive Responses:**

The increasing dominance of Avicennia species indicates a clear shift in community composition toward taxa with higher tolerance to salinity fluctuations and exposure [9], [11]. This compositional change suggests that climate-driven salinity stress is acting as an ecological filter [12], favoring stress-resilient species while reducing the competitiveness of less tolerant taxa such as some *Rhizophora* and *Bruguiera* species in exposed zones. Although such shifts may enhance short-term persistence, they often result in reduced structural complexity and functional diversity, potentially lowering ecosystem resilience over the long term [2]. The IVI and diversity analyses support this interpretation, showing dominance-driven community structures in stations experiencing stronger environmental stress. Lower Shannon diversity and higher dominance indices indicate simplified ecosystems that are more vulnerable to additional disturbances.

**3. Substrate Degradation and Nutrient Dynamics**

The decline in soil organic matter across several stations reflects reduced litter input, altered decomposition rates, and possible export of organic material due to stronger tidal flushing [13]. Organic matter plays a central role in maintaining soil fertility, sediment stability, and carbon sequestration capacity in mangrove ecosystems [14]–[16]. Its reduction compromises nutrient availability and weakens belowground structure, thereby exacerbating erosion and limiting root development [17], [18]. This degradation is closely linked to observed reductions in total nitrogen, particularly in stations with lower organic content. Such nutrient limitations may further constrain productivity and slow post-disturbance recovery.

**4. Declining Stand Density and Hydrological Disturbance**

The documented 15–25% decrease in mangrove density is a strong indicator of hydrological stress. Altered tidal regimes, prolonged inundation, and changes in freshwater inflow can exceed species-specific tolerance thresholds, leading to increased mortality and reduced recruitment. Lower stand density diminishes canopy cover and root network integrity, increasing vulnerability to wave action and further accelerating erosion processes [19]. The spatial patterns observed in this study suggest that stations with relatively stable hydrological and soil conditions maintain higher diversity, evenness, and density, highlighting the critical role of local environmental buffering in mediating climate change impacts [20].

**5. Implications for Ecosystem Resilience and Management**

The convergence of these discoveries reveals that alterations in climate significantly affect mangrove habitats in a variety of ways, influencing renewal, the types of species present, the state of the underlying material, and the layout of the forest all at the same time [21]–[23]. Although certain species demonstrate abilities to adjust and evolve, the general direction suggests an ongoing move toward the habitat becoming less complex and its capacity to recover diminishing if the existing pressures continue.

## 5. CONCLUSSION

Mangrove ecosystems in North Maluku show signs of ecological stress driven by climate change. Species composition shifts, substrate degradation, and reduced regeneration capacity highlight the need for comprehensive management strategies. Conservation planning should include restoration prioritization, community-based monitoring, and climate-adaptive measures such as hydrological rehabilitation and species selection based on tolerance thresholds.

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