The dynamics of biodiversity and sustainable agromaritime transformation in four ecoregions of Central Sulawesi

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Abstract. Biodiversity underpins ecosystem resilience and human well-being, particularly in dynamic agromaritime landscapes. In Central Sulawesi Province, however, rapid land-use change, mining expansion, and increasing economic pressures have led to ecological imbalances and declining habitat integrity. This study aims to analyse biodiversity dynamics and examine causal linkages between development activities and environmental responses across four major ecoregions: the Lore Lindu Highlands, East Tomini Bay, the Tolo Bay Coast, and the Banggai Islands. The study employs the DPSIR (Drivers–Pressures–State–Impact–Response) framework to systematically map interactions among socio-economic drivers, ecological pressures, environmental conditions, and policy responses. The results highlight how sectoral development pathways generate cumulative pressures on biodiversity, resulting in habitat degradation, reduced ecosystem services, and increased vulnerability of local communities. Furthermore, the analysis reveals gaps in current policy responses, particularly in terms of integration, adaptive governance, and cross-sectoral coordination. This study contributes to the development of a more integrated and evidence-based framework for sustainable agromaritime development by emphasizing the need to align biodiversity conservation with regional development planning.

1 Introduction

Biodiversity is a biological heritage that supports human life on earth. From providing food, clean water, clean air, to protection against natural disasters, the functions of biodiversity are irreplaceable. However, in recent decades, pressure on biodiversity has increased sharply due to massive human activities, often ignoring the carrying capacity and resilience of the environment. [1] states that around one million species are threatened with extinction, many of them in the coming decades—if no transformative efforts are made.

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Indonesia, as a mega-biodiversity country, has a strategic role in maintaining global ecological balance. Ironically, however, Indonesia is also one of the countries with the highest rates of forest loss and critical ecosystem degradation in the world. Land transformation for agriculture, plantations, and the expansion of extractive industries has triggered systemic deforestation and habitat degradation [2]. In the Wallacea region—which covers most of Sulawesi and the surrounding islands—this threat is becoming increasingly complex due to the high level of endemism that is not accompanied by adequate ecological protection systems [3].

Central Sulawesi, as part of Wallacea, has a highly diverse range of terrestrial and marine ecosystems: from the Lore Lindu mountain forests, the sedimentary coasts of Tomini and Tolo bays, to the coral-rich Banggai Islands. Each ecoregion faces different pressures: deforestation in the highlands, mangrove degradation and sedimentation in coastal areas, and overfishing and marine habitat destruction in the archipelago [4]. Unfortunately, studies mapping these pressures across ecoregions are still rare [5].

In the overlapping reality of development and environmental conservation, a scientific approach is needed that can bridge sectors that have traditionally operated independently. One such approach is *Drivers–Pressures–State–Impact–Response* (DPSIR), which not only maps ecological conditions but also unravels the root causes of pressures and the effectiveness of policy responses [6]

This study aims to present a cross-ecoregion analysis in Central Sulawesi, integrating biophysical and socio-ecological components to understand the dynamics of biodiversity in a rapidly changing development landscape. Using a systemic DPSIR approach, this study is expected to not only provide a comprehensive scientific overview, but also build a foundation for dialogue between science, policy, and society in the effort towards sustainable and equitable agromaritime transformation.

2 Method

2.1. Cross-ecoregion study design

This study adopts a cross-ecoregion approach that aims to capture the dynamics of biodiversity and different socio-ecological pressures in four major ecoregions in Central Sulawesi Province: (1) Lore Lindu Highlands, (2) East Tomini Bay, (3) Tolo Bay Coast, and (4) Banggai Islands. These four areas were selected based on the diversity of their ecosystem characteristics—which include mountain forests, large watershed coasts, lagoon areas with mangroves and coral reefs, and clusters of small tropical islands—each of which exhibits a distinct level of ecological vulnerability to agri-maritime development pressures.

This approach aims to reveal the systemic linkages between pressures on land (such as deforestation and agricultural expansion) and at sea (such as overfishing and coastal habitat conversion), and their implications for biodiversity and ecosystem services. By extending the unit of analysis across elevation and land-sea gradients, this design provides a comprehensive picture of socio-ecological interactions in dynamic agromaritime landscapes.

Data collection methods use a mixed-method approach, including:

1. Literature Study: Using official sources such as the [7, 8], and regional conservation reports [8] to describe the status and trends of biodiversity.
2. Limited Ecological Surveys: Focused on representative locations in each ecoregion, such as seagrass beds and mangroves in Tomini Bay, coral reefs in Tolo Bay, and primary forest areas in Lore Lindu.
3. Semi-structured interviews: Conducted with representatives of indigenous communities, local governments, and environmental NGOs to explore local narratives and perceptions of risk regarding environmental degradation [9].

Spatial location selection has been assessed through preliminary mapping to ensure ecological and geographical representation. Each ecoregion was analysed as a socio-ecological system with pressure structure (D), direct pressure (P), current environmental conditions (S), ecological impact (I), and policy response (R). Thus, this design integrates a systemic and region-based approach to assess the dynamics of biodiversity and agromaritime pressure as a whole.

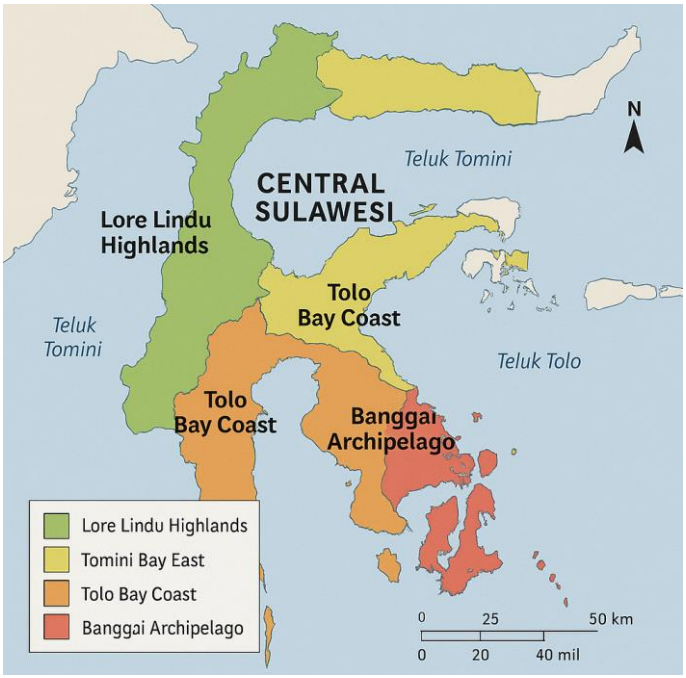

Fig. 1. Ecoregions in Central Sulawesi Province

2.2. DPSIR analysis framework

The analysis in this study was structured using the Drivers–Pressures–State–Impact–Response (DPSIR) framework, which was chosen for its ability to structure the cause-and-effect relationships between social dynamics, environmental pressures, and responsive policies [6]. This approach is also capable of bridging ecological and social perspectives across scales, as well as supporting the formulation of evidence-based interventions [10].

- Drivers include factors such as the expansion of the agricultural, mining, and intensive fishing sectors, as well as spatial planning and regional development policy dynamics [11].
- Pressures refer to direct pressures on the environment, such as deforestation, water pollution, habitat fragmentation, and overexploitation of natural resources [12].
- State refers to the current environmental conditions assessed through quantitative and qualitative indicators, such as forest cover, water quality, and coastal ecosystem health indices, such as coral reefs and seagrass beds [13].
- Impacts describe the ecological and social impacts of these changes, such as biodiversity loss, coastal erosion, decline in fisheries productivity, and loss of livelihoods for coastal communities [14].
- Responses include strategies and policies from the government, non-governmental organisations, and local communities aimed at mitigating pressures and impacts,

including conservation initiatives, governance improvements, and cross-sectoral collaboration [15].

This analysis is supplemented by spatial mapping using GIS technology to illustrate the distribution of environmental pressures, areas of degradation, and potential priority areas for conservation and restoration. Data interpretation was conducted qualitatively using an inductive approach and semi-quantitatively based on the availability of indicator data. With this approach, the study not only describes biodiversity conditions and environmental pressures but also provides a systemic basis for formulating more adaptive and ecologically equitable agromaritime policies.

3 Results and discussion

This chapter is structured to address two main research objectives: (1) to analyse the dynamics of biodiversity in four ecoregions of Central Sulawesi, and (2) to identify the relationship between these dynamics and the intensification of agromaritime development pressures from land and sea-based sources. This structure is designed to make the discussion of the results more systematic and focused, and to flow based on a cross-ecoregion approach and the DPSIR analytical framework.

3.1 Biodiversity dynamics in four ecoregions of Central Sulawesi

Four ecoregions in Central Sulawesi—Lore Lindu Highlands, East Tomini Bay, Tolo Bay Coast, and Banggai Islands—exhibit complex and interrelated biodiversity dynamics with land and marine development pressures. This analysis was conducted using a cross-ecoregion approach and the DPSIR framework, based on triangulation of secondary data (policies, spatial reports, and literature) and primary data (ecosystem observations and interviews with local stakeholders). Table 1 presents a synthesis of the ecosystem characteristics, key species, and biodiversity dynamics of each region based on the ***State*** and ***Impact*** elements of the DPSIR.

Table 1. Biodiversity dynamics per ecoregion

Ecoregion	Ecoregion Characteristics	Key Biodiversity	Biodiversity Dynamics (State & Impact)
Lore Lindu Highlands	Tropical mountain forests, main watersheds (Poso, Palu)	Anoa, Tarsius dentatus, Maleo bird	Deforestation of primary forest 28,495 ha (2001–2021) [7]; habitat fragmentation disrupts the hydrological cycle and puts pressure on endemic species.
East Tomini Bay	Large watershed coastline, seagrass beds, coral reefs	Herbivorous fish, seagrass (Enhalus acoroides, Thalassia)	Watershed sedimentation → decreased water clarity, seagrass cover decreased by 24% [7]; habitat degradation decreased the aquatic biota diversity index.
Tolo Bay Coast	Coastal lagoon, mangroves and coral reefs	Rhizophora sp., reef fish	Mangrove conversion >1,600 ha [7]; coral fish biomass declines due to habitat degradation & overfishing.
Banggai Islands	Small island group, tropical sea	Banggai Cardinal Fish, coral reefs, and endemic ornamental fish	The population of Banggai cardinalfish has declined due to the ornamental fish trade and habitat degradation; 27% of non-Acropora corals and 45.5% of Acropora corals → moderate ecological pressure [7].

The four ecoregions studied exhibit distinct biodiversity dynamics but share similar patterns of degradation, primarily driven by anthropogenic pressures both on land (deforestation, agricultural expansion, and urbanisation) and at sea (overfishing, ornamental fish trade, and coastal conversion). These pressures directly affect the *State* (ecosystem condition) and *Impact* (effects on species and ecosystem services), as conceptualised within the DPSIR framework.

In this context, ecological thresholds are understood as critical limits beyond which ecosystems may undergo abrupt and potentially irreversible changes in structure and function. Empirical evidence suggests that coral reef ecosystems tend to shift toward algal-dominated states when live coral cover declines below approximately 30%, while tropical forest systems experience significant biodiversity loss and ecological disruption when deforestation exceeds 40–50% of original cover. These thresholds provide a scientific benchmark for interpreting ecosystem degradation across the studied regions.

These threshold-based indicators provide a robust basis for assessing the *Impact* dimension, particularly as several of the studied ecoregions are approaching, or in some cases exceeding, these critical limits. Consequently, key species that previously played essential roles in maintaining ecosystem stability are increasingly threatened, and without strengthened conservation and restoration efforts, these systems risk crossing ecological tipping points that may lead to long-term or irreversible degradation.

3.1.1 Lore Lindu highlands

The Lore Lindu region is a tropical mountain forest area that serves as the headwaters of major watersheds such as Poso and Palu. This area is also known as the centre of endemism for highland species in Sulawesi, such as the Anoa (Bubalus quarlesi), Tarsius dentatus, and the maleo bird (Macrocephalon maleo). However, over the past two decades, the primary forests of Lore Lindu have experienced high deforestation pressure: a decline in forest cover of 28,495 hectares was recorded between 2001 and 2021 [7]. Landscape fragmentation has disrupted the hydrological cycle and reduced habitat connectivity for small mammals and endemic birds, leading to population isolation and increasing the risk of local extinction. This has also impacted the decline of watershed ecosystem services, such as water regulation and erosion control.

3.1.2 East Tomini Bay

Tomini Bay is a coastal and shallow marine ecoregion that receives input from large watersheds on the eastern side of Central Sulawesi. The main habitats in this region include seagrass beds, coral reefs, and muddy coasts that are home to herbivorous fish and benthic biota. In the last decade, sedimentation due to land degradation in the upstream has caused a decline in water clarity, reducing the productivity of the underwater ecosystem. Seagrass cover has declined by up to 24%, while healthy coral cover is below 30% [7]. This habitat damage has also reduced the biodiversity index of aquatic biota, including commercial and non-commercial fish populations that are important for the livelihoods of local fishermen.

3.1.3 Tolo Bay Coast

This ecoregion has a lagoon structure rich in mangrove forests (Rhizophora sp.) and fringing reefs. However, the expansion of shrimp farms and coastal settlement development has led to massive conversion of mangrove ecosystems. More than 1,600 hectares of mangroves have been converted, causing the loss of their important function as *a nursery ground* for various

reef fish species [7]. In addition, intensified fishing and habitat degradation have led to a significant decline in reef fish biomass. This phenomenon reflects the strong link between land degradation and declining marine productivity.

3.1.3 Banggai Islands

As a small group of islands at the eastern tip of Central Sulawesi, the Banggai Islands are home to a wealth of marine biodiversity, including endemic species such as the Banggai Cardinal Fish (Pterapogon kauderni). This species has a limited distribution and low fecundity, making it highly vulnerable to ecological pressures. In recent years, the Banggai Cardinal Fish population has reportedly declined dramatically due to pressure from the ornamental fish trade and coastal habitat destruction. Coral cover is only 45.5% for Acropora and 27% for non-Acropora, indicating moderate but consistent ecosystem pressure [7]. In addition, the high sensitivity of small islands to climate change exacerbates habitat conditions.

3.2 The relationship between biodiversity dynamics and the intensification of agromaritime development pressure

The relationship between biodiversity dynamics and agromaritime development pressures in Central Sulawesi can be understood systemically through the DPSIR (*Drivers–Pressures–State–Impact–Response*) framework approach. This model enables the identification of causal relationships between socio-economic drivers and environmental degradation, as well as how these pressures are manifested in ecosystem conditions and impact key species and ecosystem services.

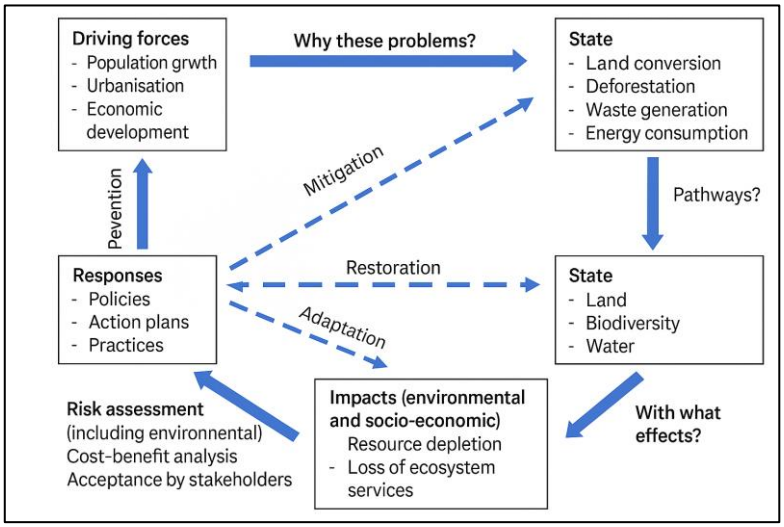

Fig. 2. Interactive DPSIR diagram: the relationship between agromaritime development and biodiversity change in four ecoregions of Central Sulawesi.

This diagram illustrates the causal relationship between drivers, pressures, state, impact, and response. This flow summarises the dynamics of the socio-ecological system in the context of integrated land- and sea-based agromaritime development.

Table 2 summarises the land- and sea-based DPSIR analysis in four major ecoregions, showing the complexity of interactions between development activities and ecological pressures that are cross-sectoral and spatial in nature.

Table 2. DPSIR analysis and agromaritime pressures on biodiversity

Ecoregion	Ecoregion Characteristics	Key Biodiversity	Drivers	Pressures		State (Ecosystem Condition)	Impacts	Response (Policy / Programme)
				Land	Marine			
Lore Lindu Highlands	Tropical mountain forests, main watersheds (Poso, Palu)	Anoa, Tarsius dentatus, Maleo bird	Population growth in upstream villages, expansion of dryland agriculture	Deforestation, watershed forest fragmentation, and road construction	Indirectly, sedimentation impacts worsen downstream marine water quality	Primary forest cover reduced by 28,495 ha (2001–2021), watershed disturbance	Declining populations of Anoa and Maleo birds; Tarsiers are losing habitat due to forest fragmentation	Rehabilitation of protected forests & watersheds in Lore Lindu [7]
East Tomini Bay	Large watershed coastline, seagrass beds, coral reefs	Herbivorous fish, seagrass (Enhalus acoroides, Thalassia)	Port area growth, coastal urbanisation	Sediment runoff from watersheds, coastal land conversion	Marine pollution from ports, and destructive fishing gear	Seagrass decline of 24%, healthy coral <30%	Decline in herbivorous fish, damage to seagrass as a habitat for larvae and spawning	No integrated programme across watersheds and coastal areas
Tolo Bay coast	Coastal lagoons, mangroves, and coral reefs	Rhizophora sp., reef fish	Demand for exports from fish farms, increase in coastal population	Conversion of mangroves into fish ponds and settlements	Overfishing, coral habitat degradation	Mangrove loss >1,600 ha, coral quality <40%	Decline in demersal fish and coastal mollusc species; loss of coastal ecosystem buffers	Small-scale mangrove restoration (local initiatives), not yet systemic
Banggai Islands	Small island group, tropical sea	Banggai Cardinal Fish, coral reefs, and endemic ornamental fish	Global demand for ornamental fish and, economic dependence of small islands	Coastal conversion for small ports, dense settlements	Live fish trade, destructive fishing practices, and coral reef damage	Banggai Cardinal Fish population declines by up to 60%	Banggai Cardinal Fish population has declined dramatically, with potential local extinction due to overfishing and habitat degradation	Regulations protecting the Banggai Cardinal Fish are not yet effective

The Lore Lindu Highlands ecoregion shows a pattern of very strong pressure from land use. Population growth in upstream villages, exacerbated by the expansion of dryland agriculture and the opening of road access, has driven large-scale deforestation. This deforestation has not only reduced primary forest cover by 28,495 ha in the last two decades, but also disrupted the functions of watersheds that support coastal areas [7]. The impact is directly felt by endemic species such as the Anoa, Tarsius dentatus, and the maleo bird, which have lost their habitat due to landscape fragmentation. Pressure from the sea may be indirect, but it is still significant because sedimentation from land affects downstream ecosystems. Responses have taken the form of forest and watershed rehabilitation programmes, although these are still limited in scale and do not explicitly address land-sea connectivity.

In East Tomini Bay, pressure dynamics are more complex because they occur in the transition zone between watersheds and coastal areas. Urbanisation and port development have led to coastal land conversion and increased sediment runoff, which directly reduces water clarity. As a result, seagrass cover has declined by up to 24% and healthy coral cover is below 30% [7]. The loss of seagrass habitat has a significant impact on the reproductive cycle of herbivorous fish and other aquatic biota that depend on this ecosystem structure. Unfortunately, there is no integrated watershed-coastal policy to address simultaneous pressures from land and sea.

The Tolo Bay Coastal Ecoregion faces chronic and systemic double pressures. Market forces driving exports of aquaculture products and coastal population growth have triggered the conversion of mangroves into aquaculture ponds and settlements. On the marine side, intensified fishing and coral degradation have worsened habitat conditions. More than 1,600 hectares of mangroves have been lost, and coral quality is below the threshold for a healthy ecosystem. The impacts are clear: loss of coastal protection functions, reduced biomass of demersal fish and molluscs, and weakened economic resilience of fishing communities. Mangrove restoration efforts have been undertaken at several sites through local initiatives, but these have not been supported by systematic, spatially-based regional policies.

The most vulnerable conditions are seen in the Banggai Islands, a small island ecoregion with high marine biodiversity. Global market demand for Banggai cardinalfish and other tropical ornamental fish has created intense fishing pressure. On land, the conversion of coastlines for settlements and small ports adds pressure to coastal zones. Data shows that the Banggai Cardinal Fish population has declined by 60% in the last decade, while Non-Acropora coral cover has declined by 27% and Acropora by 45.5% [7]. This situation highlights the cross-scale pressures from the market economy on endemic species with low fecundity and limited distribution. Policy responses in the form of species protection remain weak in implementation and enforcement.

This analysis shows that biodiversity degradation in all ecoregions is closely linked to the intensification of agri-maritime development, both on land (agriculture, deforestation, urbanisation) and at sea (intensive fishing, fish trade, coastal habitat conversion). Each of these pressures creates environmental conditions (*states*) that are more vulnerable and have a direct impact on key species and the sustainability of ecosystem services. However, the available policy responses are not commensurate with the complexity of the pressures, often being sectoral and failing to take into account the systemic interconnections between upstream and downstream areas.

Therefore, a DPSIR-based cross-ecoregion approach is important as an analytical and planning tool. These findings indicate that agromaritime transformation in Central Sulawesi is not yet balanced with the ecological capacity of each region and therefore requires an adaptive approach that takes into account local dynamics, the vulnerability of endemic species, and land-sea interrelationships in an integrated management system. This knowledge

forms an important basis for the formulation of conservation and sustainable development policies that are not only responsive but also anticipatory.

4 Conclusions and recommendations

4.1 Conclusion

This study reveals the dynamics of biodiversity in four major ecoregions of Central Sulawesi—Lore Lindu Highlands, East Tomini Bay, Tolo Bay Coast, and Banggai Islands—each of which has unique ecosystem characteristics and endemic species but is experiencing ecological degradation due to increasing agromaritime development pressures. Using a cross-ecoregion approach and the DPSIR (*Drivers–Pressures–State–Impact–Response*) analytical framework, this study shows that all ecoregions have experienced a significant decline in ecological condition, as reflected in the reduction of primary forest cover, degradation of seagrass beds and coral reefs, and loss of coastal habitats. These changes have directly affected endemic species and threatened the sustainability of ecosystem services. The pressures driving this degradation originate simultaneously from both land and sea. On land, ecosystem degradation is mainly driven by land conversion for agriculture, aquaculture ponds, and settlements. At sea, intensive fishing, the ornamental fish trade, and the destruction of coastal habitats impose additional pressure on tropical biodiversity. However, policy and programme responses remain disproportionate to the scale of these pressures and are generally sectoral, fragmented, and lacking in cross-regional as well as cross-sectoral integration. The absence of ecoregion-based management mechanisms that consider land–sea connectivity represents a critical gap in environmental governance in this region. As a result, ecoregions hosting endemic species with limited distribution, such as the Banggai cardinalfish, are facing the threat of local extinction, while upstream ecoregions such as Lore Lindu are experiencing systemic degradation that also affects downstream areas through watershed processes. These findings confirm that agromaritime transformation without a strong ecological foundation actually weakens the ecological resilience of the region, reduces the quality of life of coastal and upland communities, and threatens long-term conservation targets, both locally and nationally.

4.2 Recommendations

Based on the results of the analysis and findings, several strategic recommendations can be proposed. First, it is essential to strengthen integrated cross-ecoregion and land–sea governance. Local governments and development partners need to adopt an ecological spatial approach in order to harmonise policies related to spatial planning, conservation, and the development of both agricultural and marine sectors. Second, the DPSIR (*Drivers–Pressures–State–Impact–Response*) framework should be applied more systematically in regional development planning. This framework can serve as an important tool for formulating more adaptive and evidence-based indicators of pressure and response, particularly in the preparation of a more responsive Biodiversity Master Plan (*RIKH*). Third, the restoration of critical ecosystems should be prioritised based on biodiversity vulnerability. Restoration efforts need to focus on areas experiencing severe degradation and on habitats supporting endemic species with low fecundity, such as the Banggai cardinalfish and the forest habitat of Lore Lindu. In addition, the protection schemes for key species and habitats should be expanded. This includes improving the effectiveness of legal protection for the Banggai cardinalfish and strengthening community-based conservation areas in coastal and marine environments. Furthermore, greater cross-sectoral integration and stronger local community involvement are necessary in policy and programme design. Local

communities, traditional leaders, traditional fishers, and forest farmers should be actively engaged to ensure ecological justice and socio-economic sustainability. Finally, a dynamic monitoring and evaluation system based on spatial data needs to be established. A routine monitoring mechanism supported by GIS technology and remote sensing is required to detect changes in land cover, coastal ecosystem quality, and the distribution of indicator species.

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