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Ecological Analysis of Mangroves and Seagrasses on Large and Small Islands: Environmental Factors, Biodiversity, and Ecosystem Services

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Abstract Mangrove and seagrass ecosystems are essential to coastal protection, carbon sequestration, and biodiversity. However, their structure and function vary between large and small islands, which influences their stability and resilience. Larger islands typically support higher biodiversity and more complex ecosystem interactions, whereas smaller islands face greater environmental vulnerability due to limited resources and higher exposure to climate change impacts. This study examined how island size affects the dynamics of mangrove and seagrass ecosystems, emphasizing differences in biodiversity, carbon storage, and susceptibility to anthropogenic pressures. Degradation from land conversion, pollution, and climate change threatens ecosystem services and reduces coastal resilience and the carbon sequestration capacity. Conservation strategies including policy reinforcement, community-based management, and adaptive restoration are crucial for mitigating these threats. Strengthening governance, promoting sustainable financing, and advancing research on climate adaptation can enhance ecosystem management. Future efforts should prioritize site-specific conservation approaches to account for geographic and ecological variations and ensure the long-term sustainability of mangrove and seagrass ecosystems in different island environments.

Keywords Carbon Sequestration · Coastal Resilience · Anthropogenic Impact · Conservation Strategies · Climate Adaptation

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Introduction

Coastal ecosystems, such as mangrove forests and seagrass meadows, are vital for maintaining ecological stability and supporting human life on both global and local levels. Mangroves, which span about 136,000 km² globally, are predominantly found in tropical and subtropical areas, notably in Southeast Asia, Latin America, and Africa (Giri et al., 2011; Spalding & Leal, 2021). These ecosystems act as natural barriers against coastal erosion (Winterwerp et al., 2020), provide breeding grounds for numerous fish and invertebrate species (Abu El-Regal & Ibrahim, 2014), and serve as effective carbon sinks, with a storage capacity of up to 1,023 MgC/ha (Donato et al., 2011). In contrast, seagrass ecosystems, which cover an estimated 177,000–600,000 km² worldwide (Duarte et al., 2010), play a role in filtering sediments, offering marine habitats, and sequestering substantial carbon amounts, with an annual carbon burial estimated at 111 Tg C/year and total carbon storage between 4.2 and 19.9 Pg C (Fourqurean et al., 2012). However, human activities and climate change are increasingly threatening seagrass meadows, leading to habitat loss from coastal development, deteriorating water quality, and rising sea temperatures. Since 1990, the global degradation rate of seagrass meadows has increased to 7% annually, with a total loss of 29% since 1879 (Waycott et al., 2009a), posing a significant risk to coastal ecosystems on both large and small islands.

Large and small islands exhibit distinct geographical and ecological characteristics that influence the sustainability of their coastal ecosystems. Large islands, covering more than 10,000 km² in Indonesia, such as Kalimantan, Sumatra, and Papua (BPS-Statistics Indonesia, 2024), generally have more extensive and diverse mangrove ecosystems due to complex hydrodynamic systems and higher sedimentation rates influenced by large river systems (Nugroho, 2003; Ramadhan et al., 2021). In contrast, small islands, with an area of less than 2,000 km², are often more vulnerable to environmental changes due to limited natural resources and high human exploitation pressure. Additionally, sea level rise, estimated at 3.3 mm per year due to climate change, further exacerbates the degradation of seagrass ecosystems in low-elevation coastal areas, threatening habitat stability for various fish and invertebrate species (IPCC, 2019).

This review aims to explore how variations among islands influence the structure, function, and services of coastal ecosystems, particularly focusing on mangrove forests and seagrass meadows. By comparing the physical conditions, biodiversity, and ecosystem benefits of different island types, the study aims to pinpoint research gaps and suggest directions for future research. It also explores how human activities and climate change affect these ecosystems and how conservation and management strategies can be tailored to the geographical and ecological traits of each area. This study using Systematic Literature Review (SLR) method to identify, assess, and synthesize research on mangrove and seagrass ecosystems on both large and small islands. The SLR process involves structured steps such as literature search, selection based on inclusion and exclusion criteria, and systematic data analysis. Literature searches were conducted in major databases like Scopus, Web of Science, and Google Scholar, using key terms such as "mangrove," "seagrass," "small island," "large island," "coastal ecosystem," and "ecosystem management." The selected literature includes peer-reviewed journal articles, official reports, and policy documents published between 2001 and 2024, ensuring comprehensive and current information (Donato et al., 2011; Waycott et al., 2009a; Abu El-Regal & Ibrahim, 2014). Inclusion criteria covered studies on ecosystem characteristics, functions, environmental threats, carbon storage capacity, and coastal resource management policies in the context of large and small islands. Exclusion criteria ruled out non-peer-reviewed articles, studies not related to island environments, or those focusing on a single aspect without a broader coastal resource management context.

Adaptation and Habitat Characteristics of Seagrass and Mangroves

Mangrove and seagrass ecosystems serve unique but complementary roles in ecological functions, especially in coastal defense, carbon storage, and offering habitats for a variety of marine life. Despite their structural differences, they also differ in their ability to absorb pollutants (Govers et al., 2014; Lufthansa et al., 2021) and in their support of marine biodiversity (Bai et al., 2021; Unsworth et al., 2022). Indonesia's mangrove ecosystems are rich in biodiversity, featuring 240 mangrove species and a wide array of fauna, including 125 fish species, 169 macrozoobenthos species, and 161 terrestrial fauna species (Rahman et al., 2024). Likewise, seagrass ecosystems are vital for sustaining biodiversity and fishery productivity, with 81 fish species documented in Karimunjawa and 46 fish species along with 38 invertebrate species identified in Wakatobi (Nadiarti et al., 2012).

Mangroves are predominantly located in coastal regions with muddy grounds, whereas seagrasses are typically found in shallow, sandy waters. Mangroves possess distinctive adaptations, including aerial roots that aid in breathing in oxygen-poor environments and a strong ability to withstand changes in salinity (Salas-Rabaza et al., 2024). On the other hand, seagrasses form intricate root networks that help

stabilize sediments and enhance water quality by filtering out suspended particles (Potouroglou et al., 2017). A recent investigation in the Red Sea revealed that seagrasses are more effective at filtering heavy metals than mangroves (Cai et al., 2024).

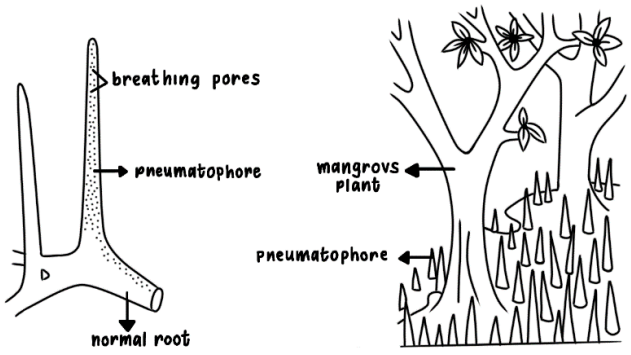


Figure 1. Mangrove respiratory roots of Rhizphora

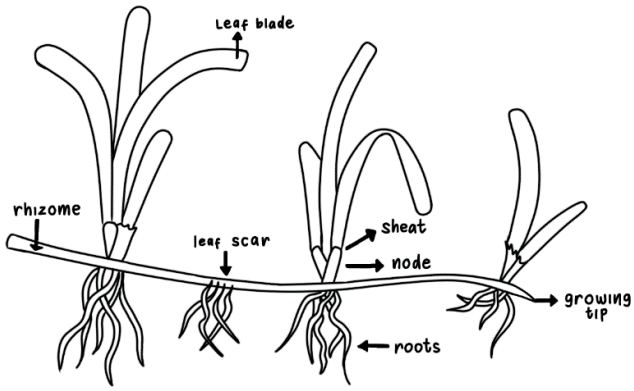


Figure 2. Seagrass roots system of Cymodoceae

In addition to structural and ecological function differences, the size and geographical features of islands also play a role in the stability of mangrove and seagrass ecosystems. Generally, larger islands support a higher level of biodiversity and demonstrate more ecological stability than their smaller counterparts. This observation is consistent with the Theory of Island Biogeography, introduced by MacArthur and Wilson (1967), which suggests that the number of species on an island is governed by a dynamic equilibrium between immigration and extinction rates, affected by the island's size and its distance from source populations. Larger islands offer more extensive habitats and resources, which sustain larger populations and a greater variety of species, thereby lowering extinction rates. Conversely, smaller islands accommodate fewer species due to their limited resources and heightened susceptibility to environmental changes (Whittaker et al., 2008). Further advancements in this field include the General Dynamic Model of Oceanic Island Biogeography, which incorporates geological and evolutionary processes to explain biodiversity patterns on oceanic islands. This model highlights that island area and isolation are key determinants of species richness, with larger and less isolated islands supporting more diverse and stable ecosystems. Small islands are often more susceptible to climate change impacts, such as sea level rise, which threatens the existence of seagrass and mangrove habitats (Maul, 2005).

Table 1. Comparison Table of Mangrove and Seagrass Ecosystem Characteristics and Functions

Indicator	Mangrove Ecosystem	Seagrass Ecosystem
Global area	137.760 km² (Bunting et al., 2018)	344.958 km² (UNEP-WCMC, 2021)
Carbon Storage (C)	1023 Mg C/ha (Donato et al., 2011)	119 Mg C/ha (Nordlund et al., 2016)
Carbon Accumulation Rate	160-500 g C/m²/year (Pérez et al., 2018)	83 g C/m²/year (Bidak et al., 2021)
Wave Absorption Capacity	Wave energy reduction up to 13-66% (Mcivor et al., 2012)	Wave energy reduction up to 30-47% (Muna et al., 2023)
Endangered Ecosystem	35% of the ecosystem has been lost since 1980 (Polidoro et al., 2010; Valiela et al., 2001)	29% of the ecosystem has been lost since 1990 (Waycott et al., 2009b)

The ecosystems of mangroves and seagrasses are essential for preserving the environmental equilibrium along coastlines, especially with regard to carbon storage and climate change mitigation. Mangrove ecosystems cover around 137,760 km² globally (Bunting et al., 2018), while seagrass ecosystems are more extensive, reaching 344,958 km² (UNEP-WCMC, 2021). A key function of theirs is the storage of carbon. Mangrove ecosystems possess a carbon storage capacity that far exceeds that of seagrass ecosystems, with mangroves storing around 1,023 Mg C per hectare (Donato et al., 2011), in contrast to the 119 Mg C per hectare stored by seagrasses (Nordlund et al., 2016). Carbon accumulation rates differ considerably; mangroves accumulate carbon at a rate of 160 to 500 grams C per square meter annually (Pérez et al., 2018), whereas seagrasses accumulate only 83 grams C per square meter per year (Bidak et al., 2021).

Besides their involvement in the carbon cycle, these ecosystems aid in coastal protection through wave energy absorption. Mangroves can diminish wave energy by 13–66% (McIvor et al., 2012), whereas seagrasses can lower it by 30–47% (Muna et al., 2023). This function is vital for protecting coastal regions against erosion and the effects of storms. Nonetheless, both ecosystems are under grave threat from human actions and shifts in the environment. Since 1980, around 35% of mangrove ecosystems have been destroyed (Polidoro et al., 2010; Valiela et al., 2001). Likewise, there has been a notable reduction in seagrass ecosystems, with

a recorded loss of 29% since 1990 (Waycott et al., 2009b). The degradation of these ecosystems could disrupt ecological balance, reduce carbon sequestration capacity, and increase the risk of coastal erosion and natural disasters.

Geographical Differences: Large Islands vs. Small Islands and Their Ecosystem Dynamics

The Island Biogeography Theory, written by MacArthur and Wilson in 1967, implies that larger islands can sustain a higher number of species. This is attributable to a broader variety of habitats and an increased population capacity, which mitigates the risk of extinction from demographic or environmental factors. Large islands harbor diverse micro-ecosystems that support a variety of organisms, ranging from forest and freshwater species to coastal ecosystems. Moreover, the elevated complexity of habitats on large islands results in increased chances for speciation and ecological interactions that boost biodiversity. Biodiversity levels and ecosystem productivity reflect the influence of island size on environmental conditions and ecosystem dynamics. The larger habitat diversity found on large islands, comprising rainforests, coastal ecosystems, and freshwater habitats, results in higher biodiversity there. In contrast, small islands often host endemic species that have evolved in geographic isolation, such as *Tarsius pelengensis* and the Banggai crow (*Corvus unicolor*) in Peleng and Banggai Islands (Riyanto & Rahmadi, 2021; Setiadi et al., 2023), as well as unique fish species found in the waters of Enggano Island (Hadiaty & Sauri, 2018). However, species on small islands are more susceptible to extinction from external disturbances like tropical storms, rising sea temperatures, and increased human activities than those on larger islands.

The scales of an island have an effect on how intricate food chains and ecological interactions are. According to Massol et al. (2017), large islands feature more intricate trophic networks with a greater incidence of apex predators, while small islands usually have shorter food chains primarily dominated by herbivores and small omnivores. This suggests that large island ecosystems are more stable and resilient to external disturbances than small island ecosystems (Latour et al., 2024). Island size also significantly affects the impact of environmental changes, particularly in the context of climate change and ecosystem degradation. Small islands are generally more vulnerable to external disturbances due to their limited resources and simpler ecosystems (Pelling & Uitto, 2001; Zhang & Managi, 2020). Small islands face significant danger from rising sea levels, which can result in the loss of coastal habitats and the penetration of saltwater into land-based ecosystems. Furthermore, because small islands have a limited ability to regulate their local climate, changes in global temperatures affect them more significantly than large islands, which possess more intricate ecosystems. According to Pinuji et al. (2018), the fragile ecosystems and limited resource dependency of small islands make them particularly vulnerable to environmental degradation processes like deforestation and land conversion, which can accelerate biodiversity loss.

Characteristics of Mangrove and Seagrass Ecosystems on Large vs. Small Islands

The physical characteristics, biodiversity, and ecosystem services of mangrove and seagrass ecosystems differ significantly between large and small islands. Hydrological systems on large islands tend to be more complex, offering stable conditions for the growth of mangroves and seagrass. Conversely, small islands typically face more dynamic environmental circumstances such as intensified waves and currents and a scarcity of freshwater, which heighten the susceptibility of their mangrove and seagrass ecosystems to environmental alterations (Forbes et al., 2013). Dominant true mangrove species on small islands include Rhizophora spp. (*Rhizophora mucronata*, *Rhizophora apiculata*, *Rhizophora stylosa*, R*hizophora mangle*), *Bruguiera gymnorrhiza*, and Avicennia spp. (*Avicennia marina*, *Avicennia germinans*) (Abubakar et al., 2020; Appadoo, 2003; Opa et al., 2021; Wicaksono et al., 2011; Wilson, 2017). Mangroves on small islands are frequently found as fragmented patches, which can have unique ecosystem functions and services. For example, mangrove patches feature a longer edge perimeter and more forest gaps, which are essential for crabs and mollusks. Moreover, numerous mangrove patches develop in urbanized regions (Suyadi et al., 2021). Conversely, the substrates of mangrove ecosystems on large islands are more stable and their organic content greater, owing to the significant contribution of organic matter from large river systems (Kida et al., 2019; Tue et al., 2012). Extensive mangrove forests enhance their effectiveness in coastal protection.

There are also pronounced differences between large and small islands in seagrass ecosystems. Large islands host a more extensive distribution of seagrass, owing to the stability of aquatic conditions in these areas. On small islands, seagrasses are typically located in shallower waters and come into greater contact with human activities. As a result, they are dominated by species that are more resilient to environmental stress, such as the large seagrass species *Thalassia hemprichii* and *Enhalus acoroides*. Water quality in seagrass ecosystems on large islands tends to be more stable, with higher nutrient levels. This is due to land-based water

flow carrying organic matter and nutrients, which support seagrass growth and associated organisms. Conversely, small islands usually have clearer water quality because of the limited organic input from land. This leads to a reduced availability of nutrients, which can impact the growth of seagrass and the diversity of organisms that rely on it. Regarding sediment dynamics, seagrass ecosystems on large islands usually have greater amounts of mud and organic material due to river input and soil erosion. These sediments are vital for seagrass growth, as they offer a substrate rich in nutrients. However, on small islands, sediments are often sandier or made up of thin layers of mud because of stronger currents. These dynamic water flows inhibit organic matter accumulation, making seagrass substrates on small islands less nutrient-rich compared to those on large islands.

Management and Conservation Strategies for Mangrove and Seagrass Ecosystems

In order to address threats to mangrove and seagrass ecosystems, a variety of management and conservation strategies have been put into action, at both the national and international levels. Included among these strategies are policies and regulations that promote habitat protection, community-based methods to increase public involvement in conservation, restoration practices, and adaptive management to restore degraded ecosystems.

Current Policies and Regulations

Various legal instruments at both national and global levels have been used to implement conservation policies for mangrove and seagrass. Globally, the Ramsar Convention and the Convention on Biological Diversity (CBD) have included coastal ecosystems like mangroves and seagrasses in their strategies for global ecosystem protection (Gardner Royal C. & Davidson, 2011). Moreover, programs such as the Blue Carbon Initiative seek to boost the contribution of mangroves and seagrasses to climate change mitigation via carbon trading (Herr et al., 2017). Several countries have adopted policies to protect coastal ecosystems in Indonesia, which hosts one of the world's largest mangrove and seagrass ecosystems, has enacted Presidential Regulation No. 73 of 2012 on the National Mangrove Management Strategy and launched a Mangrove Rehabilitation Program targeting the restoration of 600,000 hectares of mangroves by 2030. Furthermore, Indonesia's Nationally Determined Contributions (NDCs) incorporate mangroves and seagrasses within its strategy for reducing carbon emissions (Kanugrahan & Hakam, 2023). The principal difficulties in executing these policies are weak law enforcement and insufficient coordination among local stakeholders. Small islands are especially affected by this issue, as they often face unregulated resource exploitation stemming from inadequate governance structures.

Community-Based Conservation Approaches

In areas where local communities depend on natural resources for their livelihoods, community-based conservation has demonstrated effectiveness in managing coastal ecosystems. Involving local communities in the management of ecosystems boosts the sustainability of conservation efforts and generates economic advantages for coastal populations. One successful initiative is the Payment for Ecosystem Services (PES) program, where communities protecting mangrove and seagrass ecosystems receive economic incentives (Rakotomahazo et al., 2023). In the Philippines, PES programs for coastal ecosystems have increased community participation in mangrove conservation. A similar approach has been implemented in Indonesia through Dana Desa (Village Fund), which can be utilized for coastal ecosystem restoration (Thompson et al., 2017). The success of this approach depends on improving community capacity to manage coastal resources sustainably (Fikri et al., 2020; Khairani & Yulistiyono, 2023). In the case of large islands, the implementation of community-based conservation programs is facilitated by a stronger infrastructure and regulatory backing. Nonetheless, on small islands, limited resources and the absence of institutional support continue to pose major challenges.

Restoration Practices and Adaptive Management

A crucial approach to restoring degraded mangrove and seagrass ecosystems is ecosystem restoration. Restoration approaches involve reforesting mangroves, transplanting seagrass, and employing ecosystem-based management that takes into account local environmental conditions. A successful case study is the mangrove restoration in Jakarta Bay (Subambang et al., 2024), where over the last ten years, 1,500 hectares of mangroves have been restored through a mix of natural regeneration and replanting initiatives. In Gathaagudu (Shark Bay), Western Australia, a collaboration between scientists and the Malgana Aboriginal Corporation facilitated seagrass restoration through on-country workshops. This initiative combined traditional ecological knowledge with Western science, resulting in successful restoration outcomes and stronger community engagement (Sinclair et al., 2024). This program was also integrated with coastal protection measures to prevent further degradation from human activities. Adaptive management plays an essential role in tackling the growing effects of climate change on coastal ecosystems. Various countries

have implemented climate adaptation strategies, including the creation of mangrove green belts, conservation zoning, and climate-responsive ecosystem restoration, as long-term resilience measures. Research has shown that climate-adaptive restoration can bolster the resilience of mangrove ecosystems to sea-level rise by up to 25% more effectively than traditional restoration methods (Müller et al., 2024).

Implications for Coastal Resource Management Policy

Coastal resource management should take into account the varying characteristics of mangrove ecosystems on large and small islands through a multisectoral approach that involves multiple stakeholders (Muzani, 2014). In small islands like the Anambas Islands, the management of mangroves focuses on community-based rehabilitation initiatives that engage local populations in the planting and upkeep of mangroves to mitigate abrasion and boost biodiversity (Sinaga et al., 2023). There is also the goal of raising awareness and fostering joint oversight of unlawful acts with this participatory approach (Sinaga et al., 2023). Meanwhile, on larger islands like Kalimantan, mangrove management utilizes satellite monitoring technology and coordinated inter-agency patrols to prevent illegal logging and land conversion, as well as to strengthen law enforcement and institutional coordination (Yolanda et al., 2025). At the national level, the Integrated Coastal and Small Islands Management Program (PPWP) plays a key role in integrating the management of coastal ecosystems, including mangroves and seagrasses, by involving central and regional governments and local stakeholders to develop adaptive and sustainable policies (Muzani, 2014). Research indicates that poor coordination among agencies and ineffective law enforcement, especially on small islands at risk of overexploitation, are significant obstacles to ecosystem sustainability (Widayanti et al., 2023; Walker et al., 2022). Effective and adaptive management of mangroves requires robust governance and policy alignment across all levels, from local to national (Walker et al., 2022; Yolanda et al., 2025). Finally, it is essential to bolster local community involvement for the sustainable preservation of mangroves' ecological and economic functions (Sinaga et al., 2023). Therefore, management of coastal resources that takes into account the unique conditions of the ecosystems on each island is more effective in maintaining sustainability and delivering optimal benefits for both the environment and local communities (Muzani, 2014; Widayanti et al., 2023).

Conclusion

According to this study, the structure, function, and services of coastal ecosystems, especially mangroves and seagrasses, are significantly affected by variations in island size and characteristics. Large islands tend to harbor more stable and diverse ecosystems, while small islands are more susceptible to environmental pressures and human activities. Mangroves are essential for carbon storage and coastal protection, with greater capacities than seagrasses; nevertheless, both ecosystems have faced concerning worldwide reductions in extent. The implications of the study underscore the necessity for coastal resource management policies that are customized to the unique characteristics of islands, incorporating community-based strategies, adaptive restoration, and enhanced local governance. Further studies are crucial for investigating how ecosystems respond to climate change and assessing the effectiveness of management strategies specific to each island type, in order to ensure the long-term sustainability of coastal ecosystems.

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