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Mangrove restoration priorities across coastal landscape typologies

ASWIN RAHADIAN[1,♥], LILIK BUDI PRASETYO[2], YUDI SETIAWAN[2], CECEP KUSMANA[3]
[1]Graduate School of Natural Resource and Environmental Management Science, Institut Pertanian Bogor. Jl. Raya Padjajaran, Bogor 16144, West Java, Indonesia. Tel./fax.: +62-251-8332779, ♥email: rahadianaswin@apps.ipb.ac.id
[2]Department of Forest Resource Conservation and Ecotourism, Faculty of Forestry and Environment, Institut Pertanian Bogor. Jl. Raya Dramaga, Bogor 16680, West Java, Indonesia
[3]Department of Silviculture, Faculty of Forestry and Environment, Institut Pertanian Bogor. Jl. Raya Dramaga, Bogor 16680, West Java, Indonesia

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Abstract. *Rahadian A, Prasetyo LB, Setiawan Y, Kusmana C. 2026. Mangrove restoration priorities across coastal landscape typologies. Biodiversitas 27 (3): d270305. https://doi.org/10.13057/biodiv/d270305.* Mangrove restoration in Indonesia is a new episode and a milestone paradigm in the management of natural resources and the coastal environment after the era of timber extraction. It is crucial for advancing biodiversity conservation, strengthening climate change mitigation, and refining future restoration practices from conceptual, technical, and methodological perspectives. This study aims to develop restoration approaches implemented in Indonesia and to propose an integrated framework based on landscape typology. Mangrove restoration approaches were identified through a comprehensive literature review and a priority assessment using the PROMETHEE method across landscape typologies, based on sustainability indicators derived from stakeholder interviews. We integrate our PROMETHEE results with a geospatial approach to produce a spatially explicit priority map. Various mangrove restoration approaches applied in Indonesia have demonstrated both strengths and limitations. Despite their partial nature, they are evidence-based and have been tested across diverse locations. The results of the study revealed that, in deltas and estuaries, protection approaches prioritize natural regeneration; on the open coast, ecological engineering is prioritized; in the backward zone, intensive planting is prioritized; and, in addition to intact mangroves, priority protection with species enrichment is prioritized. Compared to the partial approach, integrating mangrove restoration with landscape typologies will maximize ecological success and long-term socio-economic sustainability.

Keywords: Coastal management, ecological restoration, landscape typology, mangrove restoration, PROMETHEE-GIS

INTRODUCTION

Mangrove forests form an integral part of tropical coastal ecosystems, thriving along shorelines in marine environments that contribute significantly to a wide range of ecosystem services, such as supporting biodiversity, filtering water, cycling nutrients, protecting coastlines, and helping to regulate the climate (Costanza et al. 2014; Hu et al. 2020; Mazziotta et al. 2022). Various internal and external factors control them through environmental processes, changes in biodiversity, social systems, and human activities (Figueroa-Rangel et al. 2016; Malhi et al. 2020; Hagger et al. 2022). Agriculture, oil palm plantations, rice paddies, over-wood extraction, coastal development, industrial operations, and pollution are expected to persist in many regions, which will drive deforestation and degradation, increasing coastal vulnerability (Goldberg et al. 2020; Maina et al. 2021). At the same time, natural factors such as sea level rise and land subsidence, linked to climatic and local environmental conditions, pose additional challenges (Gandhi and Jones 2019; Mafi-Gholami et al. 2020).

Indonesia, which holds the world's most extensive mangrove forests (Bunting et al. 2018; Bunting et al. 2022), plays an important role in maintaining the global climate balance (Novita et al. 2022). Various strategies and frameworks are continuously implemented to support the protection and restoration of mangrove ecosystems (Slobodian et al. 2025). The mainstreaming of mangrove restoration in Indonesia was generally based on planting, both with the concept of reforestation and afforestation (van Bijsterveldt et al. 2022). Nevertheless, these efforts have not been effective in ensuring the overall connectivity of mangrove landscapes (Bryan-brown et al. 2020; Jaramillo et al. 2023).

Planting initiatives frequently fall short in reestablishing the ecological functions of mangrove forests, and effective restoration should lead to the development of expansive, diverse, resilient, and ecologically functional mangrove systems that deliver benefits for both the environment and local communities (Hai et al. 2020). By adhering to restoration approaches grounded in typological functionality, it is possible to restore biophysical and socio-economic conditions effectively, enabling nature to maintain and further support the restoration process (Winterwerp et al. 2013). When ecological conditions align with species-specific habitat requirements, mangrove forests tend to exhibit higher survival rates, accelerated growth, increased biodiversity, and enhanced resilience (Alongi 2002; Hai et al. 2020).

The lack of integration between restoration initiatives and coastal development presents a challenge that must be addressed to achieve both environmental recovery and sustainable community development (Abelson et al. 2020; Arifanti et al. 2022; Lovelock et al. 2022). Restoration planning approaches must be tested to improve effectiveness (Wang et al. 2023). The method for improving mangrove restoration plans is the integration of restoration approaches that have proven successful at the implementation level. Most coastal studies in Indonesia tend to emphasize either biophysical-ecological assessments or economic evaluations in isolation.

The purpose of this study was to advance current insights into mangrove restoration approaches that have been implemented in Indonesia, and propose an integrated planning framework based on landscape typology. We integrate evidence-based mangrove restoration approaches, qualitative socio-economic and ecological dimensions, and a geospatial approach based on landscape typology to get the best priority restoration design. The preference ranking organization method for enrichment evaluation (PROMETHEE) provides an opportunity to combine these diverse dimensions (Caliskan et al. 2022; Fontana et al. 2023). A key limitation lies in the translation of PROMETHEE results into maps or spatial models. Most studies stop at rankings and priority recommendations, without advancing to the spatial distribution of those options. This methodological gap highlights why we are integrating PROMETHEE with spatially explicit mapping. Against this background, incorporation methodologies between qualitative and spatial explicit translation are reasonable to implement. This methodological integration carries scientific novelty by offering a more holistic, systematic, and applicable approach to coastal management compared to studies that rely only on qualitative and spatial analysis separately. Methodologically, the novelty of this study lies in bridging decision-support ranking methods with geospatial implementation, transforming abstract prioritization results into operational restoration maps. This integration enables transparent, replicable, and spatially actionable restoration planning. The proposed framework is expected to serve as a guide and provide solutions for the future improvement of mangrove ecosystems.

MATERIAL AND METHODS

Study area

Indonesia, with the largest mangrove area in the world and its various dynamics, has historically carried out many mangrove restoration activities. The study area is limited in geographical scope to the mangrove restoration approach implemented in Indonesia, covering approximately 99,000 km of coastline with a mangrove area of ±3 million ha (Figure 1). Indonesia exhibits marked variation in mangrove condition, from relatively intact forests to heavily modified aquaculture landscapes. This ecological heterogeneity, combined with diverse governance and land-use contexts, allows for robust evaluation and refinement of a typology-based restoration framework.

Data collection

Literature review

The identification of mangrove restoration approaches was conducted through a comprehensive literature review of various publications within the Indonesian context, as well as other relevant sources related to coastal and mangrove ecosystem management. Literature search was conducted through the Web of Science, Google Scholar, Scopus, and also assisted by using Publish or Perish (PoP) and Mendeley software. We did this to obtain data and information with an evidence-based approach, in this case, an approach that has a history of successful implementation. The structure of the keyword string applied in bibliographic databases was developed using combinations of core thematic and geographic terms, specifically: ("mangrove restoration" or "mangrove rehabilitation") and ("mangrove Indonesia"). These keywords were selected to capture studies addressing restoration and rehabilitation approaches within the Indonesian context.

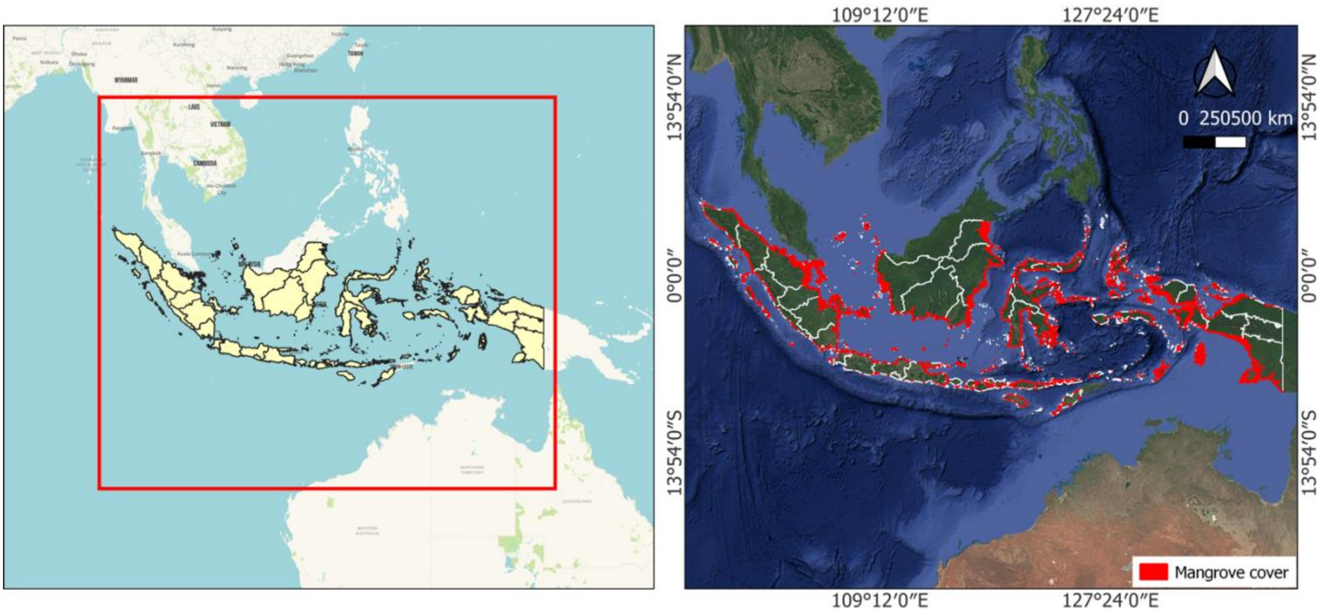

Figure 1. The map of the study area applies to all coastlines of Indonesia that have the existence of mangrove ecosystems

The overall literature search covered publications from 1980 onward to encompass the majority of scholarly work on mangrove restoration and rehabilitation. The final comprehensive search was completed in August 2025. Searches were primarily conducted in English, with supplementary searches conducted in Bahasa Indonesia. In addition to the predefined keyword searches, further relevant studies were identified through screening the reference lists of selected articles. This backward citation tracking process allowed us to capture additional sources that were not retrieved through the initial keyword-based search but were directly relevant to the study objectives.

Qualitative data

Structured and in-depth interviews were carried out with key actors affiliated with institutions that have been consistently involved in long-term mangrove restoration efforts in Indonesia, in order to enrich and validate the evolving body of information. The target respondents consist of government (Ministry of Forestry, Ministry of Marine Affairs and Fisheries), consultant government, non-profit organization (e.g., Wetlands International, Yayasan Konservasi Alam Nusantara, and Blue Forest), expert, field facilitator, and coastal communities, each of which consisted of 3 representatives, with a total of 21 respondents. The selection of three representatives per stakeholder group was considered methodologically sufficient for several reasons. First, a purposive sampling strategy was applied, targeting individuals with direct experience, technical expertise, and decision-making roles in mangrove restoration. Second, stakeholder categories were relatively homogeneous in terms of institutional mandates and operational perspectives. Third, data saturation was observed within each stakeholder group, as no substantially new sustainability indicators emerged after the third interview. Consensus was achieved through a Focus Group Discussion (FGD) session involving representatives from each stakeholder group following the individual interviews. During the FGD, interview findings were presented and collectively reviewed. An agreement was reached through structured discussion, where points of convergence and divergence were openly examined, indicators were refined based on collective feedback, and final indicators were confirmed when supported across stakeholder categories and considered practically measurable.

Geospatial dataset

We used the Landsat 8 mosaic, data acquisition by 2025, with a 30-m spatial resolution as the primary dataset, which was accessed and processed in the Google Earth Engine (Gorelick et al. 2017) to present a map. We also use biophysical typology data of mangroves by Worthington et al. (2020) for the initial identification of the distribution of mangrove typology throughout Indonesia. We also used global forest canopy height data (Potapov et al. 2021) to classify mangrove forest density classes.

Data analysis

Priority assessment

The prioritization of mangrove restoration approaches was assessed using the PROMETHEE method (Preference Ranking Organization Method for Enrichment Evaluation) developed by Brans et al. (1986). PROMETHEE is a multi-criteria decision analysis technique used to rank or prioritize alternatives based on various criteria. Its main strengths lie in its simplicity, clarity, and stability, making it accessible and practical for decision-makers (Brans and De Smet 2016; Talukder and Hipel 2018). This study is performed using the academic version of the PROMETHEE-GAIA software. Ranking is based on pairwise comparison of choices; this involves determining the extent to which approach a is preferred over approach b for a given criterion.

Scenario determination

We use mangrove typology as a reference scenario that represents the biophysical conditions of the mangrove ecosystem environment. The PROMETHEE method was applied to mangrove landscape typologies based onWorthington et al. (2020) to rank alternative restoration approaches (Table 1), from the most to the least suitable, based on various sustainability indicators. The landscape typology of mangroves has relevance to the ecosystem structure and the rate of mangrove deforestation, and is classified into deltas, estuaries, lagoons, and open coast. A delta/estuary has a high potential for accretion or land growth (Murray et al. 2019). That provides a basis for assessing the restoration potential of the provision of mangrove ecosystem services. In estuary typology, the accretion rate is very high, which causes the addition of land in the form of mud deposits as mangrove habitat (Solihuddin et al. 2021). Mangrove typology is related to ecological dynamics; in this case, it will be the basis for spatial scenarios to place appropriate restoration strategies or approaches.

Definition of alternatives

Alternative mangrove restoration schemes were distinguished based on the number of restoration approaches identified based on a literature review, combined with restoration approaches previously implemented in Indonesia. Based on literature and field reviews, we identified 8 restoration approaches that are priority alternatives, including aforestation reforestation revegetation (ARR), silvofishery (SF), ecological mangrove restoration (EMR), ecological engineering (EE), associated mangrove aquaculture (AMA), shrimp carbon aquaculture (SECURE), mangrove ecotourism (ME), and protection (PRO).

Table 1. The typology of landscape mangroves relates to ecological dynamics as a scenario attribute

Typology	Ecological dynamic
Delta	Mangrove that develops in the estuary areas of large rivers forming deltas experience more dynamic environmental conditions compared to other mangrove types. These areas are influenced by river flow, tidal fluctuations, and sedimentation, resulting in a high rate of accretion.
Estuary	Mangroves that develop in river estuaries, where freshwater from the land meets seawater, are characterized by unique environmental conditions influenced by the interaction of tidal movements, river flow, and sedimentation.
Lagoon	Mangroves that develop along sheltered coasts, shallow waters partially or fully separated from the open sea by natural barriers such as sandbanks, coral reefs, or islands, tend to experience more stable environmental conditions compared to those in open coastal or delta settings, due to reduced exposure to waves and ocean currents.
Backward	Mangroves that develop behind the main mangrove zone are often located in more sheltered areas, such as brackish swamps, lagoons, or regions situated farther inland from the coastline. These ecosystems are particularly vulnerable to anthropogenic disturbances.
Open coast	Mangroves that develop along coastlines directly exposed to the open sea, without natural barriers such as islands, sandbanks, or coral reefs, are highly vulnerable to coastal erosion.

Table 2. Definition of evalution criteria

Sub-criteria	Name	Description	Alternative score
Environment			
C11	Erosion	Ability to handle erosion; related to the ability of the restoration approach in its ability to handle coastal erosion due to waves and ocean currents	Score in ordinal scale, ranging from 1 (very bad) to 5 (very good); derived from the variability of coastal erosion rates in units of ha/year
C12	Natural regeneration	Opportunity for natural regeneration; related to the ability of the restoration approach to produce or rely on natural regeneration processes	Score in ordinal scale, ranging from 1 (very bad) to 5 (very good);
Social			
C21	Accessibility	related to accessibility to reach the location of implementation of the restoration approach	Score in ordinal scale, ranging from 1 (very bad) to 5 (very good); sourced proxy distance from the implementation location
C22	Community capabilitiess	Related to the community's ability and knowledge in implementing the restoration approach, e.g. planting is something that can be commonly done by various community groups, while community knowledge in implementing the ecological engineering approach is still limited.	Score in ordinal scale, ranging from 1 (very bad) to 5 (very good)
Technology			
C31	Technology	Application of technology; related to the need for a restoration approach in applying modern technology	Score in ordinal scale, ranging from 1 (very bad) to 5 (very good)
C32	Hydrological engineering	Related to the importance of implementing land hydrology improvement processes at the outset to implement the mangrove restoration approach.	Score in ordinal scale, ranging from 1 (very bad) to 5 (very good)
Economy			Score in ordinal scale, ranging from 1 (very bad) to 5 (very good)
C41	Implementation cost	Related to the amount of costs that need to be incurred to implement the restoration approach	Score in ordinal scale, ranging from 1 (very bad) to 5 (very good); sourced from the range of implementation cost values in rupiah/ha

Definition of criteria

Subsequently, in determining priorities, we developed a set of main criteria based on environmental, social, technological, and economic (Table 2). The sub-criteria include the ability to handle erosion, opportunity for natural regeneration, accessibility, community capacity for technical management, technology application, hydrological engineering, and implementation costs. We applied an equal weighting scheme across all sustainability indicators to avoid bias and to ensure that each criterion contributed uniformly to the decision-making process. This choice was made based on stakeholder consensus during the interviews, where no single criterion was prioritized above others. Each approach or scheme certainly has strengths and weaknesses at the implementation level. The accuracy of the typology and treatment determines performance. Some weaknesses that may not be covered in the analysis include cost, time, implementation challenges, community participation, and natural factors. Based on this history, it can at least represent the best design that is adaptive to current developments from a perspective. A proposed model for preference ranking organization method for enrichment of evaluations is presented in Figure 2.

The assessment of landscape typology scenarios was conducted using the PROMETHEE, which requires the explicit definition of evaluation criteria, sub-criteria, and preference directions. In this framework, each sub-criterion is assigned a preference orientation, indicating whether higher (max) or lower (min) values are considered more desirable. The assessment of landscape typology scenarios was conducted using the PROMETHEE multi-criteria decision analysis approach. Five landscape typologies were evaluated, namely delta, estuary, lagoon, backward, and open coast. The evaluation framework was structured around four main aspects, environmental, social, technological, and economic, each represented by specific sub-criteria. For each sub-criterion, a preference direction was defined to indicate whether higher values (Max) or lower values (Min) were considered more desirable, allowing both benefit-type and cost-type indicators to be integrated within the analysis (Table 3).

The environmental aspect focuses on the ecological suitability and resilience of each landscape typology, particularly in terms of erosion control and the potential for natural regeneration. The ability to handle erosion reflects the capacity of a landscape to reduce or withstand erosive forces, where higher values are generally preferred in more exposed systems such as open coasts, while lower requirements may be acceptable in more sheltered typologies. The opportunity for natural regeneration represents the extent to which mangrove recovery can occur through natural processes; higher values are favored in typologies such as deltas, estuaries, and lagoons, where sediment dynamics and hydrological conditions support spontaneous regeneration. The social aspect captures the feasibility of implementing restoration interventions and the degree of local involvement. Accessibility is considered a benefit-type criterion, as higher accessibility facilitates field operations, monitoring, and long-term management. Community capabilities reflect the capacity of local communities to participate in and support restoration activities, with higher values indicating greater social readiness and institutional support.

The technological aspect evaluates the level and appropriateness of technical interventions required across different landscape typologies. The application of technology is treated as a benefit criterion, where higher values indicate effective use of technical measures to support restoration outcomes. In contrast, hydrological engineering reflects the extent of engineered interventions needed to modify or restore hydrological processes; depending on the landscape context, lower values indicate greater reliance on natural processes, while higher values suggest the necessity of engineered solutions, particularly in backward and lagoon systems. The economic aspect is represented by implementation costs, which are treated as a cost-type criterion in the PROMETHEE analysis. Lower implementation costs are preferred, as they enhance the economic feasibility, efficiency, and scalability of restoration strategies across the different landscape typology scenarios.

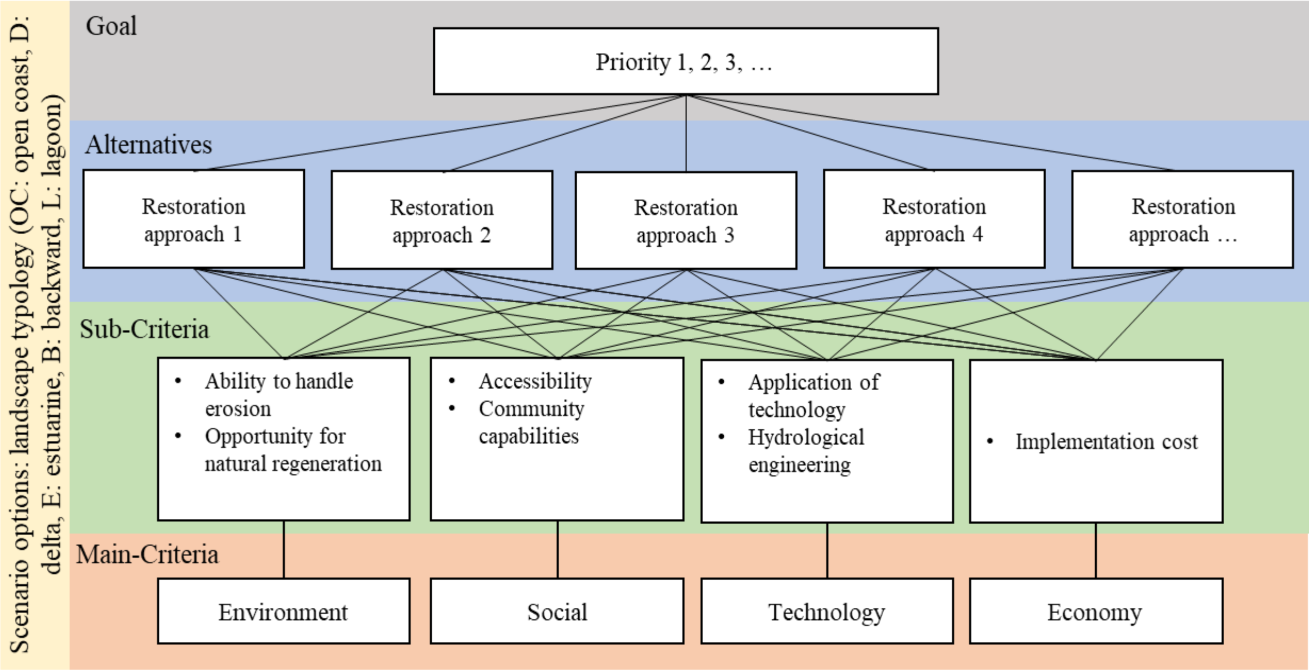

Figure 2. Proposed model for preference ranking organization method for enrichment of evaluations

Table 3. Criteria and sub-criteria for assessing landscape typology scenarios

Aspect/main criteria	Sub-criteria	Scenario assessment				
		Delta	Estuary	Lagoon	Backward	Open coast
Environment	Ability to handle erosion	Min	Min	Min	Min	Max
	Opportunity for natural regeneration	Max	Max	Max	Min	Min
Social	Accessibility	Min	Min	Min	Max	Max
	Community capabilities	Min	Min	Min	Max	Max
Technology	Application of technology	Min	Min	Min	Min	Max
	Hydrological engineering	Min	Min	Max	Max	Min
Economy	Implementation costs	Min	Min	Min	Min	Max

Table 4. Matrix of criteria of evaluation versus alternatives

Criteria	Environment		Social		Technology		Economy
Alternatives	Erosion	Nat.Reg.	Access	Community	Technology	Engineering	Cost
ARR	1	5	5	1	1	3	1
SF	1	5	5	1	1	3	5
EMR	5	5	5	5	5	3	5
EE	5	5	5	5	1	4	3
AMA	1	5	5	5	1	4	5
SECURE	1	5	5	5	5	5	5
ME	1	5	5	5	5	5	5
PRO	1	1	1	1	5	3	1

Note: ARR: Afforestation, reforestation, revegetation, SF: Silvofishery, ME: Mangrove ecotourism, EMR: Ecological mangrove restoration, EE: Ecological engineering, AMA: Associated mangrove aquaculture, SECURE: Shrimp carbon aquaculture, PRO: Protection

To rank the alternatives using the PROMETHEE method, it is necessary to define the preference function P(a,b) for alternatives a and b after establishing the evaluation criteria. In PROMETHEE, preferences are generally represented using six types of criteria: usual criteria, quasi criteria, linear preference criteria, level criteria, linear preference with indifference, and Gaussian. The evaluation was carried out using a five-point scale provided by PROMETHEE software, i.e., very good (5), good (4), average (3), bad (2), and very bad (1). The evaluation criteria versus alternatives matrix is presented in Table 4.

Weigthing of criteria

In this study, the setting of the weights is defined as assigned equally to the 4 main criteria and 7 sub-criteria. Equal weighting was selected intentionally to avoid overemphasizing any single dimension (environment, social, technology, and economic) in a national policy context where stakeholders often hold divergent priorities. Using equal weights is a common baseline approach in Multi-Criteria Decision Analysis (MCDA) when no consensus exists on the relative importance of criteria. The aim is to treat dimensions as normatively co-equal, inputs are qualitative and heterogeneous.

Sensitivity analysis

The PROMETHEE decision-making framework allows the ranking of alternatives to be re-evaluated as the weights assigned to evaluation criteria vary. This characteristic enables sensitivity analysis to assess the stability and robustness of the decision outcomes by modifying criterion weights. Within the Visual PROMETHEE, the effects of these weight variations on the ranking are examined using the visual stability intervals tool. In this analysis, the weight of a given criterion is modified within a defined range for which the overall ranking of alternatives remains unchanged, indicating stability. Subsequently, the criterion weights are altered beyond this range to identify conditions under which the ranking structure changes. The PROMETHEE framework also incorporates the selection of appropriate preference functions and their associated thresholds. As the method relies on linear preference flow functions with respect to criterion weights, sensitivity analysis can be conducted in a straightforward and transparent manner.

Ecosystem mangrove distribution mapping

The distribution of mangrove ecosystems was mapped through a combined unsupervised and supervised classification approach. Initially, an Iso Cluster unsupervised classification was applied to multispectral satellite imagery to identify preliminary spectral clusters representing potential mangrove and non-mangrove classes. These clusters were subsequently used to guide training sample selection for machine learning-based supervised classification, which exploited spectral bands and vegetation indices effective for mangrove discrimination. The resulting mangrove distribution map was further refined through visual interpretation and spatial masking within coastal and tidal influence zones, following established global mangrove mapping frameworks (Bunting et al. 2018). To develop mangrove forest density maps, we used global forest canopy height data (Potapov et al. 2021) to estimate aboveground biomass (AGB) by applying the allometric equation proposed by Simard et al. (2019). The resulting AGB estimates were subsequently reclassified into forest density classes, following the classification scheme described by Lang et al. (2021).

Mangrove typology distribution mapping

The biophysical typology of mangroves was mapped following the typology framework proposed by Worthington et al. (2020), with modifications applied to the underlying spatial datasets to better reflect local biophysical conditions. The typology was derived by integrating spatial information on mangrove position relative to the coastline and tidal influence, geomorphic setting, and vegetation structure. The mangrove proximity map was generated based on coastline data analyzed using the euclidean distance method. This analysis calculated the distance of each pixel from the coastline as a proxy for the spatial proximity of mangrove areas to coastal influences. The resulting distance surface was subsequently classified into four proximity classes: 0-100 m (fringe mangroves), 100-200 m (interior 1), 200-300 m (interior 2), and >300 m (interior 3).

Geospatial analysis

The potential for national-scale mangrove restoration was assessed using a cross-analysis overlay process. To present our results, we use a Geographic Information Systems (GIS) approach to create spatially explicit maps. The software used in the analysis is Quantum GIS Desktop with the spatial join analysis tool. Spatial join is performed to combine multi- datasets based on the spatial relationship between the features in them, namely combining the restoration approach priorities resulting from the PROMETHEE analysis.

RESULTS AND DISCUSSION

Mangrove restoration approaches in Indonesia

Since the early 1800s, mangroves have been systematically exploited in Indonesia, particularly for the construction of ponds and timber extraction, beginning in the Java region, then followed by Sumatra, Sulawesi, Kalimantan, Bali-Nusa Tenggara, Papua, and Maluku in succession (Ilman et al. 2016). Collective awareness at the national level regarding the importance of mangroves until the 1990s was not fully realized until the tsunami on 12 December 1992, on Flores Island (Shi et al. 1995), which was followed by the tsunami on the southern coast of Java Island in June 1994 (Dawson et al. 1996), and the Aceh Tsunami on 26 December 2004, which caused massive damage to coastal ecosystems.

This tragic event marked a turning point in raising awareness about the crucial role of mangrove ecosystems in coastal protection. In response, various restoration initiatives began to prioritize mangrove reforestation as a key strategy for strengthening coastal resilience (Cochard et al. 2008). During this period, the focus of ecosystem improvement efforts gradually expanded from terrestrial to coastal areas, with particular emphasis on mangrove ecosystems. Accordingly, the approaches to mangrove restoration have undergone significant and rapid development, and continue to evolve in line with improvement efforts undertaken by various stakeholders.

The approach to mangrove restoration in Indonesia is inherently linked to the various drivers of mangrove deforestation and degradation, which primarily include land-use conversions for aquaculture, agriculture, infrastructure expansion, livestock grazing, timber extraction, and land subsidence (Ilman et al. 2016; Richards and Friess 2016; Sasmito et al. 2019). We identify six approaches that have been developed, including afforestation, reforestation, and revegetation (Kusmana 2017), silvofishery (Suryaperdana et al. 2012), ecological mangrove restoration (Lewis 2005; Lewis and Brown 2014; Ellison et al. 2020), ecological engineering (Lewis 2005), associated mangrove aquaculture (Bosma et al. 2016; Ariyati et al. 2019), and shrimp-carbon aquaculture (Ahmed et al. 2018; Rifqi et al. 2022). The hotspot distribution of the implementation of various mangrove restoration approaches in Indonesia is presented in Figure 3.

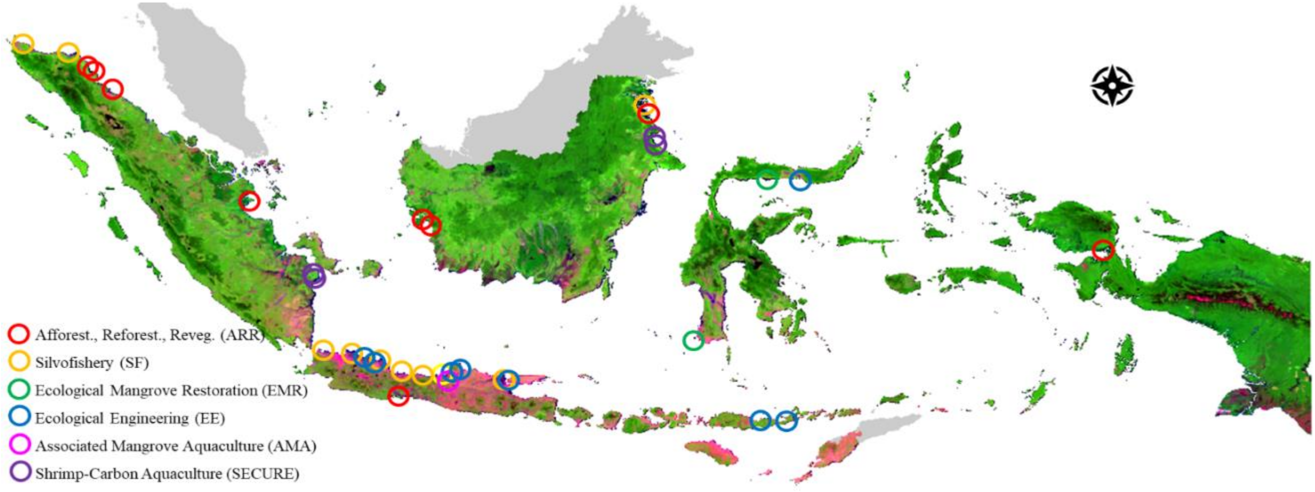

Figure 3. Hotspot distribution of implementation of various mangrove restoration approaches in Indonesia

In addition to technical approaches, Indonesia recognizes the establishment of protected and conservation areas. The designation of these protected and conservation areas is supported by a strong legal foundation derived from various national laws and regulations. From a public policy perspective, mangrove protection efforts may be undertaken by government authorities through the formal designation of areas as protected forests or conservation forests within the national forest area classification system. The principal aim of such designation is to establish a clear and legally recognized status for these areas, ensuring their acknowledgment and legitimacy among multiple stakeholders. In essence, the governance framework for mangrove ecosystem protection comprises a series of systematic procedures that integrate both technical and non-technical approaches to secure the long-term sustainability and ecological integrity of the ecosystem. In this study, the term "protection" extends beyond spatial designation to include proactive measures aimed at avoiding and reducing deforestation, with the ultimate goal of preserving critical mangrove habitats.

Afforestation, reforestation, revegetation (ARR)

Afforestation, reforestation, and revegetation are three approaches that share a common goal of increasing or restoring vegetation cover, particularly trees. However, they differ in terms of context and objectives. Afforestation refers to the establishment of forests in areas that have not been forested for a long period, effectively creating new forested landscapes (Shi et al. 2015). Reforestation, on the other hand, involves replanting trees in areas that were once forested but have undergone deforestation (Mohan et al. 2021). Revegetation is a broader concept that includes the recovery of various types of vegetation on degraded lands, often aimed at strengthening soil structure and preventing erosion (Shanahan et al. 2011). At the initial milestone of the concept, the mainstream was planting, and for a long time, planting has been widely adopted as a preferred strategy (Ellison 2000).

Mangrove restoration efforts were carried out in state forest management, which was regulated by government regulations, by applying the silvicultural system (Jenke et al. 2021). The silvicultural system is the practice of controlling the growth, composition/structure, and quality of forests to meet values and needs, particularly timber production. In general, silviculture is the science and art of growing and cultivating forest plants, based on knowledge of the general characteristics of trees and forest stands, with particular reference to local/regional factors (Pommerening et al. 2024).

We define the silvicultural system as an inseparable part of rehabilitation efforts. Generally, planting (for the purpose of afforestation, reforestation, revegetation) activities have become the basis of activities, and planting provides the potential for accelerating the increase in mangrove colony stands. In addition, planting will be beneficial in conditions where the supply of seeds and natural propagules is very limited due to the unavailability of the mother tree or hydrological disconnection, inhibiting the spread of seeds and propagules (Broadhurst et al. 2008). This can happen in coastal areas that are experiencing extensive mangrove degradation. Plantings may also be undertaken for the reintroduction of certain valuable and lost species from the area, referred to as enrichment plantings (Mangueira et al. 2019).

Silvofishery (SF)

The utilization of coastal resources for pond-based enterprises should ideally take into account both community needs and the preservation of mangrove ecosystems (Musa et al. 2020). To achieve this balance, a sustainable and environmentally friendly land-use model can be adopted, namely, the development of silvofishery system (Primavera 2004). Silvofishery (SF), or integrated mangrove-pond farming, is an agroforestry approach implemented as part of social forestry programs in densely vegetated mangrove areas. This model combines aquaculture ponds with mangrove vegetation, aiming to enhance community livelihoods while simultaneously ensuring the conservation of mangrove ecosystems (Walters et al. 2008)

The concept of SF in Indonesia developed as a response to the high rate of mangrove forest conversion into intensive aquaculture ponds, which has led to the degradation of coastal ecosystems since the 1970s, and began to be adopted in Indonesia in the late 1970s through the 1980s (Fitzgerald 2000; Susilo et al. 2018). Since 1986, Perum Perhutani has developed a Social Forestry program. This program integrates fish cultivation and mangrove forest management, known as *tambak* intercropping or *wanamina,* which they later called the *wanamina* concept (Suryaperdana et al. 2012). Mangrove forest management in this area is carried out by actively involving the community through the joint community forest management (*Pengelolaan Hutan Bersama Masyarakat*) system through the intercropping pond system, most of which are made with a trench pattern, and a small part with a *komplangan* pattern and a pathway pattern. The practice of silvofishery was first introduced and developed in Subang District with the initiation by Perhutani.

Overall, SF has evolved into a strategic model for managing coastal zones in Indonesia by integrating ecological conservation, economic utilization, and community-based empowerment (Suyono and Fithor 2025). The effectiveness of this approach is largely influenced by the availability of institutional support, access to education, formal recognition of land tenure, and the ability to adapt to site-specific biophysical characteristics. As a result, silvofishery is increasingly acknowledged as a key method for mangrove restoration and for enhancing the socio-ecological resilience of coastal communities across the country.

Ecological mangrove restoration (EMR)

Ecological mangrove restoration (EMR) is defined as an approach to rehabilitation or restoration of coastal wetlands that seeks to facilitate natural regeneration in order to produce a self-sustaining wetland ecosystem (Lewis and Brown 2014). EMR is based on the number of failed planting activities; this approach is considered more effective, namely by creating adequate conditions for mangroves to grow back naturally. Mangroves that are restored in this way will generally survive and function better. Planting single-species mangroves, growing non-functional mangroves provides little ecological advantage and is less resilient. Rehabilitation and restoration techniques are not limited to how to plant good mangroves with a high survival rate.

Various rehabilitation techniques were developed by the researchers. Mangrove planting failures often stem from selecting inappropriate species or planting in unsuitable sites, such as areas that are permanently submerged, unaffected by tides, exposed to strong wave action, or lacking adequate soil and water quality. Planting in locations where hydrological disruptions persist, or where mangroves naturally regenerate, can hinder broader ecological recovery. Similarly, introducing mangroves into non-mangrove habitats like mudflats, seagrass beds, or sandy beaches can lead to habitat degradation and biodiversity loss.

EMR approach in which the intertidal zone is manipulated (dragged or filled) so that the biophysical conditions, especially inundation, are within tolerable limits for the formation, growth, and reproduction and regeneration of mangroves (Lewis 2005; Ellison et al. 2020). EMR emphasizes facilitating natural regeneration by first addressing biophysical constraints such as hydrology and soil conditions. While planting is typically unnecessary under ideal conditions, due to natural propagule dispersal, there are cases where it is implemented for stakeholder engagement or due to institutional commitments. When conducted carefully, planting can support natural succession without disrupting ecosystem dynamics. Successfully restored mangrove ecosystems tend to exhibit structural complexity, functional diversity, and greater ecological resilience, contributing to a wide range of ecosystem services and community-based benefits (Lewis 2005; Primavera and Esteban 2008; Ellison et al. 2020).

Community-Based Ecological Mangrove Restoration (CB-EMR) is an improvement from the EMR approach by involving the community in its implementation (Brown et al. 2014). EMR basically only focuses on biophysical assessment and eco-hydrological improvement. When implemented in Indonesia, EMR requires a higher cost biophysical approach if carried out without community involvement. CB-EMR accommodates the socio-cultural-political environment of the local community to reduce the cost of repairing the mangrove ecosystem. Several things are taken into consideration, one of which is that sometimes the program's failure is because local communities are not involved in supporting conservation ideas or because alternative livelihoods are not adequate. For example, when local communities rely heavily on aquaculture activities, newly planted mangroves are more likely to be converted into ponds. EMR has been well implemented and documented over the last few decades (Lewis 2005), and EMR practices in Indonesia have been tested, one of which is in the Sulawesi Region (Brown et al. 2014).

Ecological engineering (EE)

The ecological engineering (EE) approach in mangrove ecosystems is an ecological design strategy that applies ecological principles to design, rehabilitate, or engineer mangrove ecosystems with the goal of achieving sustainable ecological functions and ecosystem services (Lewis 2005). This approach integrates the disciplines of ecology, civil engineering, and coastal governance to restore the natural structure and functions of mangrove ecosystems, including biodiversity, productivity, and climate change mitigation capacity. It aims to reduce disaster risks such as coastal erosion, shoreline retreat, and tidal flooding through the use of nature-based solutions, while enhancing socio-ecological resilience, for example, by incorporating local community needs into restoration or conservation design (van Zetten et al. 2023).

EE approaches to mangrove ecosystem restoration do not rely solely on planting efforts, as wave exposure, submersion duration, and sediment conditions in eroded areas are often no longer suitable for direct planting. Inappropriate site selection can damage natural mangrove formations and result in fragile stands. Instead, it is necessary to construct temporary semi-permeable barriers to dissipate wave energy and trap sediments, thereby creating protected nearshore areas that facilitate accretion. Once the coastal substrate elevation becomes sufficient, mangroves will regenerate naturally, developing natural defenses that protect inland areas from further erosion.

Natural mangrove forest shows a clear land-to-ocean zoning with different species. That is because not all species are equally able to survive inundation, wave exposure, and salinity levels in the ocean front (Ellison et al. 2022). In practice, EE is physically implemented through the application of environmentally friendly coastal protection technologies, such as permeable breakwaters with hybrid engineering structures (Sugianto et al. 2022). The fundamental philosophy behind the construction of permeable breakwaters is to rehabilitate mangrove habitats by restoring sediment dynamics, thereby promoting natural mangrove growth (Winterwerp et al. 2020). The core principle of this approach is that the effectiveness of permeable breakwaters depends on a comprehensive understanding of the physical and biological systems, as well as a thorough analysis of relevant processes. It also requires patience in terms of maintenance, as the natural timescale for rehabilitating mangrove greenbelts can be lengthy, along with intensive stakeholder involvement throughout the process.

Associated mangrove aquaculture (AMA)

Associated mangrove aquaculture (AMA) is an approach that integrates aquaculture with mangrove forestry by establishing green belts of mangroves along the shorelines of waterways in estuary areas (Bosma et al. 2020a). This approach contrasts with conventional aquaculture ponds, which often lack sufficient mangrove coverage or have none at all. AMA is a form of silvo-aquaculture, sometimes referred to as mixed mangrove-aquaculture. However, it differs from traditional silvo-aquaculture systems, where mangroves are typically planted on pond embankments or within ponds (Bosma et al. 2016). In the AMA approach, mangroves are planted outside the pond areas.

The AMA system was first introduced in Demak District, where supporting activities preceded its implementation.

Farmers were encouraged to participate in coastal field schools to enhance their knowledge and awareness of the ecological and economic importance of mangrove ecosystems (Widowati et al. 2021). Through these programs, farmers recognized the need to reestablish mangrove green belts along coastal areas, estuaries, rivers, and canals. As a result, more than 24 farmers voluntarily gave up their degraded ponds for coastal green belt restoration, covering an area of 50 ha. Additionally, 48 other farmers withdrew portions of their ponds from riverbanks and implemented the AMA system on an area of up to 10 ha.

The coastal field school also educates local communities on how to adopt low external input sustainable aquaculture, which originally developed as an agricultural cultivation method, aiming to minimize the use of chemical inputs that can pollute and degrade the environment (Kessler and Moolhuijzen 1994). The implementation of AMA shows that the reduction in pond area in the conversion of extensive ponds to AMA ponds does not reduce yield gains, considering that smaller pond areas actually yield more. In addition, AMA practices also provide benefits for farmers, such as increasing additional catches of shrimp and fish trapped in water gates and catches around ponds (Bosma et al. 2020b).

Shrimp-carbon aquaculture (SECURE)

Shrimp-carbon aquaculture (SECURE) is an approach and initiative to restore mangrove ecosystems and increase the production of traditional ponds by reducing the cultivated area to 20% and utilizing 80% for the mangrove ecosystem. An effort to support environmentally friendly shrimp farming practices with the primary objectives of restoring mangrove ecosystems, reducing carbon emissions, increasing the volume and sustainability of shrimp harvests, improving shrimp quality through certification, enhancing community income, and reducing disaster risk. SECURE was introduced in 2020 with pilot locations in Kampung Pegat Batumbuk and Kampung Tabalar Muara, East Kalimantan. SECURE was first introduced by the Berau District Fisheries Service, supported by the Yayasan Konservasi Alam Nusantara, Ministry of Marine Affairs and Fisheries, and Archipelagic Maritime Institute in 2022.

The problems faced by brackish water ponds are usually low seed quality, inappropriate management of pond water and soil quality, and uncontrolled use of pesticides. The SECURE approach attempts to address this by improving pond design and construction, managing environmental quality, and adapting aquaculture technologies. In the future, ponds will serve as demonstration plots for learning, sharing experiences through field school programs, and supporting group and business development. By implementing sustainable aquaculture practices, SECURE demonstrates that economic growth can align with global efforts to reduce greenhouse gas emissions. Based on the results of this initial trial cycle, the SECURE approach can enhance pond productivity while engaging local communities in restoring previously unproductive ponds into healthy mangrove ecosystems.

Protected area (PRO)

One of the key efforts in forest protection is the designation of protected areas (Slobodian et al. 2025). The regulatory approach to mangrove protection is a primary strategy employed by the government to safeguard the existence and ecological functions of mangroves through legal and policy instruments (Mohamed et al. 2023). This approach typically involves the formal designation of areas with specific legal status. The establishment of protected and conservation areas is a strategic component of forest protection policy. With robust regulations, community-based management, and an appropriate ecosystem-based approach, mangrove ecosystems can continue to provide ecological and economic benefits without further degradation (Anggraeni 2024). Mangrove conservation is not solely the responsibility of the government, but also of local communities, the private sector, and the scientific community to ensure the long-term sustainability of coastal ecosystems (Macamo et al. 2024).

However, a more comprehensive understanding requires that protection also encompass proactive efforts to prevent, mitigate, and control deforestation pressures that are actually occurring on the ground. This proactive approach encompasses variety of mechanisms, from patrol monitoring and enforcement of conversion prohibition regulations, economic incentives for communities to conserve mangroves, to the use of satellite-based monitoring technology. The goal is to minimize the risk of both planned and unplanned deforestation.

Mangrove ecotourism (ME)

While mangrove ecotourism may not be classified as a formal restoration approach, its successful transformation of mangrove landscapes into ecotourism sites has demonstrated its potential to sustain and protect mangrove ecosystems (Hidayat et al. 2024). Ecotourism was first conceptualized in the early 1980s as an alternative for people who wanted to learn about the environment without causing harm (Cobbinah 2015), and today, ecotourism continues to grow as more people travel with environmental awareness.

In addition to generating income for local communities, mangrove ecotourism can foster a sense of stewardship and collective responsibility toward conservation. By providing tangible economic benefits, such as employment opportunities and alternative livelihoods, ecotourism reduces local dependence on destructive practices like timber extraction or aquaculture expansion. Moreover, ecotourism activities that incorporate education and community engagement can increase public understanding of the ecological importance of mangroves, thereby strengthening long-term conservation outcomes. When well-managed, ecotourism thus serves as both a socio-economic driver and an indirect restoration tool that complements more formal ecological interventions. The summary of the identified mangrove restoration approaches is presented in Table 5.

Table 5. Summary of mangrove restoration approach, key innovation, and core implementation

Restoration approach	Geo. setting	Key innovation	Core implementation
ARR	Log over area/ intertidal open land	Early reforestation through tree planting	Focused on re-greening degraded logging sites
SF	Traditional active pond	Integration of aquaculture ponds with mangrove stands	Traditional silvofishery model for dual productivity
EMR	Abandoned pond/intertidal open land	Ecological mangrove restoration based on natural conditions	Rehabilitation of abandoned ponds using ecological principles
EE	Eroded coast	Eco-engineering for coastal stabilization	Building with nature technology to counter coastal erosion
AMA	Traditional pond associated open coast	Integration of aquaculture associated with mangroves	Sustainable production while maintaining ecosystem functions
SECURE	Traditional pond	Low-emission aquaculture with blue carbon approach	Climate-friendly shrimp farming linked with carbon certification
ME	Landscape	Use of ecotourism as a conservation incentive	Local economic diversification based on ecosystem services
PRO	Landscape	Landscape-scale mangrove protection through regulation	Institutional strengthening and technical implementation units

Note: ARR: Afforestation, reforestation, revegetation, SF: Silvofishery, ME: Mangrove ecotourism, EMR: Ecological mangrove restoration, EE: Ecological engineering, AMA: Associated mangrove aquaculture, SECURE: Shrimp carbon aquaculture, PRO: Protection

Preference ranking evaluation for mangrove restoration approach

Delta/estuary

Mangrove restoration approaches (Table 5) have been developed through an extensive process of implementation, monitoring, and evaluation. These approach variations also provide an overview of the historical development and serve as implementation references across various coastal landscape typologies. At least five landscape typologies yield several combinations of priorities. Delta typologies show morphodynamic evolution characterized by land expansion and the formation of new islands at river mouths. Alongside this land growth, natural colonization by mangrove vegetation also occurs (Kodikara et al. 2017). That highlights the importance of protecting delta areas to sustain key ecosystem functions such as carbon sequestration, flood protection, and land formation (Friess et al. 2019). Accordingly, the PRO obtained the highest Φ^+ and the lowest Φ^- values, highly recommended for delta and estuary typologies. ARR and ME/SF are identified as the most effective active interventions for ecological recovery in productive areas such as deltas and estuaries. AMA and EMR are well-suited for areas that have undergone pond conversion and require socio-ecological approaches. While EE plays an important role in coastal protection, it demands substantial technical support and high investment.

The ARR and ME/SF approaches also demonstrated strong performance, with positive net Φ values. ARR is considered suitable for delta areas because the delta typology has a high level of anthropogenic deforestation. SF and ME are also relevant for restoring delta areas that have been converted into fishponds, providing a balance between economic and ecological values (Bosma et al. 2020b). In contrast, the AMA and EMR approaches showed lower Φ^+ and higher Φ^- values, indicating that other strategies often outperformed them. This may be attributed to their reliance on social infrastructure and community technical capacity, which require strong support, particularly in highly dynamic delta environments (Bayraktarov et al. 2016). The EE approach has the lowest net Φ value among all alternatives. Although effective in open coastal areas, this approach may be less relevant for delta environments due to their ecological characteristics, which naturally support sediment stabilization. As a result, technical interventions tend to be less efficient than vegetation-based restoration and protection strategies in such settings (Temmerman et al. 2013). PROMETHEE results in the form of a partial complete ranking of delta/estuary are presented in Figure 4.A.

Based on the results of the same weighting exercise conducted in the previous section, it was found that both increasing and decreasing community capacity appeared to be favorable factors for various restoration approaches. To test the significant impact of these constraints, a sensitivity analysis was conducted to test the robustness of the results by verifying the ranking changes resulting from variations made to the sub-criteria weights. As shown in Figure 4.B to 4.H delta/estuary scenario, it was found that no changes in results occurred whilst the weights were kept interval ability to handle erosion: 11.11%-17.24%, accessibility: 0-100%, community capabilities: 0-100%, application of technology 9.43%-15.79%, opportunity for natural regeneration: 12.73%-23.81%, implementation cost: 13.04%-21.05%, and hydrological engineering: 3.57%-15.63%. The ability to handle erosion and application of technology criteria has the narrowest intervals, making them the most sensitive criteria. This indicates that small changes in the weights of these two criteria can directly influence changes in the ranking of restoration alternatives in delta/estuary landscapes. In contrast, the accessibility and community capabilities criteria show very wide stability intervals, meaning that changes in the weights of these two criteria do not affect the ranking of alternatives. Thus, in the context of delta/estuary landscapes, these social factors are relatively insignificant in influencing decision-making outcomes. Meanwhile, the implementation cost, opportunity for natural regeneration, and hydrological engineering criteria have moderate sensitivity, with wider stability intervals than the two most sensitive criteria, but are still limited. Substantively, these results confirm that in delta/estuary ecosystems, biophysical and technical factors, particularly the ability to handle erosion and the application of technology, are the primary determinants in prioritizing restoration alternatives.

Lagoon

Lagoon typology scenarios, the priority for restoration activities is ME and PRO, particularly focused on preventing the spread of invasive species. The calm waters in lagoons are also well-suited for mangrove-based ecotourism, providing safe conditions for activities such as boat tours, birdwatching, and environmental education, while minimizing risks from abrasion or high wave disturbance. Implementing mangrove ecotourism in lagoon areas has been shown to raise public awareness about conservation and deliver sustainable economic benefits to local communities (Rönnbäck 1999). In contrast, interventions such as mangrove planting (ARR) or extensive EE are generally not prioritized in lagoon settings. This is because lagoon ecosystems often already provide stable hydrological conditions and natural regeneration potential, making intensive engineering unnecessary and sometimes even disruptive. PROMETHEE results in the form of a partial complete ranking of lagoon are presented in Figure 5.A.

The results of the sensitivity analysis show that in lagoon scenario, it was found that no changes in results occurred whilst the weights were kept interval ability to handle erosion: 0-17.24%, accessibility: 5.88%-100%, community capabilities: 5.88%-100%, application of technology 12.73%-100%, opportunity for natural regeneration: 9.43%-15.79%, implementation cost: 11.76%-20%, and hydrological engineering: 5.26%-20.59% (Figure 5.B-5.H). The opportunity for natural regeneration criterion has the narrowest interval, making it the most sensitive criterion in the lagoon scenario. This means that small changes in the weighting of natural regeneration opportunities can directly influence changes in the ranking of restoration alternatives. The next criteria with relatively high sensitivity are implementation cost and hydrological engineering, indicating that both aspects are also quite important in influencing decision stability. Meanwhile, the ability to handle erosion has a moderate sensitivity level. Conversely, accessibility, community capabilities, and application of technology show very wide stability intervals, making them insensitive. Changes in the weighting of these three criteria do not significantly affect the ranking of alternatives. Substantively, these results indicate that in lagoon landscapes, ecological factors, particularly natural regeneration opportunities, are the primary determinants in determining restoration priorities, while social and technological factors have relatively less influence on decision changes.

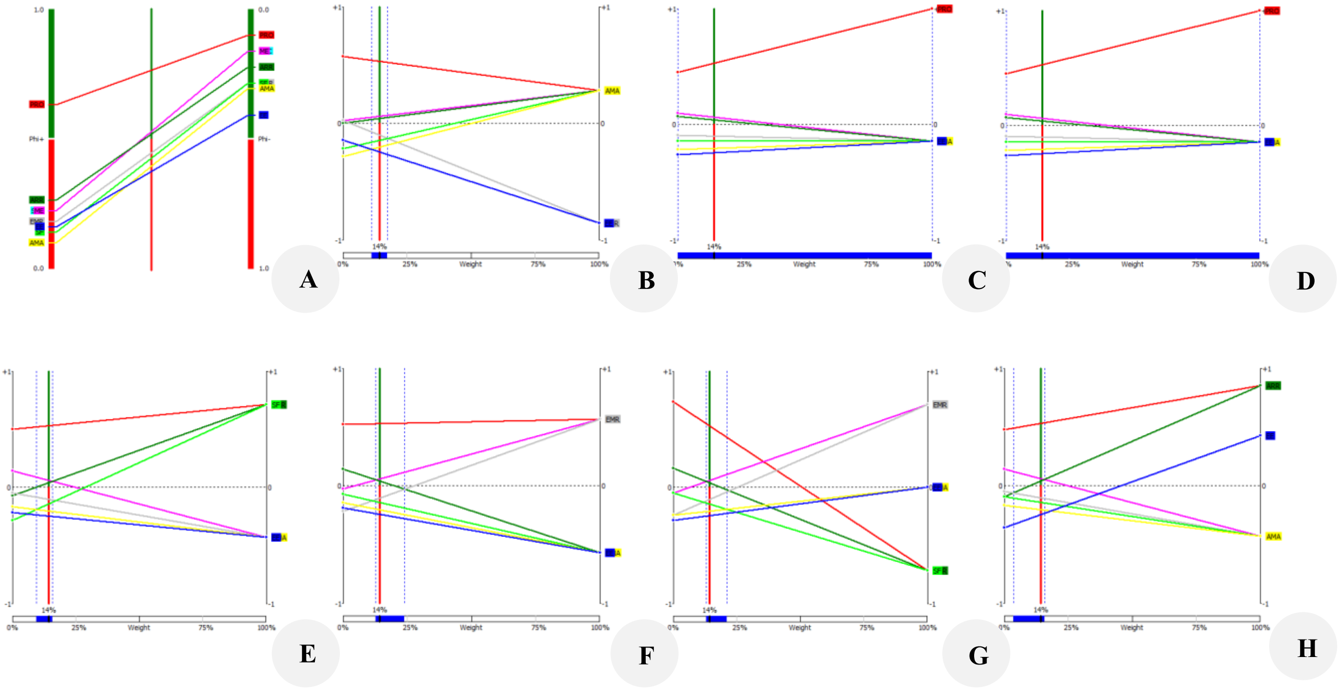

Figure 4. A. Partial complete ranking of scenario in delta/estuary; sensitivity analysis, B. Ability to handle erosion, C. Accesibility, D. Community capabilities, E. Application of technology, F. Opportunity for natural regeneration, G. Implementation cost, H. Hydrological engineering

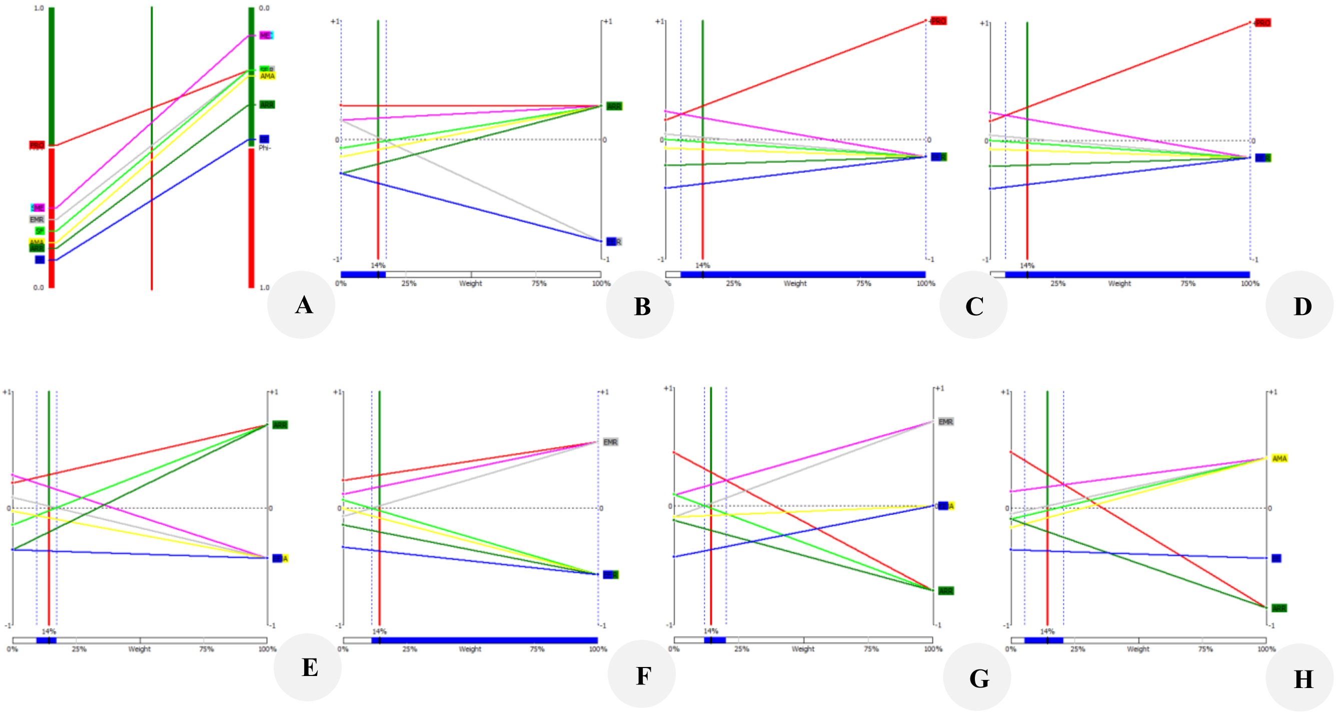

Figure 5. A. Partial complete ranking of scenario in lagoon, sensitivity analysis, B. Ability to handle erosion, C. Accesibility, D. Community capabilities, E. Application of technology, F. Opportunity for natural regeneration, G. Implementation cost, H. Hydrological engineering

Backward

In backward zones, the priority activities are SF and AMA, followed by ARR. The SF and AMA approaches ranked highest, with the most positive net Φ values. This reflects optimal and consistent performance, indicating that approaches combining ecological and economic functions are most suitable for fringe zones with existing or abandoned aquaculture ponds (Primavera et al. 2011). The effectiveness of this approach relies heavily on the availability of a controllable hydrological system and a high level of community engagement. Planting techniques in sheltered areas can be successful as long as basic tidal flushing and drainage are maintained. These conditions support successful vegetative regeneration, particularly for species that are tolerant of salinity fluctuations and muddy substrates (Kodikara et al. 2017). Meanwhile, EMR and EE showed moderate performance, with balanced Φ^+ and Φ^- values. Although these approaches are based on the restoration of natural ecological processes, their success in the backward zone is highly dependent on the reconstruction of hydrological systems, which are often disrupted by human activities (Hai et al. 2020). Conversely, PRO occupies the lowest position in this scenario, because this area has low potential for natural regeneration (Friess et al. 2019; Worthington et al. 2020). PROMETHEE results in the form of a partial complete ranking of backward are presented in Figure 6.A.

The results of the sensitivity analysis show that in backward scenario, it was found that no changes in results occurred whilst the weights were kept interval ability to handle erosion: 5.88%-33.33%, accessibility: 0-100%, community capabilities: 0-100%, application of technology 9.43%-18.64%, opportunity for natural regeneration: 9.43%-15.79%, implementation cost: 10.45%-20%, and hydrological engineering: 10%-20.59% (Figure 6.B-6.H). As the value increases dominantly over those figures, then the priorities appeared to change in all alternatives. The opportunity for natural regeneration criterion has the narrowest interval, making it the most sensitive criterion in the backward scenario. This means that small changes in the weighting of natural regeneration opportunities have the potential to immediately change the ranking of restoration alternatives. The next relatively sensitive criteria are application of technology and implementation cost, indicating that technological and cost aspects also have a fairly strong influence on decision stability. Meanwhile, hydrological engineering and the ability to handle erosion are at a moderate to low sensitivity level because they have a wider stability interval. In contrast, accessibility and community capabilities show a range of 0-100%, meaning that changes in the weighting of these two criteria do not affect the ranking of alternatives. Substantively, these results indicate that in the backward landscape, ecological factors, especially natural regeneration opportunities, along with technical and cost aspects, are the main determinants in determining restoration priorities, while social factors have relatively little influence on decision changes.

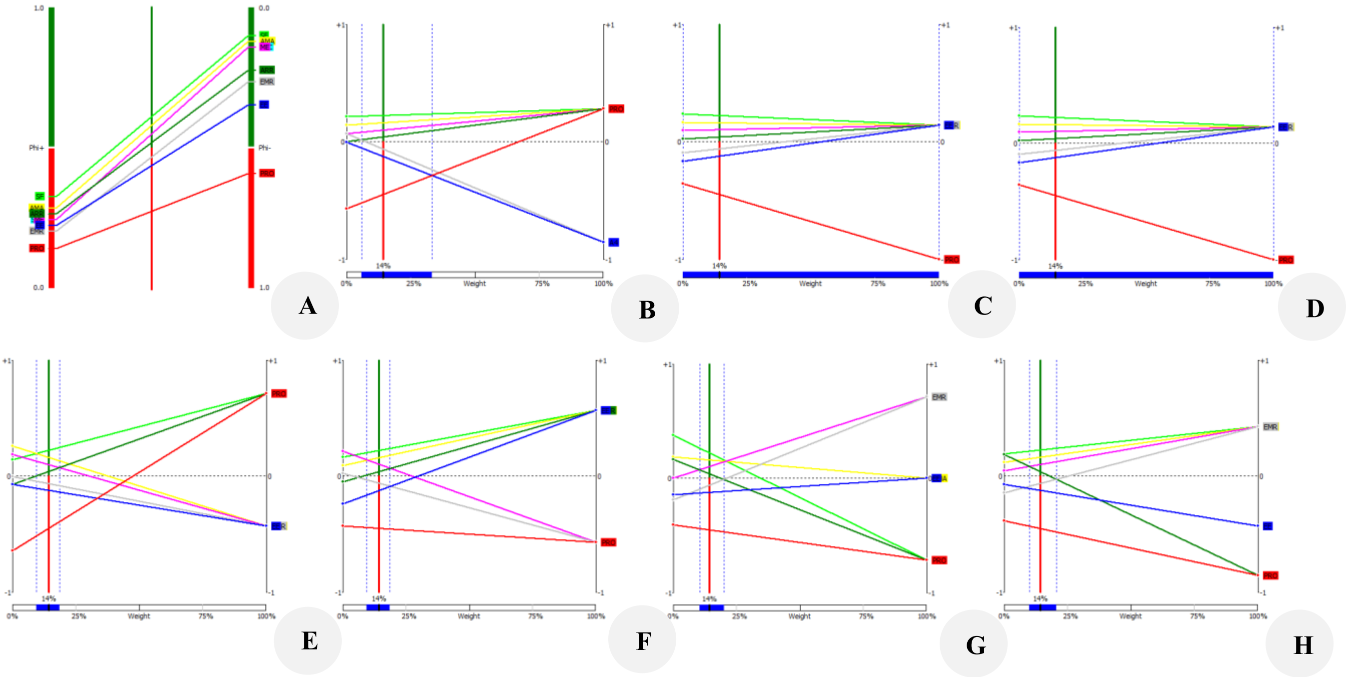

Figure 6. A. Partial complete ranking of scenario in backward; sensitivity analysis, B. Ability to handle erosion, C. Accesibility, D. Community capabilities, E. Application of technology, F. Opportunity for natural regeneration, G. Implementation cost, H. Hydrological engineering

Open coast

In the open coast typology, EE approach achieved the highest leaving flow (Φ^+) and the lowest entering flow (Φ^-), making it the best-performing alternative with the most positive net flow (Φ). EE is identified as the top priority for implementation. The high potential for coastal erosion highlights the importance of constructing shoreline protection structures first to reduce wave energy, which would otherwise lead to planting failures or hinder natural regeneration. EE is considered the most effective approach for open coast conditions due to its technical capacity to cope with extreme environments and to provide an ecological foundation for natural mangrove regeneration. This indicates that EE is the most dominant approach owing to its ability to reduce abrasion and strengthen the shoreline through nature-based bioengineering techniques such as sediment trapping and hybrid structures (Temmerman et al. 2013; Winterwerp et al. 2020).

Other alternatives, such as AMA and EMR, also demonstrated strong performance with positive Φ values. This reflects that socio-ecological approaches can still contribute meaningfully in these areas, particularly in sites that have experienced severe degradation or aquaculture conversion but are located within sheltered zones (Lewis 2005). Meanwhile, the PRO approach showed the weakest performance, with a very low Φ^+ and a very high Φ^-. This is consistent with the context of highly dynamic open coastlines, where passive strategies without technical or vegetative interventions are unlikely to succeed in countering erosion rates or sustaining ecosystem functions (Alongi 2008). Similarly, although ARR is ecologically relevant, it is considered less suitable for open coastlines due to the high failure rate of planting efforts in areas with high wave energy dynamics, especially in the absence of substrate conditioning and initial protective measures (Balke et al. 2011). PROMETHEE results in the form of a partial complete ranking of backward are presented in Figure 7.A.

The results of the sensitivity analysis show that in open coast scenario, it was found that no changes in results occurred whilst the weights were kept interval ability to handle erosion: 5.88%-100%, accessibility: 0-100%, community capabilities: 0-100%, application of technology: 12.73%-100%, opportunity for natural regeneration: 9.43%-15.79%, implementation cost: 13.04%-21.05%, and hydrological engineering: 0-15.63% (Figure 7.B-7.H). As the value increases dominantly over those figures, then the priorities appeared to change in all alternatives. The opportunity for natural regeneration criterion has the narrowest interval, making it the most sensitive criterion in the open coast scenario. This means that small changes in the weighting of natural regeneration opportunities can directly affect changes in the ranking of restoration alternatives. The next relatively sensitive criteria are hydrological engineering and implementation cost, indicating that hydrological engineering and implementation costs also have a significant influence on decision stability. Conversely, the ability to handle erosion and application of technology has very wide stability intervals, making them relatively insensitive. Similarly, accessibility and community capabilities (0-100%) do not affect ranking changes at all. Substantively, these results indicate that in open coast landscapes, ecological factors, particularly natural regeneration opportunities, are the primary determinants in determining restoration priorities, while social factors and some technical factors remain relatively unchanged despite significant modifications in their weighting.

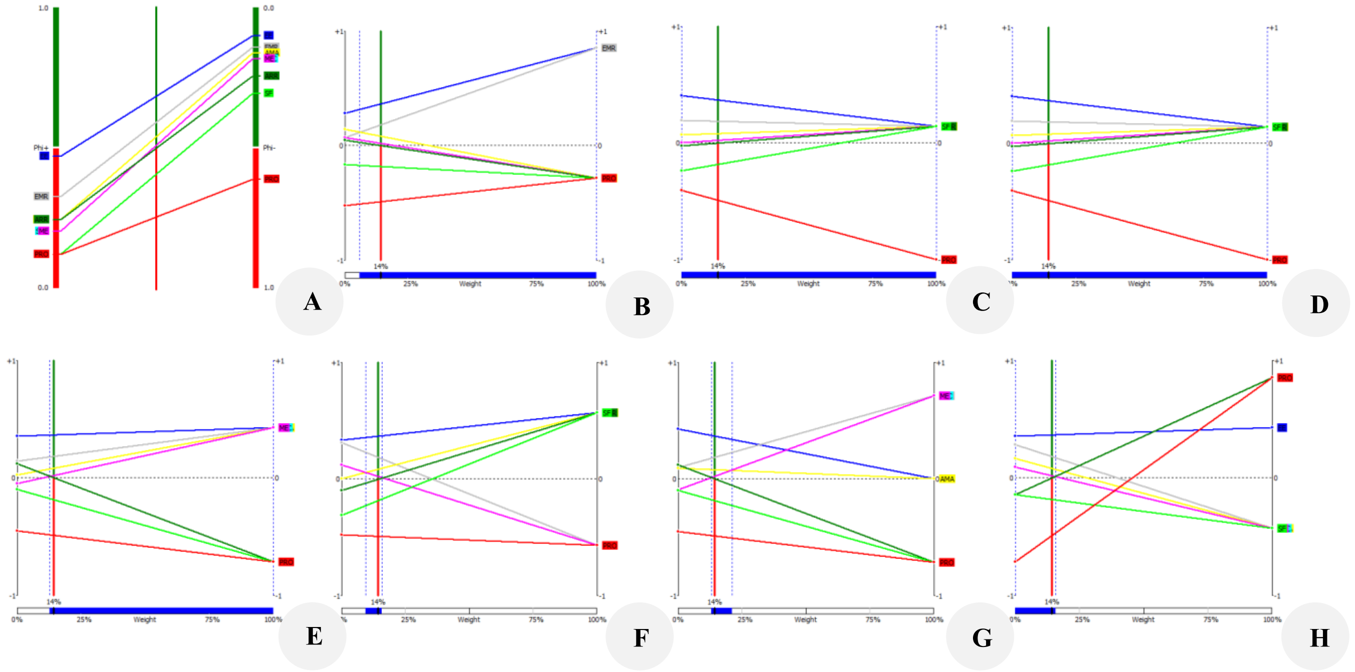

Figure 7. A. Partial complete ranking of scenario in open coast; sensitivity analysis, B. Ability to handle erosion, C. Accesibility, D. Community capabilities, E. Application of technology, F. Opportunity for natural regeneration, G. Implementation cost, H. Hydrological engineering

Priorities across coastal landscape typologies

The integrated priority maps for mangrove restoration in Indonesia illustrate multi-layered scenarios. Priority distribution is derived from the distribution map of mangrove landscape typology. Across the three maps, different approaches are highlighted, reflecting varying levels of urgency and contextual needs. Summary of mangrove restoration approach priorities in landscape typology and policy recommendation presented in Table 6.

Ecosystem mangrove and typology distributions

The quantified mangrove mapping results show that Indonesia has approximately 4 million ha of mangrove ecosystems. Of this total area, about 3.2 million ha remain under mangrove cover, while the remaining 0.8 million ha have been converted into aquaculture ponds. The map shows that mangrove ecosystems across Indonesia are unevenly distributed, with extensive and relatively intact forests concentrated in the eastern and parts of central regions, while western coastal areas exhibit higher fragmentation and stronger overlap with aquaculture (Figure 8). Spatial patterns of mangrove forest density are essential for adjusting restoration and rehabilitation strategies to existing ecological conditions. Variations in canopy cover and structural integrity reflect differing levels of degradation, regeneration capacity, and disturbance history, thereby serving as a practical basis for determining the appropriate level of intervention. By integrating spatial density patterns into restoration planning, interventions can be aligned with ecological realities while improving efficiency in resource allocation and policy implementation. Restoration approaches are differentiated across three density classes low, medium, and high each corresponding to distinct management priorities (Table 7).

In low-density mangrove forests, reduced canopy cover and structural degradation indicate significant ecological disturbance, often associated with land conversion, hydrological alteration, or overexploitation. In such contexts ARR are prioritized to re-establish vegetative structure and recover fundamental ecosystem functions. Enrichment (EN) and protection (PRO) act as complementary strategies to stabilize ecological recovery. Policy recommendations therefore emphasize habitat-suitability-based planting, the establishment of national guidelines for ARR using native species, and ecological calibration to enhance long-term restoration success. For medium-density mangrove forests, ecological structure remains partially intact but may exhibit reduced species diversity or resilience. Consequently, EN becomes the dominant strategy across all priority levels. The objective shifts from structural reconstruction toward ecological enhancement, biodiversity improvement, and strengthening ecosystem services. Policy interventions focus on reinforcing enrichment programs, incorporating systematic monitoring mechanisms, and integrating restoration performance into payment for ecosystem services (PES) and carbon financing schemes. In high-density mangrove forests, which represent relatively intact and functional ecosystems, preventive conservation is more appropriate than active rehabilitation. Accordingly, PRO is consistently prioritized. Maintaining canopy integrity, preventing deforestation, and safeguarding ecological connectivity are more cost-effective and sustainable than reactive restoration. Policy measures therefore emphasize strict protection frameworks, satellite- and community-based monitoring systems, and enforcement mechanisms against illegal conversion. The integration of spatial density patterns into restoration planning enables differentiated, context-specific, and policy-aligned interventions. This approach moves beyond uniform restoration prescriptions and supports more adaptive, ecologically grounded, and strategically targeted mangrove management.

Table 6. Mangrove restoration approach priorities in landscape typology and policy recommendation

Typology	Geo. setting	Priority approach 1	Priority approach 2	Priority approach 3	Policy recommendations
Delta/estuari	Landscape	PRO	ARR	ME	Strengthen land-use zoning and legal protection to prevent land conversion; integrate protection into coastal spatial planning
Open coast	0-100 m	EE	AMA	EMR	Promote ecological engineering and natural regeneration through hybrid green-grey infrastructure; develop community-based coastal protection programs
Backward	100-200 m	AMA	SF	ARR	Provide incentives for aquaculture redesign into silvofishery; introduce eco-certification and soft loans for sustainable aquaculture
	200-300 m	SF	ARR	ME	Encourage intensive mangrove planting combined with silvofishery; integrate restoration into district-level coastal rehabilitation plans
	>300 m	ARR	EMR	SF	Implement intensive planting and ecological restoration in degraded areas; prioritize local mangrove species for reforestation
Lagoon	Landscape	ME	PRO	SF	Establish spatial planning for lagoon ecosystems; strengthen regulation to control invasive species; promote sustainable mangrove-based ecotourism

Note: ARR: Afforestation, reforestation, revegetation, SF: Silvofishery, ME: Mangrove ecotourism, EMR: Ecological mangrove restoration, EE: Ecological engineering, AMA: Associated mangrove aquaculture, SECURE: Shrimp carbon aquaculture, PRO: Protection

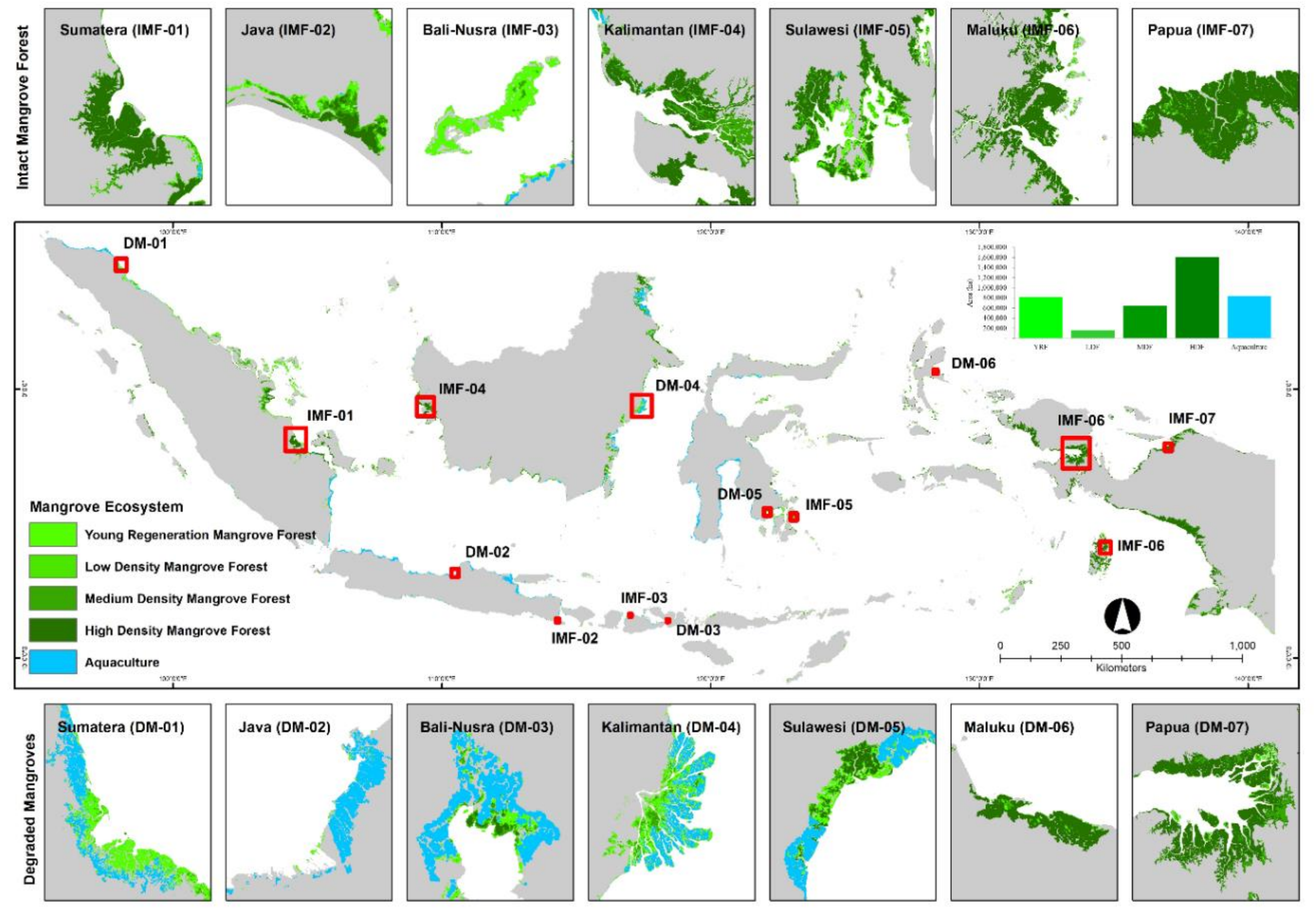

Figure 8. Distribution map of Indonesian mangrove ecosystems

Indonesia's mangrove ecosystem is dominated by the delta typology, covering 1,475,232.26 ha (36%) of the total national mangrove area. This typology is the largest mangrove landscape, reflecting the role of large river systems and sedimentation processes in shaping Indonesia's coastal landscape. The estuary typology ranks second, covering 1,177,673.12 ha (29%), followed by the retreating typology, covering 1,109,152.11 ha (27%). These three typologies cumulatively cover approximately 92% of the total national mangrove area, indicating that most Indonesian mangroves thrive in coastal systems influenced by fluvial dynamics and land-sea transition zones. Meanwhile, the open coast typology covers 280,132.14 ha (7%) of the national total. Despite its relatively small percentage, the presence of mangroves in this typology holds strategic significance given Indonesia's extremely long coastline, reaching over 95,000 km, one of the longest in the world. Mangroves in open coastal areas generally grow on exposed shores directly exposed to wave energy and ocean currents, thus playing a crucial role in coastal protection from abrasion and oceanographic dynamics. The lagoon typology is the smallest, with an area of 29,452.54 ha, or approximately 1% of the total 4,071,642.19 ha of Indonesian mangrove ecosystems. This distribution confirms that Indonesia's coastal geomorphology is heavily dominated by delta and estuary systems (Figure 9), yet still has typological variations that require different management and restoration approaches according to the physical characteristics and dynamics of each coast.

Table 7. Priority adjusment by mangrove forest density

Mangrove forest density	Adjusment priority			Policy recommendations
	1	2	3	
Low-density forest	ARR	EN	PRO	Implement enrichment planting based on habitat suitability; set national guidelines for afforestation and reforestation with native species
Meduim-density forest	EN	EN	EN	Strengthen species enrichment programs to increase biodiversity and resilience; integrate monitoring into payment ecosystem services/carbon projects
High-density forest	PRO	PRO	PRO	Ensure strict protection from deforestation; adopt satellite and community-based monitoring; establish sanctions for illegal conversion

Note: ARR: Afforestation, reforestation, revegetation, EN: Enrichment, PRO: Protection

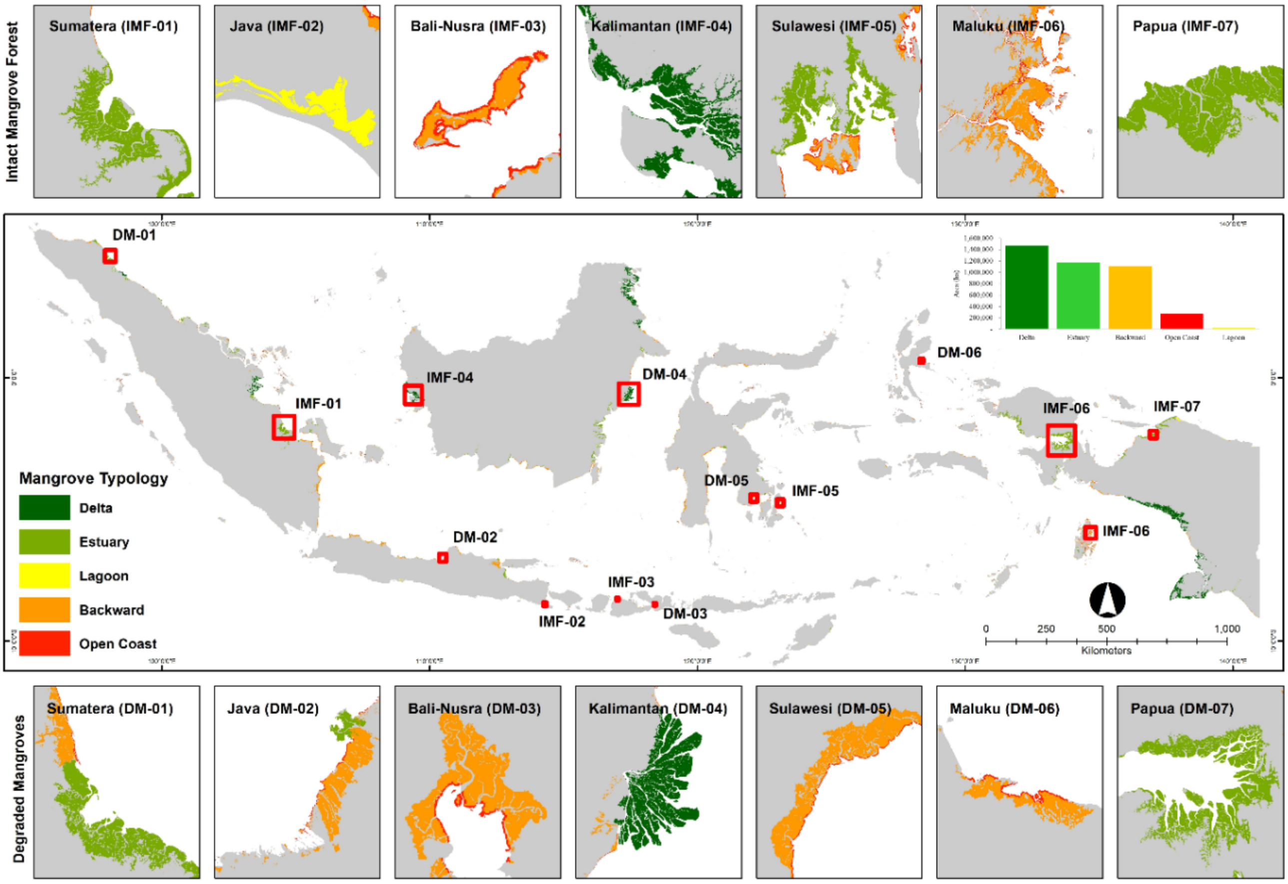

Figure 9. Distribution map of Indonesian mangrove ecosystem typology

Spatial design of mangrove restoration planning based on PROMETHEE analysis

Priority 1 emphasizes critical interventions PRO, ARR, and EE, given the extensive coverage of delta and estuary typologies in Indonesia, as well as the continued existence of intact mangrove forests in several protected and conservation areas, particularly the well-preserved mangrove ecosystems in eastern Indonesia. PRO emerges as the primary and dominant management priority across mangrove ecosystems. PRO overwhelmingly dominates mangrove management strategies in Indonesia, covering 2.6 million ha (65.16%) of the total 4 million ha (Figure 10). This suggests that the majority of Indonesia's mangrove ecosystems remain in conditions that warrant conservation through protection schemes, particularly in areas with relatively intact forest cover and high ecological value. The predominance of PRO highlights that current mangrove management is primarily oriented toward preventing degradation rather than implementing large-scale rehabilitation. The ARR approach ranks second, covering 899,785.92 ha (22.10%) of the total area. This substantial proportion reflects significant rehabilitation needs in degraded areas, including those affected by aquaculture conversion, land-use change, and other disturbances. Meanwhile, EE accounts for 280,132.14 ha (6.88%), indicating the importance of hydrological restoration and coastal stabilization interventions, particularly in physically dynamic environments such as open coasts. EE areas are concentrated in zones vulnerable to coastal erosion and high anthropogenic pressures, such as the northern coast of Java, where EE is essential. EE protects settlements, infrastructure, and productive lands. Sustainable production-based approaches such as AMA (109,466.37 ha; 2.69%) and SF (99,899.83 ha; 2.45%) demonstrate efforts to integrate conservation with livelihood-based economic activities, although their overall proportion remains relatively limited. ME represents the smallest share at 29,452.54 ha (0.72%), suggesting that ecosystem service–based utilization remains a complementary strategy. ME is a potential that creates new income opportunities for communities and protects fisheries and carbon stocks.

Priority 2 reflects a management configuration strongly oriented toward active restoration rather than protection. In this priority level, ARR dominates with 2.7 million ha (67.61%) (Figure 11). This indicates that under priority 2, the majority of mangrove areas are classified as requiring direct planting and revegetation interventions, suggesting widespread degradation or conversion that limits natural recovery processes. The second largest component is EMR, covering 899,785.92 ha (22.10%). The substantial proportion allocated to EMR highlights the importance of restoring ecological functions, particularly hydrological connectivity before or alongside planting efforts. The combined dominance of ARR and EMR (nearly 90% of the total area) clearly characterizes priority 2 as a rehabilitation-focused strategy emphasizing ecosystem recovery through both technical and process-based restoration approaches. Meanwhile, production-integrated approaches such as AMA (280,132.14 ha; 6.88%) and SF (109,466.37 ha; 2.69%) play a complementary role. Their inclusion suggests that, even within a restoration-driven priority, socio-economic integration remains relevant to ensure community engagement and long-term sustainability. In contrast, PRO accounts for only 29,452.54 ha (0.72%), indicating that relatively few areas under priority 2 are categorized as intact ecosystems requiring strict conservation.

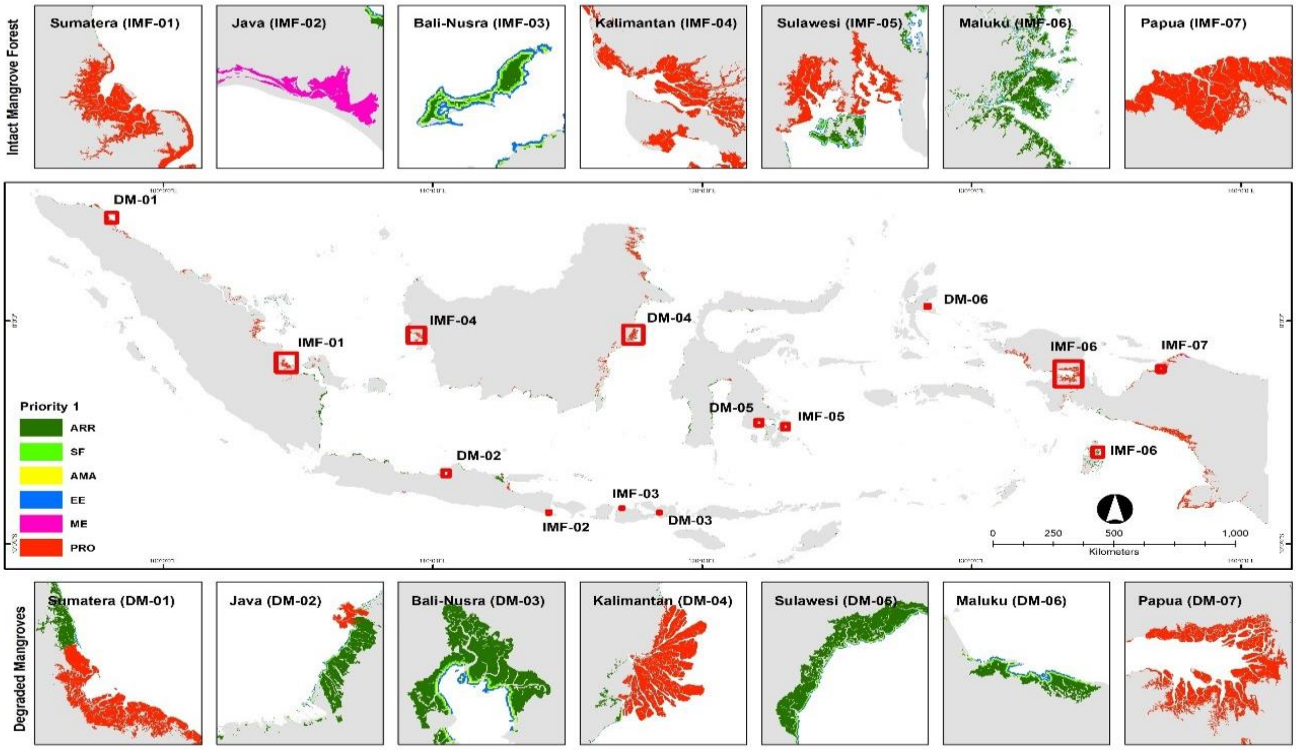

Figure 10. Spatial explicit distribution of priority 1 mangrove restoration approaches

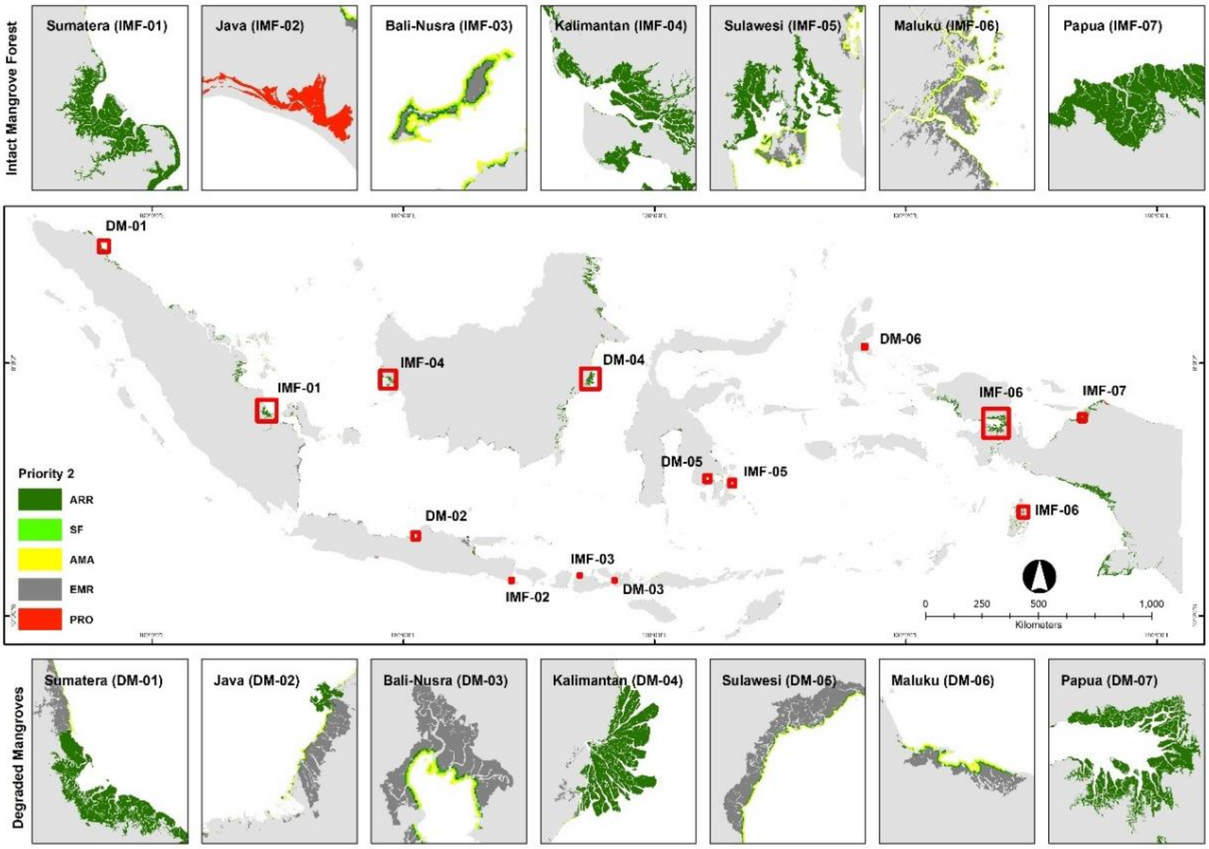

Figure 11. Spatial explicit distribution of priority 2 mangrove restoration approaches

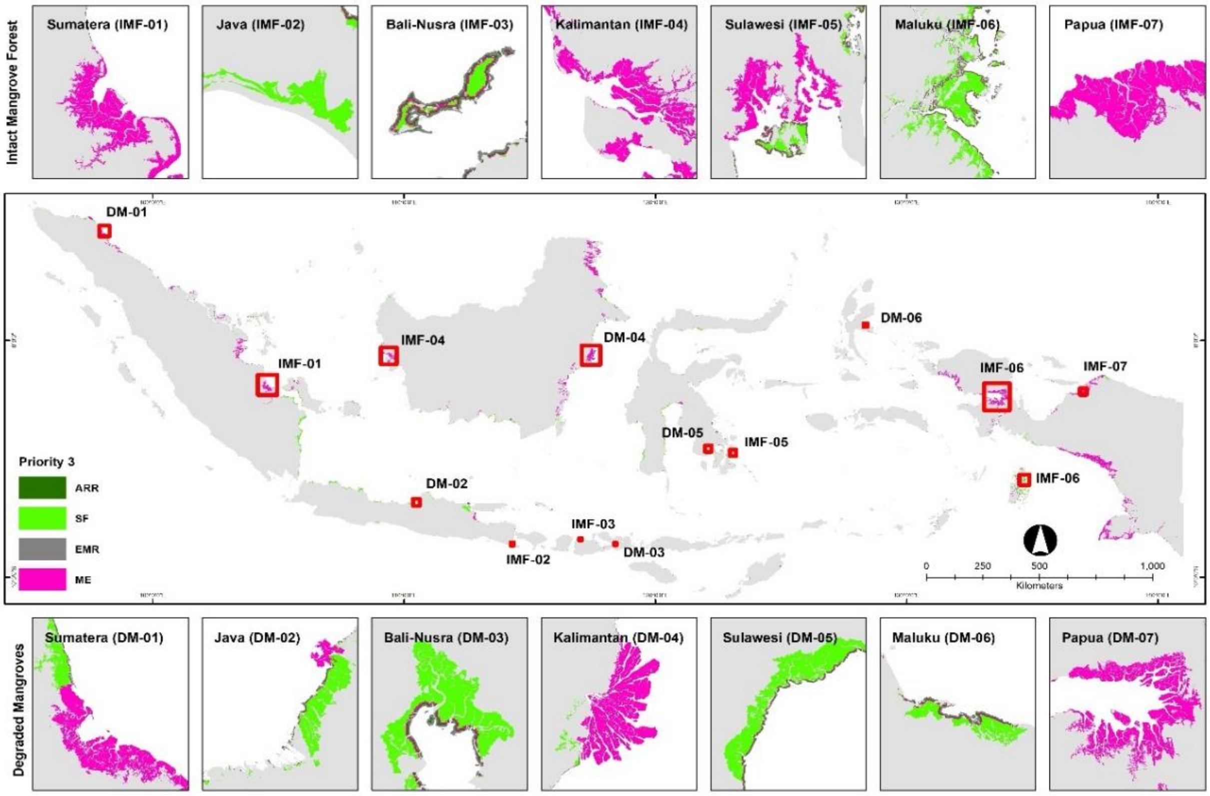

Figure 12. Spatial explicit distribution of priority 3 mangrove restoration approaches

Priority 3 indicates a management orientation that is strongly driven by sustainable utilization, particularly ecosystem service-based and community-oriented approaches. ME dominates with 2.7 million ha (67.61%) (Figure 12). This substantial proportion suggests that under priority 3, a large share of mangrove ecosystems is considered suitable for conservation-based economic activities centered on tourism and environmental services, emphasizing the valorization of intact or semi-intact ecosystems. The second largest component is SF, covering 929,238.46 ha (22.82%). This indicates a strong integration of mangrove conservation with sustainable aquaculture practices, reflecting a landscape where livelihood-based production systems are harmonized with ecological functions. The combined dominance of ME and SF (over 90% of the total area) clearly characterizes priority 3 as a socio-economic utilization–focused scenario that leverages mangrove ecosystems for community-based income generation while maintaining ecological integrity. Meanwhile, EMR accounts for 280,132.14 ha (6.88%), suggesting that ecological rehabilitation remains necessary in certain areas to restore hydrological and ecosystem functions. ARR represents 109,466.37 ha (2.69%), indicating a relatively limited need for large-scale planting interventions under this priority.

Overall, this distribution reveals that mangrove management in Indonesia is strongly dominated by protection-oriented strategies as priority 1, with rehabilitation as a secondary priority and sustainable utilization approaches serving as supporting measures. This structure reflects the reality that a large portion of Indonesia's mangroves remains extant and requires strict protection, while degraded areas continue to demand restorative interventions and socially inclusive management innovations. Priority 2 reflects a scenario in which mangrove management is heavily centered on active ecological rehabilitation, with limited emphasis on protection and moderate integration of sustainable livelihood-based approaches. Furthermore, priority 3 reflects a management framework centered on sustainable use and ecosystem service optimization, with ecotourism and silvofishery as the primary strategies, complemented by targeted ecological restoration where needed.

Integration and adjustment of mangrove restoration priorities

Mangrove restoration priorities should be adjusted based on existing biophysical conditions and landscape context to ensure ecological effectiveness and efficient resource allocation. A differentiated approach is necessary because mangrove areas are not homogeneous; they range from converted aquaculture ponds to forests with low, medium, and high forest density. In addition, proximity to the coastline serves as an important proxy for hydrological suitability, sediment dynamics, and exposure to coastal processes, all of which strongly influence restoration success. Overall, the west–east gradient in mangrove integrity suggests that restoration strategies in Indonesia should be spatially differentiated: conservation-oriented protection in relatively intact eastern landscapes, ecological restoration in degraded and hydrologically altered western coasts, and integrated rehabilitation in aquaculture-dominated areas. The distribution pattern highlighted in the map therefore provides a strategic basis for prioritizing restoration investments and aligning rehabilitation methods with landscape typology and socio-economic context (Figure 13.A).

Integration of the three priorities results in a highly diversified combination of management approaches, as reflected in the distribution of composite strategies above. The largest share remains under single protection (PRO), covering 1.6 million ha (39.55%), confirming that strict conservation continues to serve as the foundation of Indonesia's mangrove management framework. The second largest component, ARR/EMR/SF, accounts for 1 million ha (25.08%), indicating that a substantial portion of mangrove areas requires a blended strategy that combines active revegetation, ecological process restoration, and sustainable silvofishery. Other significant combinations such as PRO/EN/ME (14.92%) and EN/ME/PRO (6.05%) further demonstrate the integration of conservation, enrichment planting, and ecosystem service-based utilization.

Importantly, this integrated configuration is not arbitrary, it reflects spatial considerations such as mangrove forest density and proximity to the coastline as key proxies in determining appropriate interventions. Areas with high mangrove density and relatively intact structure, particularly those located further inland or within stable geomorphological settings are predominantly allocated under PRO or PRO-based combinations, emphasizing conservation and enrichment rather than heavy intervention. Conversely, areas with lower canopy density or degraded conditions are more frequently assigned to ARR and EMR-based combinations, indicating the need for active rehabilitation and ecological recovery.

Proximity to the coastline also plays a critical role. Mangroves located closer to the shoreline, especially in zones exposed to wave energy and coastal erosion, are more likely to involve EE and hydrological restoration components within their integrated strategies. In contrast, inland or pond-converted areas with altered hydrology are commonly associated with combinations such as ARR/EMR/SF or EE/AMA/EMR, reflecting the need to restore ecological function while integrating sustainable aquaculture practices. Overall, the integrated prioritization demonstrates a density and distance-sensitive management framework, where intervention types are aligned with both structural condition (forest density) and geomorphological exposure (distance from the coastline). This reinforces the adoption of a landscape-based and adaptive approach, ensuring that protection, restoration, and sustainable utilization strategies are spatially optimized according to ecological vulnerability and socio-economic context across Indonesia's mangrove ecosystems.

The combined distribution shows that provinces with the largest mangrove extents, such as South Papua, West Papua, East Kalimantan, and North Kalimantan account for the greatest total intervention areas, with stacked compositions reflecting a mixture PRO, ARR, EMR, and EE, sustainable utilization approaches such as SF, AMA, and ME (Figure 13.B). This pattern indicates that large mangrove landscapes require layered and integrated strategies in which conservation, ecological rehabilitation, and socio-economic utilization are implemented simultaneously within the same regions. In provinces with medium mangrove coverage, such as South Sumatra, Riau, South Sulawesi, and parts of Java reveals a more balanced proportion between ARR, EMR, SF, and AMA. This suggests landscapes that have experienced partial degradation and therefore require both ecological recovery and livelihood integration. Meanwhile, provinces with relatively smaller mangrove areas such as Bali, Bengkulu, and several eastern Indonesian provinces with limited coastal extent, show smaller total intervention areas and simpler combinations of approaches, reflecting more localized and site-specific management priorities. Overall, the integrated prioritization demonstrates that Indonesia's mangrove management is inherently multi-dimensional and scale-dependent. Large provinces with extensive mangrove systems emphasize landscape-scale protection and restoration, transitional provinces balance rehabilitation with sustainable production systems, and smaller provinces apply targeted, multifunctional interventions.

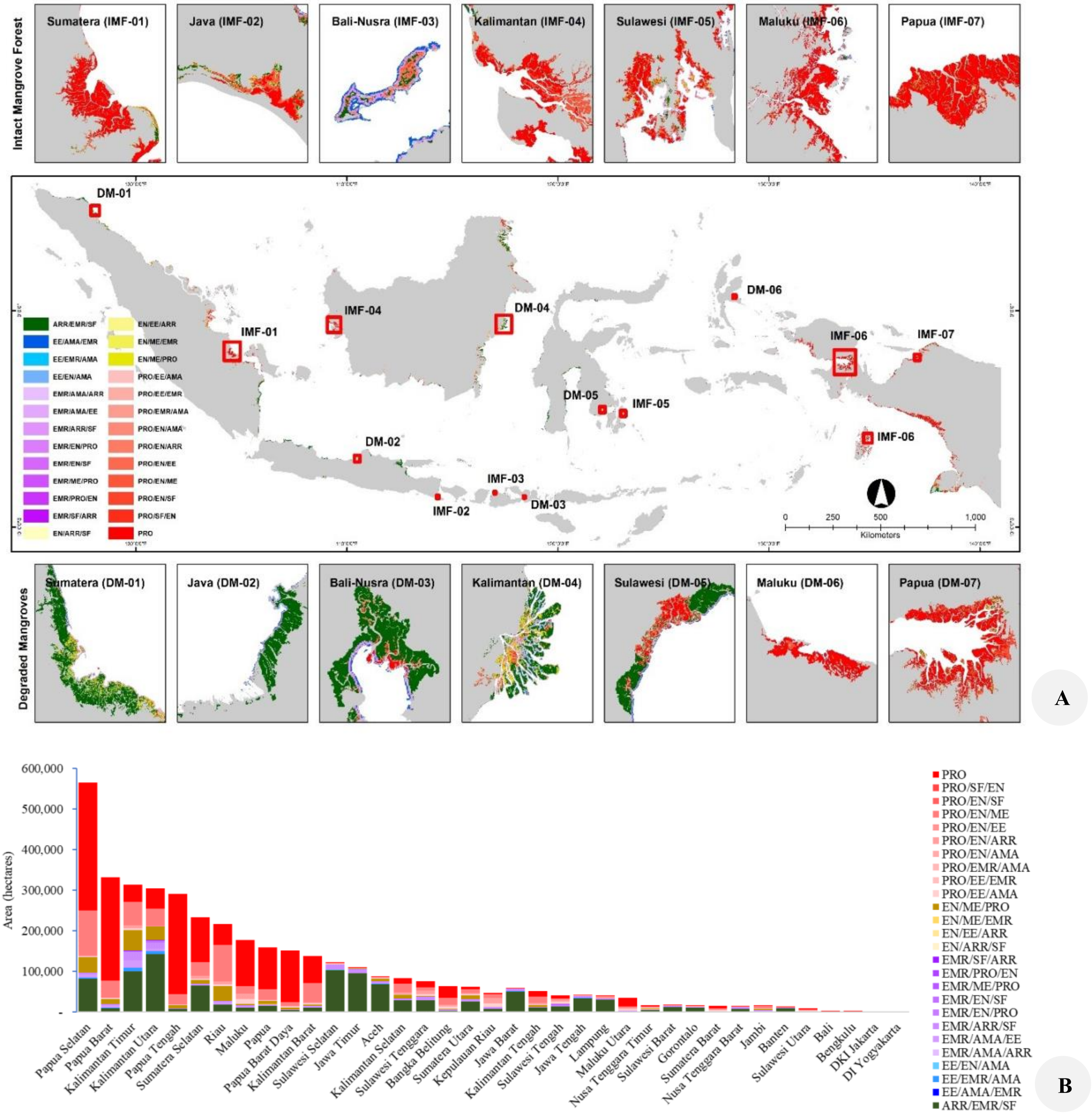

Figure 13. A. Map of integration and adjustment of mangrove restoration priorities in spatial explicit, B. Mangrove extent area based on integrated mangrove management strategy by province in Indonesia

Discussion

The mangrove restoration paradigm depends on the type of disturbance encountered, whether resulting from anthropogenic degradation or natural events (Yando et al. 2021). That highlights the ecological principle that succession plays a critical role in shaping restoration strategies (Biswas et al. 2009). However, recovery rates can be enhanced through well-planned restoration initiatives. The conventional philosophy of ecosystem restoration emphasizes returning a degraded ecosystem to its pre-disturbance condition. On the other hand, it is a structured and iterative process of learning and decision-making that responds to ongoing environmental, social, cultural, or political changes and associated uncertainties (Magnuszewski et al. 2005; Kaplan-Hallam and Bennett 2018).

Based on the restoration approaches identified in this study, four of them (i.e., SF, EMR, AMA, and SECURE) are restoration approaches that are related to aquaculture management. This shows that the current approach cannot be done partially with the current land use; it is key that restoration activities can support solutions to the socio-economic problems of coastal communities. The success of mangrove restoration activities is often pragmatically measured by the number of seedlings planted and, at times, by their initial growth rates. However, numerous cases have shown that planting efforts with high early growth rates may eventually fail due to subsequent seedling mortality (Cameron et al. 2019). The mainstreaming of natural regeneration has been comprehensively accommodated by several approaches (i.e., EMR, EE, PRO) which focus on restoring the ecological function of mangrove forests sustainably (Su et al. 2021), and lead to mangrove ecosystems that are extensive, diverse, functional, and self-sustaining (Ellison et al. 2020).

This study reveals a clear relationship between evidence-based mangrove restoration approaches and mangrove landscape typologies. The integration of this approach is essentially to avoid the failure of the misguided restoration program (Sharma et al. 2017; Lovelock et al. 2022). Landscape-based approaches can support a high biodiversity (e.g., crustaceans, mollusks, corals, birds, mammals, and other fauna), some of which are rare, endangered, or even endemic. In fact, certain mangrove areas are an integral part of shorebird habitats. In several locations along major global flyways, mudflats and their surrounding habitats, upon closer examination, serve as critical resting and foraging sites for migratory waterbird species (Yong et al. 2022). The reduction of available intertidal areas due to planting activities may lead to a decline in shorebird diversity, resulting in restoration efforts potentially conflicting with shorebird conservation objectives (Mohd-Azlan et al. 2015). Maintaining a balanced ratio between the extent of intertidal mudflats and mangrove cover is recommended for the conservation of both mangroves and shorebirds, and maintaining this ratio can help reduce conflicts between mangrove restoration and the conservation of waterbirds, while also promoting sustainable development (Yang et al. 2021). Mangrove planting (ARR) is currently a minor approach, as such ecologically important areas may disrupt the ecological functions that support resident fauna, and could potentially threaten local biodiversity (Choi et al. 2022)

Open coastal areas, particularly those that have experienced severe erosion, can benefit from short-term recovery when mangroves are planted on the remaining embankments, which can help slow down further erosion (Primavera and Esteban 2008; Dong et al. 2024). These stands often fail to deliver the desired ecosystem services, such as coastal protection or enhanced fisheries, and some planting efforts have resulted in monospecific stands grown at unnaturally high densities (Samson and Rollon 2008). Therefore, within the framework of ecological engineering (EE), especially prioritized for open coast typologies, the initial focus should be on stabilizing the shoreline, followed by promoting natural regeneration. This is supported by studies from Kamali and Hashim (2011) and van Bijsterveldt et al. (2022), where natural regeneration is a priority compared to planting. Some records of success in implementing the ecological engineering approach, for example, in Malaysia (Hashim et al. 2010), Thailand (Saengsupavanich 2013), and Vietnam (Schmitt and Albers 2014; Van Cuong et al. 2015; Nguyen and Parnell 2017; Nguyen 2018).

This study also finds that delta and estuary typologies, the priority restoration approach is protection (PRO) through natural regeneration, considering the gradual land accretion and natural colonization by mangroves (Sidik et al. 2016), which demonstrates that sediment accumulation promotes mangrove expansion and the natural establishment of pioneer species (Fickert 2020). Consequently, all restoration scenarios for delta and estuary landscapes emphasize the importance of conserving these ecosystems. Protection, in this context, refers to enabling natural regeneration without active planting. It may also involve formally designating these areas as protected zones, either legally recognized at the local or regional level, or classified under conservation or protected area management frameworks.

In backward zones that are sheltered by intertidal flats or existing mangrove stands associated with open coasts, this study recommends implementing associated mangrove aquaculture (AMA) or silvofishery systems (SF) or, when feasible and based on land tenure, intensive planting activities (ARR). This recommendation is particularly relevant in the context of Indonesia's coast, which has a long history of aquaculture (Brown and Prayitno 1987; Tran et al. 2017). Coastal communities are heavily dependent on aquaculture, and raising environmental awareness, strengthening social capital, and managing ponds, especially within protected zones, requires time. In such cases, mixed mangrove-aquaculture systems represent a practical alternative to support both mangrove ecosystem recovery and the economic needs of local communities (Peng et al. 2009). AMA provides multiple benefits, restoring riparian greenbelts to protect riverbanks from erosion, enhancing sediment capture by mangroves to stabilize pond dikes, and improving water quality through mangrove-root filtration at pond edges (Bush et al. 2010; Bosma et al. 2016). Additionally, areas with mangrove canopy should be managed accordingly, planting low-density mangrove species, species enrichment in moderately dense areas, and protection in high-density areas (Rahadian et al. 2022).

Lagoon systems are naturally protected mangrove landscape typologies, sheltered from direct wave energy, making them ideal sites for a stable mangrove forest (Alongi 2008). In such settings, sediment accretion rates tend to be high and can accumulate rapidly if not regulated by balanced hydrological dynamics, potentially altering mangrove vegetation distribution and overall ecosystem function (Woodroffe et al. 2016). Furthermore, mangrove ecosystems in lagoons offer crucial biodiversity benefits, including nursery habitats for various fish, crustaceans, and waterbirds (Nagelkerken et al. 2008), which makes the lagoon a priority to become a mangrove ecotourism (ME) area. For example, the successful management of lagoon ecotourism in Taiwan as a means of livelihood diversification, which encourages changes in the economic and social system of society (Phuah and Chang 2023).

PROMETHEE, qualitatively provides a scenario alternative that is translated in the form of a priority well, which fills the gap of empirical approaches that are not always based on quantitative data. Furthermore, Integration PROMETHEE with GIS-based mapping can show where to implement mangrove restoration approaches explicitly. Although the study tested at the macro-scale, in practical terms, the integration of PROMETHEE and GIS-based mapping can be replicated micro-scale level, by increasing the level of detail of environmental, social, and economic data.

The policy implications of these integrated priorities highlight the need for a multi-level and cross-sectoral governance framework. Priority 1 aligns with disaster risk reduction and climate adaptation policies, particularly in erosion-prone coasts. This provides urgent responses to critical ecosystems under immediate threat. Priority 2 directly supports Indonesia's national mangrove rehabilitation targets (i.e., 600,000 ha) and blue economy agenda and expands restoration through replanting and aquaculture integration. Priority 3 links strongly to adaptive management strategies, sustainable ecotourism, and aquaculture reform, and builds resilience by linking ecological recovery with socio-economic incentives.

Across all priorities, financing mechanisms such as blue carbon credits, green financing instruments, and payment for ecosystem services are essential to ensure implementation, accompanied by benefit-sharing schemes to guarantee that local communities derive tangible socio-economic benefits from restoration and protection efforts. The urgency of adopting an integrated restoration approach lies in its ability to capture the dynamic interactions among ecological processes, human livelihoods, and governance systems in Indonesia's coastal zones. This layered strategy underscores that mangrove restoration should not be regarded merely as ecological restoration, but as a comprehensive socio-ecological policy instrument capable of delivering multiple co-benefits, including biodiversity conservation, climate change mitigation, coastal protection, and sustainable community development.

The implementation of typology-based restoration is confronted with a range of challenges and limitations. From a governance perspective, overlapping mandates between national, provincial, and local authorities often create confusion regarding management responsibilities. In many coastal regions, mangrove areas are simultaneously categorized under protected zones, other land use, or even concession schemes, which complicates coherent planning. Moreover, institutional capacity at the local level to adopt and sustain typology-based approaches is often limited, particularly in terms of human resources, financial support, and regulatory instruments. On the other side, land tenure uncertainty represents another critical constraint. Many coastal ecosystems, especially mangroves, fall within areas where ownership and user rights are contested or overlapping, such as between state land, customary claims, and local communities. This often results in conflicts that delay or undermine restoration efforts, since local stakeholders are reluctant to participate in initiatives where their rights are not formally recognized. Typology-based approaches require land allocation and management that align with ecological conditions, yet such measures are difficult to implement in the absence of secure tenure arrangements.

Socio-economic complexities also shape the feasibility of typology-based restoration. Local communities often rely on coastal land for aquaculture, agriculture, or settlement. Restoration programs can therefore be perceived as competing with, or threatening, livelihoods if not accompanied by adequate incentive mechanisms or viable alternative income sources. Moreover, community preferences may diverge from technical project objectives, underscoring the importance of inclusive participation, consultation, and negotiation processes. Without addressing these socio-economic dimensions, restoration outcomes are unlikely to be sustainable in the long term. The challenges of governance, land tenure, hydrological barriers, socio-economic dynamics, data and technical limitations, and financial sustainability highlight the complexity of implementing typology-based restoration. Acknowledging these constraints is essential to designing realistic strategies and ensuring that mitigation measures are incorporated from the outset, thereby increasing the likelihood of long-term success.

The study has several caveats and limitations, our focus may have excluded relevant insights of local knowledge that could provide important contextual understanding. Although the study highlights methodological integration (PROMETHEE-GIS), the evaluation of such frameworks is still on a large scale. Policy makers must be able to translate into a finer, so that it can be implemented at the micro landscape level. Future research should address several gaps that are needed for standardized protocols to harmonize sustainability indicators across (i.e., ecological, technological, social, and economic), which would improve the robustness of PROMETHEE, and more empirical case studies are required that integrate multi-criteria decision analysis with spatial mapping at different scales.

In conclusion, the diverse typologies of coastal landscapes reflect complex and interconnected ecological, social, and economic dynamics. These multidimensional dynamics influence the structure, function, and pressures on coastal ecosystems, necessitating a diverse restoration approach. A contextual, landscape-typology-based approach allows restoration to be more effectively directed by selecting appropriate interventions and prioritizing locations, thereby maximizing ecological success and long-term socio-economic sustainability. This study reveals the importance of relating concepts to appropriate typologies at the landscape scale by considering the dynamics and characteristics of coastal landscapes. The partial nature of these concepts and approaches has qualitatively contributed to the development of a new, more integrated concept for future mangrove ecosystem management using a landscape-based approach. In open coast typologies, to prevent planting failure caused by strong currents and wave action, this study suggests the construction of natural coastal structures or the integration of structural engineering approaches at the initial stage or prior to planting, particularly in areas prone to coastal erosion. In delta and estuary typologies, protection through natural regeneration is considered appropriate, given that land accretion and natural mangrove colonization tend to occur progressively in these dynamic environments. In backward zones, which are naturally shielded by the open coast, intensive planting is identified as suitable. Furthermore, for intertidal areas with varying mangrove densities, different strategies are advised. Areas with low mangrove density should be prioritized for planting and species enrichment, areas with moderate density should undergo species enrichment, and areas with high density should be designated for protection. The priorities illustrate policy implications that emphasize multi-level and cross-sectoral governance to address coastal vulnerability, enhance community resilience through adaptive management, ecotourism, and socio-economic incentives. PROMETHEE can be applied qualitatively to establish alternative priority scenarios, filling the gap left by empirical approaches that rely mainly on quantitative data. The integration of PROMETHEE with GIS-based mapping enables more explicit identification of locations for mangrove restoration.

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