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RESEARCH

Social–ecological dynamics of mangrove restoration in Pondok Bali, North Coast of Java, Indonesia

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Abstract

This study applies the social–ecological system (SES) framework to analyze mangrove degradation in Pondok Bali on the North Coast of Java, Indonesia. Integrating the SES framework with the Management and Transition Framework (MTF) and systems thinking tools, particularly causal loop diagram (CLD), the study traces historical changes in coastline morphology, mangrove coverage, and community livelihoods. Analysis of satellite imagery (using MNDWI and NDVI) combined with field observations reveals a substantial coastal retreat of up to 2.36 km and significant loss of mangrove area since 1992. The findings identify multiple interacting drivers of degradation, including land use change, unregulated aquaculture expansion, river diversion, land subsidence, and sea level rise. While recent adaptive measures, such as wave-breaking structures and community-based mangrove planting, show potential, public support remains uneven. Overall, the study underscores the need for a coordinated national and regional master plan with clearly defined stakeholder roles and sustainable financing mechanisms. It concludes that successful mangrove restoration depends on integrated engineering and ecological approaches, supported by blended finance and guided by SES-informed planning.

Keywords Sustainable restoration · Mangrove ecosystem · Social–ecological system · Coastal management · Java coastline

Introduction

Understanding the complex interconnections between human and natural systems is essential for addressing coastal environmental challenges (Berkes et al. 2016; Biggs et al. 2021; Gain et al. 2020). The social–ecological systems (SES) framework views human and ecological components as interdependent and co-evolving, providing an analytical basis for understanding coupled social–ecological dynamics (Biggs et al. 2021). The SES approach provides valuable insights into how social and ecological processes interact across spatial and temporal scales (Petrosillo et al. 2015; Liehr et al. 2017; Turner II et al. 2016).

The degradation of mangrove ecosystems in Pondok Bali, Subang Regency, West Java Province, illustrates the urgent need for integrated socio-ecological analysis. Located along the North Coast of Java, this area has experienced significant environmental decline driven by both natural processes and human activities (Suroso and Firman 2018). Changes in sediment dynamics, driven by the diversion of the Cipunegara River since the 1960s, have led to coastal erosion and diminished conditions for mangrove growth (Achiari et al. 2015; Kikuyama et al. 2017; BBWS Citarum, 2024). Additional pressures include large-scale mangrove conversion to fishponds beyond sustainable limits (Richards and Friess 2016; Royna et al. 2024), as well as offshore oil exploitation and associated land subsidence, which collectively exacerbate the vulnerability of the coastal system (Abija and Abam 2022; Sroka and Hejmanowski 2006).

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In addition to the biophysical factors, local livelihoods highly depend on mangrove resources, particularly through aquaculture, fisheries, and tourism (Solihuddin et al. 2021). Salinization of agricultural land caused by sea water intrusion has compelled communities to convert rice fields to fishponds; however, these activities face growing risks from tidal surges and environmental instability (Henriksson, et al. 2017). The degradation of Pondok Bali's coastal ecosystem exemplifies how ecological and social vulnerabilities co-evolve through reinforcing feedback mechanisms, underscoring the need for a systematic examination of these dynamics within an integrated socio-ecological framework.

While the SES framework provides a useful basis for understanding these dynamics, addressing such complex, interrelated challenges requires complementary approaches. Partelow (2018) and Liu et al. (2023) emphasize that SES analysis is particularly valuable for identifying cross-scale interactions and institutional dynamics affecting ecosystem sustainability. In the context of Pondok Bali, the SES framework enables the analysis of how shoreline retreat, mangrove degradation, livelihood transformation, and governance responses interact dynamically over time.

To complement the SES perspective, this study adopts the Management and Transition Framework (MTF), which focuses on governance transformation, institutional learning, and adaptive management processes across multiple spatial and temporal scales. The MTF framework conceptualizes environmental management as a transition process shaped by interactions among actors, institutions, knowledge systems, and operational outcomes (Pahl-Wostl et al. 2010). Previous studies demonstrate that the MTF is effective for analyzing long-term governance transitions and adaptive resource management in complex environmental systems (Edelmann et al. 2020).

By integrating SES and MTF frameworks therefore provides a more comprehensive analytical approach for understanding not only ecological degradation processes but also the institutional and governance transformations influencing mangrove restoration in Pondok Bali. This approach is further complemented by systems thinking to examine processes of social–ecological co-evolution (Elsawah et al. 2017; Nugroho and Uehara 2023).

Addressing the limited integration of long-term social and ecological analyses in mangrove research, this study is grounded in the hypothesis that the mangrove ecosystem of Pondok Bali has experienced sustained degradation since the early 2000 s, disrupting both ecological functions and community livelihoods. The study therefore examines how ecological and social systems have coevolved and whether these dynamics indicate a trajectory toward sustainability, through analysis of biophysical change, social transformation, and their reciprocal interactions.

Previous studies emphasize local participation in mangrove restoration (Dinda et al. 2018; Basyuni et al. 2018), the role of ecosystem services in coastal resilience (Hilmi et al. 2023), and the potential of community-based rehabilitation approaches such as CBEMR (Brown et al. 2014). However, these studies typically address these aspects in isolation and provide limited understanding of their long-term co-evolution within an integrated socio-ecological governance framework. Collectively, they highlight the need for a socio-ecological approach to mangrove rehabilitation, which integrates local knowledge, active community engagement, and the protection of ecosystem services.

This study advances mangrove restoration research by documenting long-term socio-ecological change in a degraded system, applying an integrated SES–MTF perspective to examine interactions between governance and ecological processes, and identifying key leverage points for hybrid restoration approaches that align ecological recovery with social and institutional contexts.

Materials and methods

The study area where this research was conducted is the coastal area of Pondok Bali, specifically Mayangan Village and Legonwetan Village in Legonkulon District, Subang Regency, West Java Province, Indonesia (Fig. 1). These areas have experienced significant coastal erosion and mangrove degradation due to the interaction between anthropogenic and natural processes (Kikuyama et al. 2017; Novianty et al. 2011).

The study framework is presented in a conceptual model (Figure 2) that highlights key ecological and social components and their interconnections. The social and ecological systems were analyzed in parallel, and their results are presented in the form of Social-Ecological System analysis diagram (Figure 3). The ecological system was analyzed using a multi-temporal spatial analysis approach integrating remote sensing techniques, field observations, and abiotic parameter validation. Historical coastline and mangrove changes were examined using Landsat imagery from 1992, 2002, 2013, and 2022 obtained from the United States Geological Survey (USGS). The available satellite imagery for 2012 exhibited scene truncation, in which the Pondok Bali coastal region fell partially outside the image extent and was therefore not fully captured. This limitation rendered the dataset unsuitable for consistent multi-temporal analysis, as spatial completeness and scene consistency are essential for reliable temporal comparison and change detection (Coppin et al. 2004; Zhu and Woodcock 2012). Coastline dynamics were identified using the Modified Normalized Difference Water Index (MNDWI), which effectively distinguishes water bodies from terrestrial surfaces by utilizing Green

Fig. 1 Location map of study area

and Short-Wave Infrared (SWIR) spectral bands (Szabó et al. 2016). Shoreline change rates were subsequently calculated using the Digital Shoreline Analysis System (DSAS) within ArcGIS. Mangrove distribution and density changes were analyzed using the Normalized Difference Vegetation Index (NDVI), which measures vegetation density based on the contrast between Near Infrared (NIR) and Red spectral bands. The NDVI classification enabled the identification of high-, medium-, and low-density mangrove categories across the study area.

Field validation was conducted during March 14–18, 2026, to verify spatial analysis results and assess abiotic environmental conditions. Water temperature, salinity, and pH measurements were collected from three observation clusters (Fig. 6) representing major mangrove zones in Mayangan and Legonwetan Villages. The field assessment followed the environmental quality standards

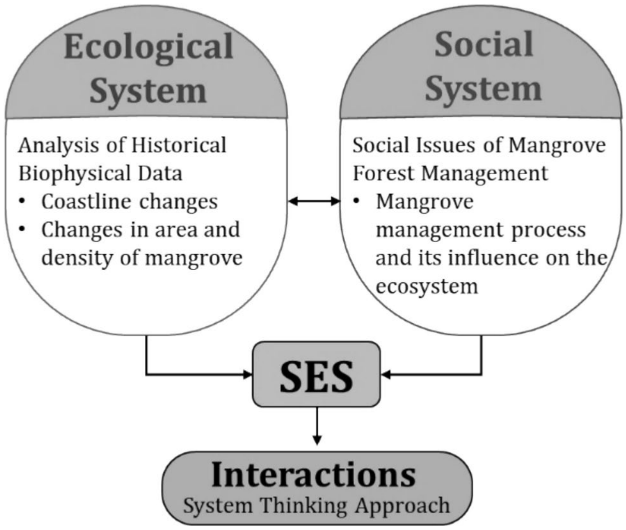

Fig. 2 The SES framework of the study

established in the Indonesian Minister of Environment Decree No. 51/2004 (Government of the Republic of Indonesia 2004a). In addition, mangrove vegetation conditions were validated using the Line Transect Plot Method based on the criteria outlined in the Indonesian Minister of Environment Decree No. 201/2004 (Government of the Republic of Indonesia 2004b).

The social system was analyzed qualitatively using semi-structured interviews guided by the Management and Transition Framework (MTF) to evaluate mangrove management processes and their ecological impacts (Table 1). Data collection was conducted between July 17 and July 21, 2023, through purposive sampling involving village officials, local community organizations, and mangrove management stakeholders. Snowball sampling was further employed to identify additional respondents until thematic saturation was achieved, resulting in a total of 11 participants. Interview data were analyzed using qualitative content analysis through open coding, axial coding, and selective coding stages following Corbin and Strauss (2008). To ensure reliability and validity, data triangulation was conducted by cross-checking interview results, field observations, and secondary documentation.

Finally, the interaction between ecological and social subsystems was analyzed using system thinking tools, particularly causal loop diagram (CLD). These diagrams were developed based on insights from both data analysis and relevant literature, allowing for the identification of feedback mechanisms and potential leverage points for intervention strategies (Van Nguyen and Nguyen 2013).

Results

Biophysical changes of Pondok Bali Coastal Area based on past and current conditions

Coastline changes

Coastline changes in Mayangan Village and Legonwetan Village were analyzed using the Digital Shoreline Analysis System (DSAS), an extension of the ArcMap application, for the years 1992, 2002, 2013, and 2022. The results indicate a general trend of coastal retreat in both Mayangan and Legonwetan Villages (Fig. 4). Legonwetan Village experienced a more significant shoreline reduction, totaling 2361.75 m, compared to 1704.92 m in Mayangan Village. The average rate of retreat was − 78.65 m/year in Legonwetan and − 56.78 m/year in Mayangan. The most substantial period of coastline reduction in Mayangan Village occurred between 2002 and 2013, with a retreat of 1353.34 m. In contrast, Legonwetan Village saw its most significant loss between 2013 and 2022, reaching 1653.02 m, surpassing the corresponding reduction in Mayangan Village during that time frame.

Mangrove ecosystem

The mangrove ecosystem was analyzed based on both biotic and abiotic conditions. Biotic conditions were assessed through changes in mangrove area, mangrove density, and species density. Abiotic conditions were evaluated using three key parameters: temperature, pH, and salinity. Measurements were taken at designated sampling points, divided into three clusters: the Pulau Burung Cluster (PB), the Pondok Bali Cluster (BL) located in Mayangan Village, and the Pondok Putri Cluster (PP) in Legonwetan Village. The assessment of abiotic conditions followed the standards outlined in the Minister of Environment Decree N 51 of 2004 on Sea Water Quality Standards (Government of the Republic of Indonesia 2004a). According to these standards, optimal conditions for mangrove ecosystems include a temperature range of 28–32 °C, a seawater pH range of 7–8.5, and salinity levels up to 34‰.

As shown in the map (Fig. 4) and graph (Fig. 5), mangrove areas in Mayangan Village and Legonwetan Village declined by 53% and 38%, respectively, between 1992 and 2022. Although a general decrease in all density classes was observed over the years, there was a noticeable increase in high-density mangrove coverage between 2013 and 2022.

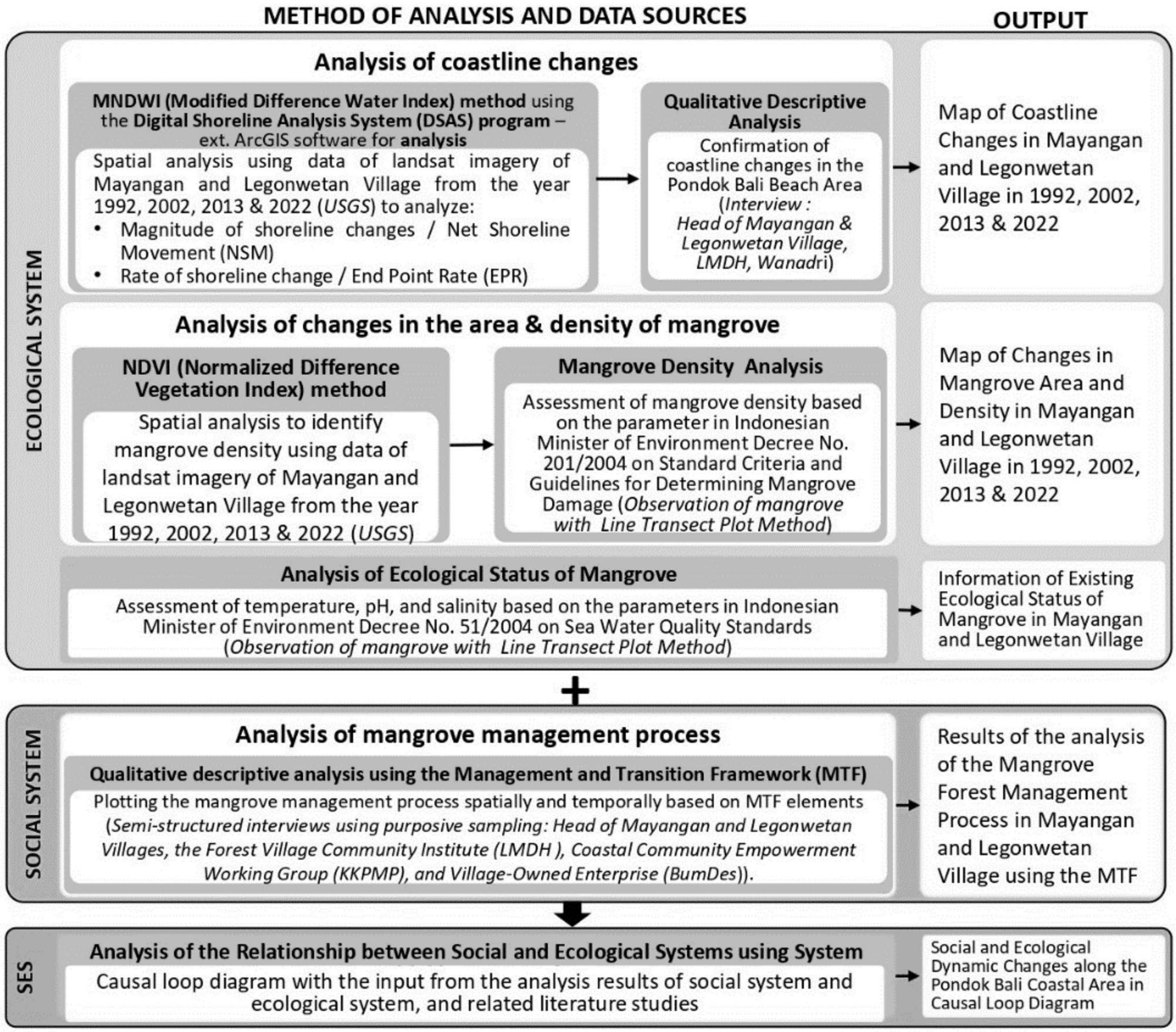

Fig. 3 Research methods and outputs of the study

The mangrove forests in Mayangan and Legonwetan Villages can be differentiated into two species: Rhizophora mucronata and Avicennia marina. The locations of mangrove ecosystem observations in the Pulau Burung, Pondok Bali, and Pondok Putri clusters are illustrated in Fig. 6.

a) Pulau Burung Cluster

In the Pulau Burung cluster, mangroves with high density were concentrated in the central part of the forest, with an average density of 2533 trees/ha. Abiotic conditions showed that the temperature remained within optimal limits, ranging from 29 to 32 °C, and salinity was within the normal range of 20–28‰. However, the pH level in this cluster was below the standard threshold, ranging between 5.3 and 6.6, indicating slightly acidic conditions.

b) Pondok Bali Cluster

Survey results indicated that mangrove density in the Pondok Bali Cluster was very high (3066 trees/ha). The temperature range was similar to that of the Pulau Burung Cluster (29–32 °C), and salinity levels were also optimal for mangrove ecosystems, ranging from 26 to 30 ‰. However, as in the Pulau Burung Cluster, the pH levels remained below the recommended standard, falling between 5.6 and 6.2.

c) Pondok Putri Cluster

The mangrove forests in the Pondok Putri Cluster were in good condition and were categorized as very dense, i.e., 3466 trees/ha. This suggests that despite sig-

Table 1 Elements of Management and Transition Framework (Pahl-Wostl et al. 2010)

Elements	Description
Action arena	Specific issues in politics that focus on social functions
Actions situations	Structured social interactions that produce certain outcomes including knowledge, institutions, and operational outcomes
Institutions	A social construct that contains a set of formal (laws) or informal (norms) rules
Knowledge	Meaningful information and experiences
Operational outcome	Physical or social changes that affect management methods
Actor	Individual or collective participants in the action arena who take part in the action situation by holding certain roles
Role	The actor-based nature is based on a shared understanding of the meaning and function of individuals in an action situation
Management paradigm	A set of guiding assumptions that determine management actions

nificant degradation of mangrove areas in Legonwetan Village, the sample area in this cluster retained excellent forest density. Temperatures at all observation stations in this cluster exceeded 30 °C, but still within the upper limit of the optimal range. pH levels at two sampling points were notably acidic. Nevertheless, salinity remained within the optimal range for mangrove growth, between 25 and 30‰.

Social issues of mangrove forest management at Pondok Bali Beach

The social dynamics of mangrove forest management at the study area are identified using the Management and Transition Framework (MTF), enabling an understanding of key issues from the village to the national level. This analysis spans from the time of the diversion of the Cipunegara River in the 1960s to the present (Fig. 7). Four major social issues are identified: (1) mangrove exploitation, (2) ecosystem degradation, (3) a shift in mindset from exploitation to restoration, and (4) adaptive management. These issues involve a range of actors, each holding distinct perspective on mangrove forest management. Their interactions have driven both biophysical and social changes, which in turn shape subsequent management practices.

Table 2 summarizes the temporal evolution of mangrove management, showing a shift from exploitation to adaptive restoration, based on the Management and Transition Framework (MTF) analysis of the Pondok Bali coastal area.

The table delineates the transition of Pondok Bali's coastal management across four distinct social aspects identified through the MTF approach. The Mangrove Exploitation phase was initially induced by a top-down silvofishery policy that ultimately failed due to inadequate supervision and limited local capital. This failure led to the Ecosystem Degradation phase, during which coastal abrasion and land subsidence emerged as the primary threats. The subsequent Mindset Shift phase involved external interventions; however, structural shortcomings necessitated a transition toward Adaptive Management. In this final stage, the successful implementation of community-installed wave breaking equipment (APO) fostered "natural reclamation" and enabled the integration of ecological restoration with local economic development through ecotourism and social forestry initiatives.

Social–ecological system (SES) of mangrove ecosystem in Pondok Bali using a systems thinking tool

The social–ecological system (SES) of mangroves is shaped by multiple interacting factors, including infrastructure development, land use change, and tourism (Rahman et al. 2020). Decision-making in mangrove conservation should therefore incorporate the socio-cultural valuation of ecosystem services, as local communities often maintain symbolic and relational ties to these ecosystems (de Souza Queiroz et al. 2017). In addition, institutional conditions, such as weak regulatory frameworks and market pressures, can significantly influence household access to and entitlements over provisioning services derived from mangrove system (Orchard et al. 2015).

Climate change and extreme weather are exerting significant pressures on mangrove ecosystems. Ward et al (2016) highlight substantial regional variation in these impacts, identifying sea level rise, increased storm intensity, altered precipitation patterns, and temperature changes as key drivers. Similarly, Gilman et al (2008) emphasize the heightened risks of flooding, erosion, and storm surges, alongside the role of sea level rise in reshaping mangrove distribution. Focusing on the Sundarbans mangrove forests in Bangladesh, Dasgupta et al (2017) examine how climate-induced changes in aquatic salinity may lead to significant species losses in some cases, while allowing others to expand. Collectively, these studies underscore the vulnerability of mangrove ecosystems to climate change and extreme weather

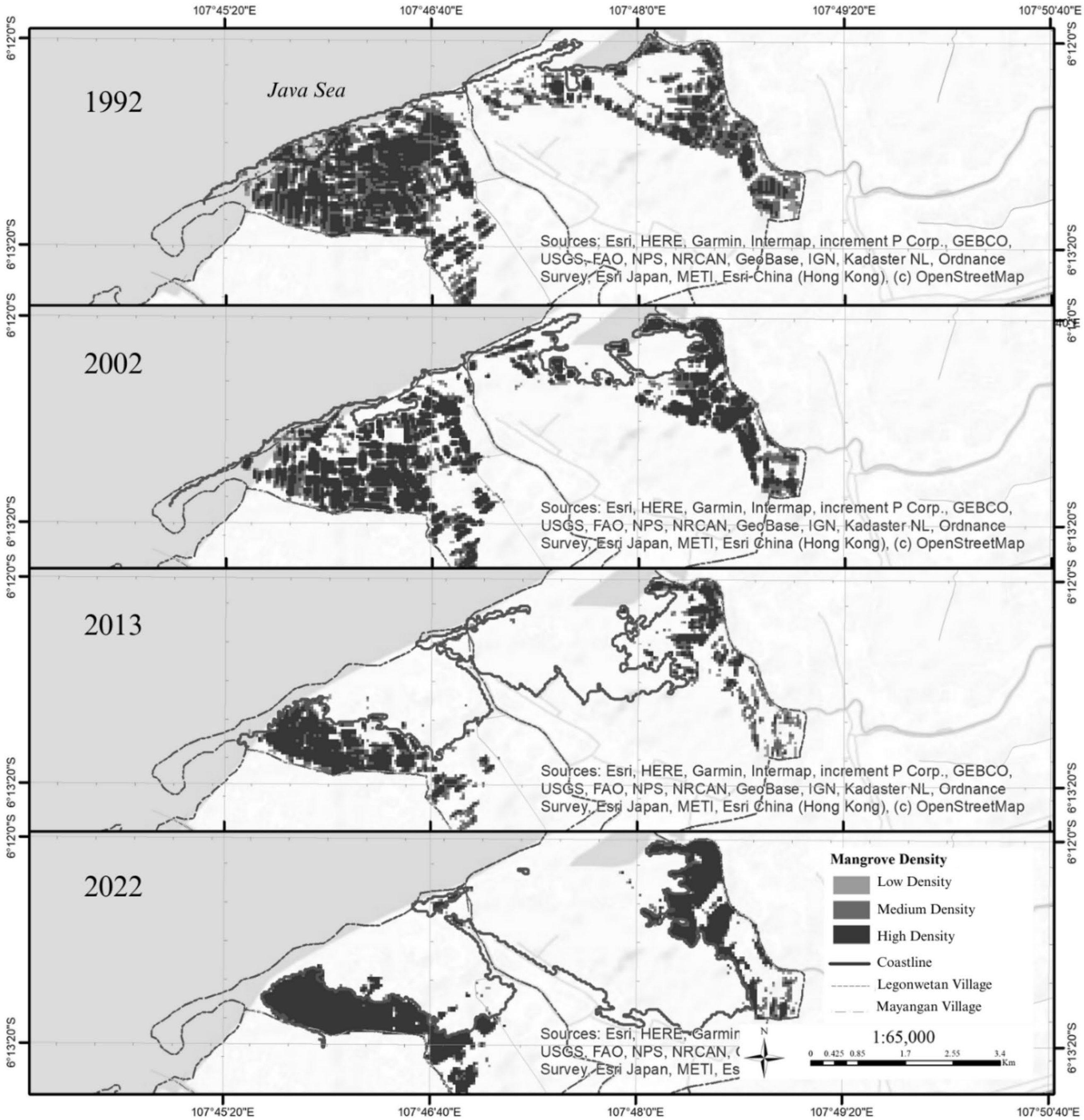

Fig. 4 Map of coastline changes, and changes in mangrove area and density in Mayangan and Legonwetan Villages from 1992 to 2022

events, highlighting the urgent need for further research to better understand and mitigate these impacts.

The livelihoods of coastal communities in tourism areas represent a complex and multifaceted issue shaped by a range of interconnected factors. Singgalen and Simage (2018) and Agam et al. (2021) emphasize that tourism can enhance local livelihoods, particularly when supported by sustainable development practices and community empowerment initiatives. However, Lakshmi and Shaji (2016) caution that uncontrolled tourism may generate adverse effects, including environmental degradation and social challenges within coastal settlements. Vallega (2013) proposes an integrated approach to coastal management and economics as a means of conserving resources while ensuring the long-term sustainability of coastal tourism.

Research indicates a negative correlation between beach tourism and the extent of fishing pond areas (Fig. 8). Hidayat and Agusliani (2020) note that while beach tourism can

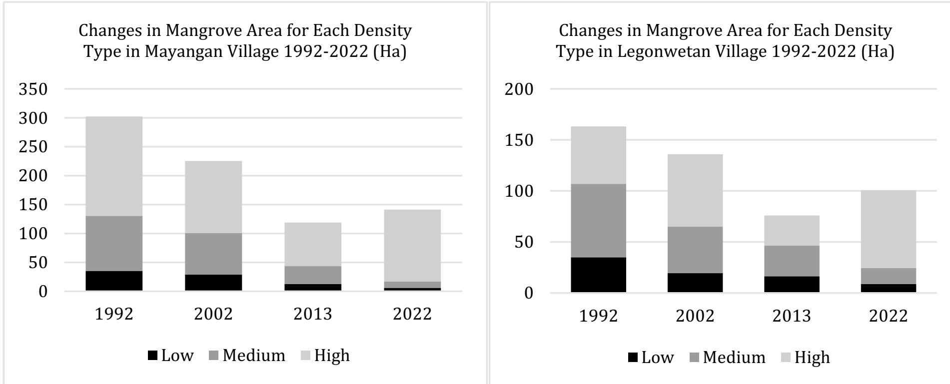

Fig. 5 Changes in mangrove area by density category in Mayangan Village (left) and Legonwetan Village (right) during 1992–2022 (Ha)

stimulate the economic well-being of coastal communities, it may also contribute to the reduction of fishing pond areas. This finding is reinforced by Torres-Bejarano et al (2018), who identify a direct correlation between the number of beach visitors and increased pollution levels in both water and sand. Similarly, Gheskiere et al (2005) further demonstrate that tourism activities can alter beach environments, with potential consequences for adjacent fishing pond areas.

Systems thinking analysis of Pondok Bali Area

The analysis of social–ecological dynamics of the Pondok Bali coastal area is used to create a causal loop diagram as demonstrated in Fig. 8. The diagram reflects the co-evolution of the coastal communities and mangrove ecosystems of Pondok Bali area, which is part of the Cipunegara deltaic system.

Under natural conditions, deltaic coastlines tend to experience gradual accretion, which allows mangrove vegetation to grow and expand over time, often taking centuries to develop into mangrove ecosystems. This typical sedimentation process, common along the northern coast of Java, including in Pondok Bali, has been significantly disturbed by social and human activities.

One major disruption occurred in the 1960 s, when the flow of the Cipunegara River was diverted eastward, thereby reducing sediment supply to the coastline of Pondok Bali. Another major driver of ecological degradation linked to the social system was the extensive conversion of mangrove areas into fishponds, which, since the 1980 s, has reduced mangrove coverage beyond the critical threshold of 20%. According to local accounts, severe coastal abrasion began around 2004.

The area has also experienced land subsidence, which is widely believed to be associated with offshore oil and gas extraction activities near Pondok Bali. These local pressures are further compounded by global drivers, including sea level rise and extreme wave events driven by climate change.

Various interventions, including the construction of seawalls and mangrove planting initiatives since the 2010 s, have proven largely ineffective. More recently, a hybrid approach combining low-cost physical structures with mangrove restoration has been implemented. While it is still too early to assess the effectiveness of this approach, it is clear that a more strategic and integrated response is needed.

The restoration of the mangrove ecosystem in Pondok Bali requires a comprehensive master plan that enables coordination and synergy among national, provincial, and local governments, as well as NGOs and academic institutions. This master plan should clearly define the roles and responsibilities of each stakeholder, establish mechanisms for shared financial support, and set out a clear, phased implementation timeline to ensure an integrated and sustainable restoration process.

Discussion

The findings of this study indicate that the degradation trajectory of the Pondok Bali mangrove ecosystem is not merely the result of isolated biophysical disturbances but rather reflects a long-term co-evolution between ecological change and shifting governance regimes. The pronounced coastline retreat and decline in mangrove area since 1992 should be understood as indicators of systemic imbalance within the social–ecological system (SES), in which anthropogenic pressures, particularly river diversion, aquaculture expansion, and weak regulatory enforcement, have disrupted natural sedimentation processes. From a systems thinking perspective, these disturbances generate reinforcing feedback loops; reduced sediment supply constrains mangrove regeneration, increasing coastal exposure, which in turn accelerates erosion and drives further ecosystem loss (Meadows 2008; Elsawah et al. 2017). Although the recent increase in high-density mangrove patches points to localized recovery, this improvement remains fragile and spatially uneven,

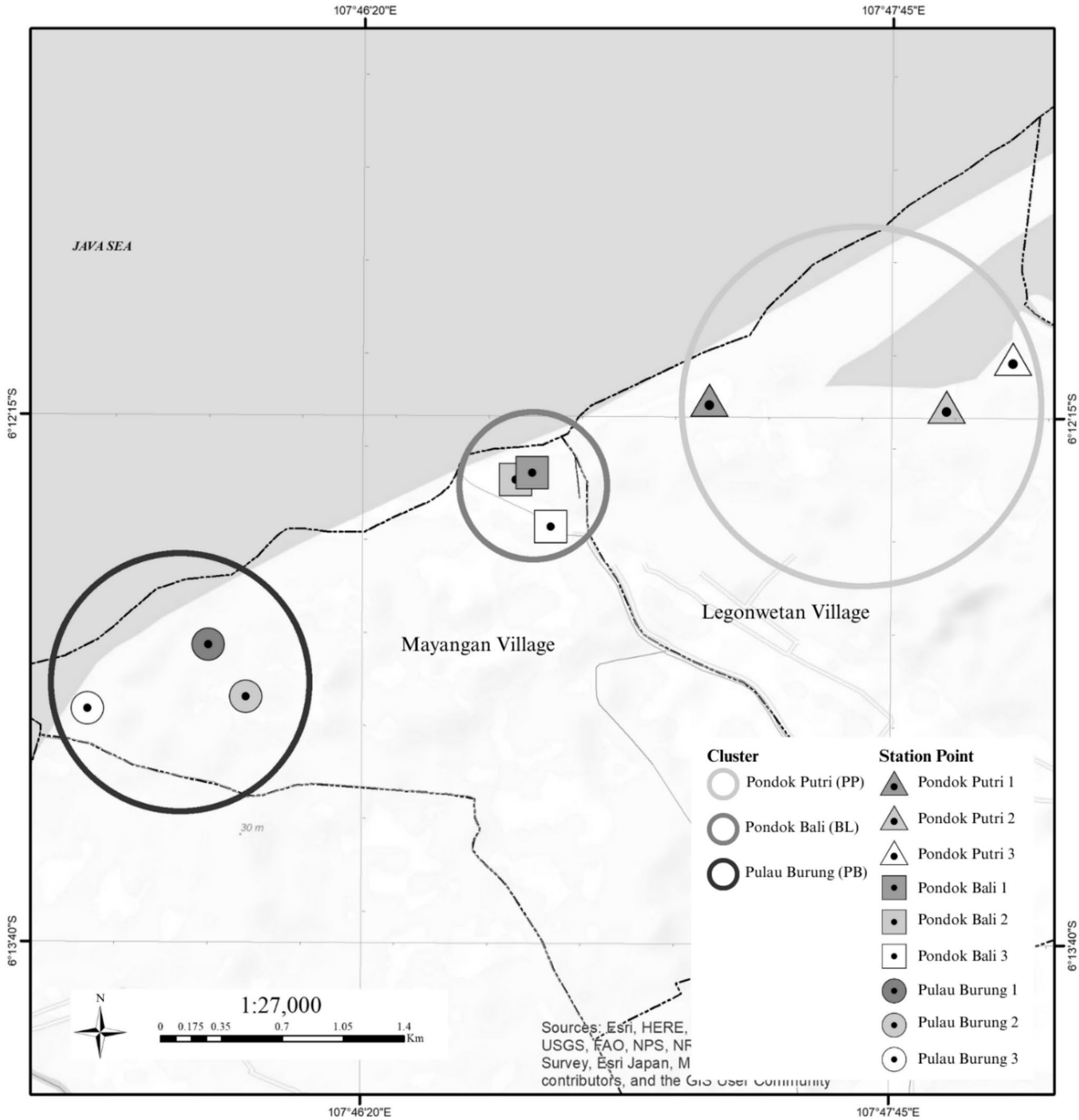

Fig. 6 Map of mangrove clusters in Mayangan and Legonwetan Villages

suggesting that the system has yet to transition into a stable, regenerative state.

The integration of the Management and Transition Framework (MTF) offers deeper insight into how governance transformations shape ecological outcomes. The observed shift from exploitation to adaptive management reflects a gradual transition from an exploitation-oriented paradigm toward a more sustainability-oriented approach. However, this transition remains incomplete. While the adaptive phase is characterized by community-led initiatives and hybrid engineering–ecological interventions, persistent institutional fragmentation indicates that the system continues to operate within what Pahl-Wostl et al (2010) describe as a "transitional regime," in which legacy and emerging governance paradigms coexist. This condition helps explain why restoration outcomes remain inconsistent despite increasing

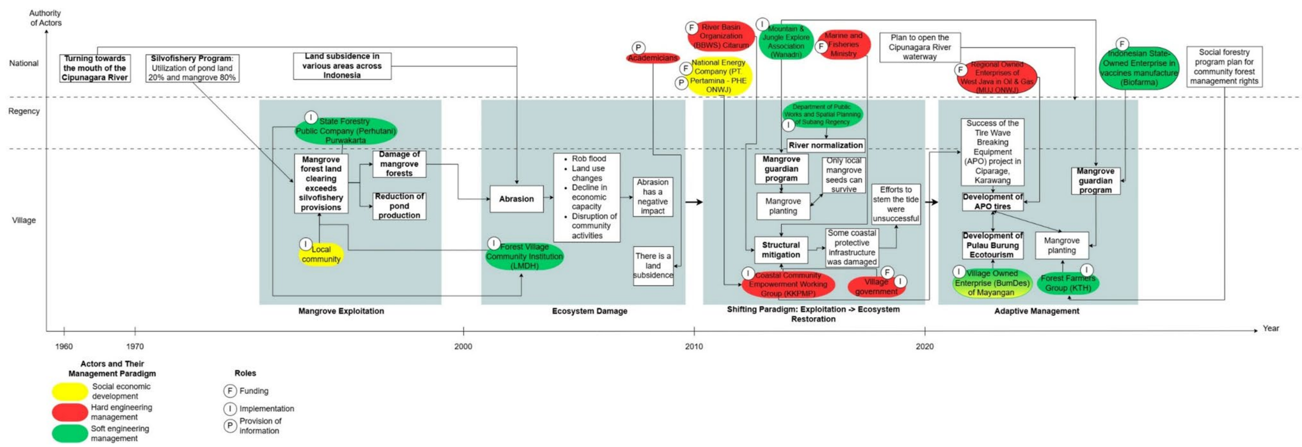

Fig. 7 Mangrove forest management process in Mayangan and Legonwetan Villages, based on the management and transition framework

Table 2 Chronological evolution of mangrove management and resulting social aspects in Pondok Bali (result of MTF analysis, 2026)

No.	Phase/social aspect	Period	Actors involved	Management paradigm and primary drivers	Ecological and social impacts
1	**Mangrove exploitation**	1976–1990s	Perhutani, Local Community	**Socio-economic Development:** National Silvofishery Program aimed at balancing production and conservation	Widespread unauthorized logging and plot sales; production collapse by 1990
2	**Ecosystem degradation**	2000–2010	LMDH, scholars, researchers	**Sustaining consequences:** Cumulative effects of river diversion (1965), land subsidence, and over-clearing	Severe coastal abrasion and frequent tidal flooding; transition from farmers to fishermen/laborers
3	**Mindset shift**	2010–2020	Wanadri, PT. Pertamina, KKPMP, Government Agencies (BBWS Citarum, Marine & Fisheries Ministry, Department of Public Works and Spatial Planning of Subang Regency, Village Government)	**Transition towards Restoration:** Introduction of hard engineering (geotubes) and soft engineering (Mangrove guardian program)	Ineffective/inadequate impacts of mitigation efforts through official projects due to the scale of the degradation; emergence of community-led restoration groups
4	**Adaptive management**	2021–present	KKPMP, KTH, Village and Regional Owned Enterprises of West Java, Biofarma	**Iterative learning:** Implementation of Wave Breaking Equipment (APO) and Social Forestry permits	Rapid sediment trapping and land accretion; development of mangrove ecotourism and issuance of formal land rights

stakeholder involvement. These findings underscore that ecological recovery depends not only on biophysical interventions but also on the maturity of governance systems and the depth of social learning processes (Edelmann et al. 2020).

Compared to previous studies, these findings are consistent with broader evidence across Southeast Asia identifying aquaculture expansion and hydrological alteration as primary drivers of mangrove loss (Richards and Friess 2016; Primavera 2004). However, this study offers a more nuanced perspective by explicitly linking these drivers to evolving institutional dynamics over time. While Van Wesenbeeck et al (2015) emphasize the role of aquaculture in triggering coastal erosion, the present analysis demonstrates that such practices were facilitated by weak governance structures and inadequate enforcement during earlier management phases. In addition, this research highlights the critical importance of governance transitions and solid networks of stakeholders in shaping restoration outcomes, in contrast to Brown et al (2014), which primarily focuses on ecological restoration techniques. Furthermore, the application of Causal Loop Diagrams (CLDs) extends prior SES research by explicitly visualizing feedback mechanisms, as also recommended by Cassidy et al (2022) for analyzing complex policy environments.

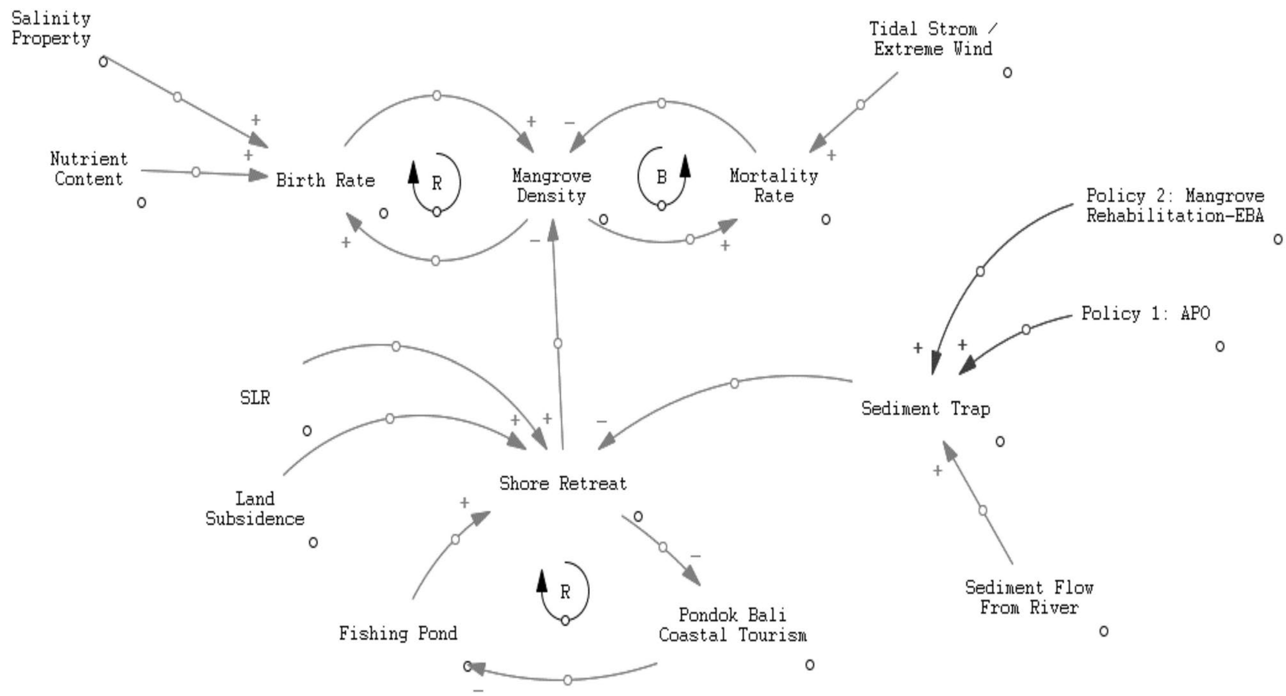

Fig. 8 Social–ecological dynamic change in the Pondok Bali Coastal Area as shown in a causal loop diagram

As a case study, Pondok Bali illustrates how long-term interactions between hydrological change, land-use transformation, and governance dynamics can generate reinforcing patterns of coastal degradation. The integration of remote sensing analysis, field validation, and stakeholder perspectives enables a comprehensive understanding of both past and current system conditions. Despite emerging signs of recovery, several key challenges remain, including ongoing coastal erosion, uneven public support for restoration programs, limited coordination among institutions, and constraints in sustainable financing. These challenges indicate that restoration efforts remain fragmented and have yet to achieve the scale required to reverse broader system decline.

Theoretically, this study advances the application of the SES framework by integrating it with MTF and systems thinking tools, thereby offering a more operational approach to analyzing coastal ecosystem degradation. While SES frameworks have often been criticized for being descriptive (Liehr et al. 2017), this study demonstrates that combining SES with CLD can help identify key leverage points for intervention, including sediment management, institutional coordination, and community engagement. From a practical perspective, the findings highlight the need for a coordinated and phased mangrove restoration strategy that aligns ecological processes with governance mechanisms. In the short term, priority should be placed on stabilizing the coastline through hybrid engineering interventions, such as wave-breaking structures, to enhance sediment accumulation. In the medium term, ecosystem-based approaches, including mangrove rehabilitation and community-based management, should be strengthened to support ecological recovery and local livelihoods. In the long term, sustainable restoration depends on stronger institutional integration, a clear division of stakeholder roles, and the establishment of stable financing mechanisms. This requires coordinated involvement from national and local governments, community organizations such as LMDH and KKPMP, NGOs, universities, and the private sector, supported by blended financing approaches combining public funding, private investment, and community participation. Without such coordination, restoration efforts risk remaining localized and insufficient to address system-wide degradation.

Research limitations

Despite these contributions, several methodological limitations should be acknowledged. The reliance on medium-resolution satellite imagery constrains the precision of long-term ecological analysis, particularly in capturing fine-scale mangrove dynamics, although it remains effective for identifying broader trends. The multi-temporal analysis is based on selected years with consistent data availability, which is sufficient to show overall patterns but does not fully represent continuous year-to-year changes in shoreline dynamics.

Field validation was conducted within a specific period and focused on three observation clusters, providing reliable ground verification but reflecting conditions at the time of observation. The social analysis, based on semi-structured interviews with a limited number of key stakeholders, enables in-depth insights into governance dynamics, although it may not capture the full diversity of perspectives. While the Management and Transition Framework (MTF) effectively capture institutional evolution, it may underrepresent informal socio-cultural dimensions that shape community behavior and decision-making (Orchard et al. 2015). Similarly, the use of Causal Loop Diagram (CLD) helps illustrate system interactions and feedback mechanisms but remains conceptual and does not provide quantitative prediction. In addition, the SES analysis is largely qualitative, which supports a holistic understanding of system dynamics but limits the ability to project future trajectories under different intervention scenarios. Taken together, these considerations define the scope of the study rather than its validity, and the findings should be interpreted as indicative rather than definitive representations of system dynamics. Nevertheless, the results provide a strong foundation for future research, including the integration of higher-resolution spatial data, participatory mapping, and local ecological knowledge (LEK) to enhance contextual accuracy (Fritz et al. 2010), as well as the application of quantitative modeling approaches such as agent-based models or system dynamics simulations to support scenario analysis and decision-making (Oliveira et al. 2022; Nugroho and Uehara 2023).

Conclusion

This study examines how biophysical changes and social dynamics within the mangrove ecosystem of Pondok Bali have coevolved, and whether these dynamics indicate a transition toward sustainability. The findings show that mangrove degradation is driven by multiple interacting factors, including river diversion, land subsidence, aquaculture expansion, and fragmented governance. Although recent hybrid interventions that combine structural measures with mangrove restoration have generated localized improvements, the system remains in a transitional phase in which adaptive practices have yet to be fully institutionalized.

As a case study, Pondok Bali demonstrates how long-term interactions between ecological processes and governance structures can create reinforcing patterns of coastal degradation that are difficult to reverse without coordinated intervention. The results indicate that ecological recovery cannot rely on technical measures alone but requires broader transformation in governance systems. This includes stronger coordination among stakeholders, clearer institutional roles, and sustained financing mechanisms. In practical terms, this highlights the importance of developing an integrated and adaptive coastal management framework supported by a phased implementation strategy that combines engineering approaches with ecosystem-based restoration. Such an approach requires active collaboration among government agencies, community organizations, NGOs, universities, and the private sector (Ostrom 2009; Partelow 2018).

Several methodological limitations should be acknowledged, including the use of medium-resolution spatial data, the predominantly qualitative nature of the analytical frameworks, and the limited exploration of socio-cultural dimensions shaping local behavior and governance. These limitations define the scope of the study rather than its validity, and the findings should be interpreted as indicative of broader socio-ecological dynamics. Future research should integrate higher resolution spatial data, participatory approaches, and quantitative modeling techniques to enhance predictive capacity and policy relevance. Expanding comparative studies across coastal regions in Indonesia and Southeast Asia will further support the identification of both context-specific and transferable strategies and contribute to more effective and inclusive governance of mangrove social–ecological systems.

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Declarations

Conflict of interest The authors declare no competing interests.

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