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SOCIAL-ECOLOGICAL SYSTEM OF MANGROVE REHABILITATION INITIATIVES: A COMPREHENSIVE STUDY IN BREBES REGENCY, CENTRAL JAVA

SISTEM SOSIAL-EKOLOGI INISIATIF REHABILITASI MANGROVE: STUDI KOMPREHENSIF DI KABUPATEN BREBES, PROVINSI JAWA TENGAH

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ABSTRACT

Mangrove ecosystem rehabilitation based on a social-ecological systems (SES) approach is a holistic analysis that integrates ecological and social dimensions in coastal restoration and conservation efforts. The success of this rehabilitation is influenced by the complex interaction between environmental biophysical factors and governance dynamics, including government policies, public participation, and local wisdom practices. This study aims to map and analyze the dynamics of SES in a mangrove rehabilitation program. Data were collected using the rapid rural appraisal (RRA) method from June to August 2024. The study results were formulated into a conceptual model of the basic SES network for mangrove rehabilitation in Brebes Regency. The identified network model consists of 85 components (nodes) and 141 causal relationships (links). The research findings indicate that the managing resource actors (RAs) act as the central component (core of the network) that drives the sustainability of rehabilitation activities in the coastal areas of Brebes Regency. The synergy of roles between actors within this SES framework is crucial in increasing the effectiveness and sustainability of the program. It is expected to optimize ecological functions and provide socio-economic added value for coastal communities.

Keywords: Brebes Regency, mangrove ecosystem rehabilitation, social-ecological system

ABSTRAK

Rehabilitasi ekosistem mangrove berbasis pendekatan sistem sosial-ekologi (*social-ecological systems*/SES) merupakan analisis holistik yang mengintegrasikan dimensi ekologis dan sosial dalam upaya pemulihan serta konservasi pesisir. Keberhasilan rehabilitasi ini dipengaruhi oleh interaksi kompleks antara faktor biofisik lingkungan dan dinamika tata kelola yang mencakup kebijakan pemerintah, partisipasi publik, dan praktik kearifan lokal. Penelitian ini bertujuan untuk memetakan dan menganalisis dinamika SES dalam program rehabilitasi mangrove. Data dikumpulkan menggunakan metode *rapid rural appraisal* (RRA) pada periode Juni hingga Agustus 2024. Hasil penelitian dirumuskan ke dalam model konseptual jejaring dasar SES rehabilitasi mangrove di Kabupaten Brebes. Model jejaring yang diidentifikasi terdiri atas 85 komponen (*nodes*) dan 141 hubungan kausal (*links*). Temuan penelitian menunjukkan bahwa *resource actors* (RA) pengelola bertindak sebagai komponen sentral (*core of the network*) yang menggerakkan keberlanjutan aktivitas rehabilitasi di pesisir Kabupaten Brebes. Sinergitas peran antaraktor dalam kerangka SES ini menjadi krusial dalam meningkatkan efektivitas dan keberlanjutan program, sehingga diharapkan mampu mengoptimalkan fungsi ekologis serta memberikan nilai tambah sosial-ekonomi bagi masyarakat pesisir.

Kata kunci: Kabupaten Brebes, rehabilitasi ekosistem mangrove, sistem sosial-ekologi

INTRODUCTION

The mangrove ecosystem is a coastal ecosystem that plays a crucial ecological and economic role (MEA 2005). Mangroves maintain the balance of the coastal environment through various mechanisms, such as protecting the coast from physical processes such as tides, currents, and waves, and producing organic matter that supports coastal water productivity (Rahman 2016). Furthermore, mangrove ecosystems also serve as important habitats for various aquatic organisms, including feeding grounds, nursery grounds, and spawning grounds for various fish species and other aquatic biota (Yulianto 2017). Thus, the presence of mangroves significantly contributes to supporting the sustainability of coastal ecosystems and local-scale fisheries activities. Despite their crucial role, the condition of mangrove ecosystems in various coastal areas is pressured from anthropogenic activities such as land conversion, shrimp pond expansion, coastal development, and excessive resource exploitation. Indonesia, as the country with the largest mangrove forest area in the world, has also experienced a significant decline in the area and quality of mangroves in recent decades (Setyawan and Winarno 2006; Phong 2024). Mangrove ecosystem degradation not only reduces ecological function but also has social and economic impacts on coastal communities that depend on these resources. One area experiencing mangrove degradation is the coast of Brebes Regency, Central Java Province. Mangrove ecosystem degradation in this area has caused various environmental impacts, such as increased coastal abrasion, declining coastal environmental quality, and reduced fisheries productivity, which are a source of livelihood for coastal communities. This situation indicates that mangrove damage is not only an ecological problem but also closely related to the social and economic dynamics of coastal communities. Therefore, various mangrove rehabilitation efforts have been implemented as part of conservation and sustainable development programs in the region (Suryadi 2022).

Mangrove rehabilitation is an ecosystem management strategy aimed at restoring degraded ecosystems. Ecosystem rehabilitation is defined as an effort to restore the structure, function, and ecological processes of a damaged ecosystem to its natural state before the disturbance (Rivera-Monroy *et al.* 2017). Furthermore, rehabilitation can also be defined as the process of restoring ecosystem quality to provide better ecological, social, and economic benefits than before (Djamaluddin 2018). In the context of coastal management, mangrove rehabilitation focuses not only on replanting mangrove vegetation but also on social, economic, and institutional aspects, as well as community participation in coastal resource management.

Previous studies indicate that the complex interactions between ecological and social factors often influence the success of mangrove rehabilitation programs. Many mangrove rehabilitation programs fail due to insufficient consideration of the biophysical conditions of the site, community social dynamics, and institutional governance aspects (Berkes *et al.* 2003; Anderies *et al.* 2004; Kittinger *et al.* 2012; Levin *et al.* 2013; Mahon and McConney 2013). Therefore, an analytical approach is needed that can understand the reciprocal relationship between humans and ecosystems more comprehensively. The social-ecological systems (SES) approach is one analytical framework that can be used to understand the dynamics of interactions between social and ecological systems in natural resource management. This approach emphasizes that ecosystems and humans are two interconnected components that form a complex, adaptive, and dynamic system (Berkes *et al.* 2003; Anderies *et al.* 2004). In the context of mangrove rehabilitation, the SES approach allows researchers to analyze the relationship between ecological components (such as habitat conditions, vegetation, and ecological processes) and social components (such as actors, institutions, policies, and community economic activities) in an integrated manner. This approach is expected to provide a more comprehensive understanding of the factors influencing the success or failure of mangrove rehabilitation programs. Furthermore, the SES approach is also beneficial in identifying interactions between actors, resource utilization patterns, and governance mechanisms that influence the sustainability of coastal ecosystem management (Hafsaridewi *et al.* 2018; Schlüter *et al.* 2019; Adrianto 2023). By understanding these relationships, mangrove management can be designed more adaptively and based on the integration of ecological and social aspects.

Based on the above description, this study was conducted to map and analyze the dynamics of the social-ecological system (SES) in mangrove ecosystem rehabilitation activities in the coastal area of Brebes Regency, Central Java, by identifying the interactions between social actors, ecological systems, and management processes that influence the success of mangrove rehabilitation. The results of this study are expected to provide scientific contributions in the development of a social-ecological system-based mangrove management approach and serve as a reference for stakeholders in formulating more effective and sustainable mangrove rehabilitation policies and strategies.

METHODS

Time and location

The research was conducted in the coastal area of Brebes Regency, Central Java Province, focusing on two villages with intensive mangrove rehabilitation activities: Sawojajar Village (Wanasari District) and Kaliwlingi Village (Brebes District) (Figure 1). Both locations were selected because they have mangrove rehabilitation programs that have been ongoing for several years and involve various stakeholders. Data collection was conducted from July to August 2024. This period was chosen to obtain comprehensive information on the dynamics of ongoing mangrove management and rehabilitation in the study area.

The study used primary and secondary data to obtain a comprehensive picture of the dynamics of mangrove ecosystem rehabilitation. Primary data were obtained through in-depth interviews and a focus group discussion (FGD) with various stakeholders involved in mangrove management in the study area. Information collected included the condition of mangrove rehabilitation, the roles and involvement of stakeholders, institutional dynamics, and community interactions with the mangrove ecosystem during rehabilitation activities. Meanwhile, secondary data were obtained from various sources, such as mangrove rehabilitation program reports from government agencies, policy documents related to coastal management, regional statistical data, and mangrove area maps, as well as various scientific publications and previous research results.

Interviews were conducted using a rapid rural appraisal (RRA) approach to obtain rapid yet in-depth field information regarding social conditions and coastal resource management (Chambers 1994; Sofield and Marafa 2019). Respondents were selected using a purposive sampling method, which involves deliberately selecting respondents based on specific criteria relevant to the research objectives (Puspitawati *et al.* 2022). The selected respondents were individuals with knowledge, experience, or direct involvement in mangrove rehabilitation activities in the study area. Interviews were conducted with 20 respondents, consisting of administrators and members of coastal community groups and local communities utilizing the mangrove ecosystem. Respondents came from the Mangrove Sari Coastal Forest Conservation Community Group (KMPHP), the Wana Lestari Natural Resource Conservation Group (KPSA), the Tourism Awareness Group (Pokdarwis), the Community Monitoring Group (Pokmaswas), and local communities utilizing the mangrove rehabilitation area.

The FGD was conducted by involving various stakeholders who have a role in mangrove area management, both at the national, regional, and local levels. The FGD participants consisted of representatives from the Ministry of Marine Affairs and Fisheries (KKP) through the Directorate of Coastal and Small Islands Utilization, the Ministry of Environment and Forestry (KLHK) through the Pemali Watershed and Protected Forest Management Center (BPDAS-HL), the Central Java Provincial Forestry Office Branch, the Brebes Regency Fisheries Office, the Brebes Regency Environmental Office, and village governments in Sawojajar and Kaliwlingi Villages. The FGD was attended by approximately 10 participants representing government agencies, village officials, and representatives of coastal community groups. This FGD aimed to identify the roles of each stakeholder, understand the dynamics of coordination between institutions, and identify various challenges and opportunities in mangrove rehabilitation activities in the study area.

Data analysis

Identification of the social-ecological system (SES) of mangrove ecosystem rehabilitation

The identification of the social-ecological system (SES) in this study referred to the framework developed by Ostrom (2009) and McGinnis and Ostrom (2014), with several adjustments to suit the context of mangrove ecosystem rehabilitation in Brebes Regency. The SES framework was used to understand the interrelationships between ecological and social components that interact in natural resource management. Within this framework, the social-ecological system is analyzed through four main components: resource system (RS), resource units (RU), resource actors (RA), and resource governance (RG).

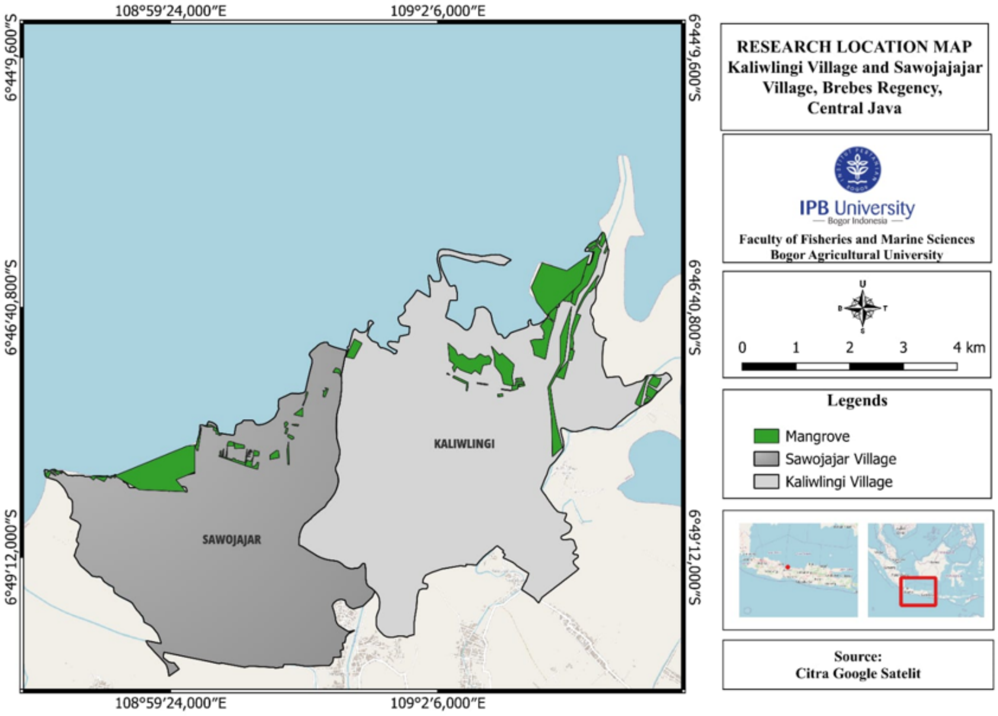

Figure 1. Map of research locations on the coast of Sawojajar Village (Wanasari District) and Kaliwlingi Village (Brebes District), Brebes Regency.

The resource system (RS) refers to the resource system that is the object of management in this study, namely the mangrove ecosystem in the coastal area of Brebes Regency, including the mangrove areas in Sawojajar and Kaliwlingi Villages. This system encompasses the biophysical characteristics of the mangrove area, coastal environmental conditions, and the dynamics of rehabilitation occurring in the area. Resource units (RU) are the resource units produced or contained within the system. In the context of this research, resource units include mangrove vegetation, the resulting ecosystem products, and ecosystem services such as coastal protection, carbon storage, and livelihoods for surrounding communities. Resource actors (RA) are actors or parties involved in the utilization, management, and rehabilitation of mangrove ecosystems. These actors include the central government, local governments, area management institutions, community groups, community organizations, and other parties with an interest in mangrove management. Resource governance (RG) refers to the governance system that regulates the management of these resources, including policies, regulations, institutions, and coordination mechanisms among stakeholders in mangrove ecosystem rehabilitation. The process of identifying these components was carried out through field observations, in-depth interviews, and FGDs with stakeholders. The data obtained were then analyzed through a scoping process to identify relationships between components within the social-ecological system. The results of this identification were used to describe the structure and characteristics of the social-ecological system of mangrove rehabilitation in Brebes Regency.

Analysis of interactions between social-ecological systems (SES) in mangrove ecosystem rehabilitation

The analysis of interactions between actors in the social-ecological system of mangrove ecosystem rehabilitation was conducted using a social-ecological network analysis approach to understand the relationship structure, level of connectivity, and role of each actor in the coastal resource management network. This approach allows for the identification of interaction patterns between stakeholders and the strategic positions of actors within the resource management system (Luke 2015). In this analysis, the system connectivity attributes assessed include network size, network density, centrality, and community or clustering detection (Mullon 2014; Luke 2015). Each stakeholder is represented as a node, while relationships between actors are represented as edges (connection lines) that illustrate the form of coordination, information flow, and collaboration in mangrove rehabilitation activities. Network size indicates the number of nodes or actors involved in the mangrove management system. Meanwhile, network density describes the level of connectivity between actors in the network, namely the proportion of established relationships compared to the maximum number of relationships possible in the system (Luke 2015).

Network density can be analyzed in two forms: directed networks and undirected networks. A directed network describes one-way relationships between actors, typically indicating a specific flow of information or influence, while an undirected network demonstrates two-way or reciprocal relationships between actors within the network (Mullon 2014). Density was calculated by comparing the number of observed relationships within the network with the maximum possible number of relationships between actors. In addition to density, centrality analysis was also performed to identify actors with important positions within the network. Centrality is a measure of the degree of connectedness of a node within a network, both structurally and functionally (Luke 2015).

One indicator used is degree centrality, which is the number of direct relationships a node has with other nodes. Actors with high degree centrality values demonstrate a high level of involvement in the network and have more interactions with other actors. Centrality analysis also includes betweenness centrality, a measure that describes a node's role as a connector or intermediary within the network. Betweenness centrality values indicate how often a node is on the shortest path connecting other nodes within the network. Actors with high betweenness centrality values have strategic positions in facilitating information flow and coordination between actors in resource management systems (Luke 2015). Furthermore, this study also analyzed hubs and authorities as part of the eigenvector centrality measurement. This concept is used to identify influential actors in a network based on their connections to other important actors (Newman 2010). The hubs value indicates the number of outgoing links a node has to other nodes in the network. Actors with high hub values generally act as information sources or actors who have influence in disseminating information to others. Conversely, the authority value indicates the number of incoming links a node receives from other nodes, indicating that the actor is a reference or primary beneficiary in the network (Newman 2010). Furthermore, analysis is conducted on community detection or clustering, which is the process of grouping nodes based on the level of closeness of relationships, similarity of interaction patterns, and characteristics of the network structure (Mullon 2014). The social network analysis in this study was conducted using RStudio software (R Core Team 2023) using the igraph package to map and calculate structural metrics of the nodes and links formed (Csardi and Nepusz 2006). Furthermore, the visualization of the dynamics of interactions and the flow of contributions between categories in the social-ecological system was presented using the ggalluvial package (Brunson 2020).

RESULTS AND DISCUSSION

Characteristics of the social-ecological system of the mangrove ecosystem in Brebes Regency

Based on the results of field observations, interviews, and FGD, the mangrove social-ecological system in Brebes Regency shows a relationship between the biophysical conditions of the mangrove ecosystem, the use of resources by the community, and the roles of various actors in managing mangrove areas (Table 1).

Mangrove ecosystems offer various material and non-material benefits to coastal communities. These benefits include their ecological function as coastal protectors, providing habitat for aquatic biota, and their economic function as a source of livelihood for coastal communities (Dharmawan *et al.* 2016; Malik *et al.* 2017). Therefore, mangrove ecosystem management is not only related to environmental aspects but also closely linked to the social and economic systems of the communities that utilize them through an integrated social-ecological systems approach (Satria 2015; Muawanah *et al.* 2018). Within the social-ecological systems (SES) framework, the condition of the mangrove ecosystem in coastal Brebes can be explained through the interrelationships between the components of resource systems, resource units, resource governance, resource actors, interactions, outcomes, and related ecosystems that shape the dynamics of mangrove management as a whole.

Resource systems (RS)

The resource systems component describes the biophysical characteristics of the mangrove ecosystem, which serve as the basis for mangrove management and rehabilitation in the coastal area of Brebes. The mangrove ecosystem in this area is a coastal mangrove ecosystem with extensive vegetation cover that has developed through rehabilitation activities carried out by the community and government (RS1). The coastal substrate conditions, dominated by muddy sediment (RS2), are a crucial factor in supporting mangrove vegetation growth because the muddy substrate provides a suitable growing medium for mangrove roots. Furthermore, mangrove rehabilitation activities in the study area utilize specific planting patterns, such as block or regular plot patterns (RS3). These planting patterns aim to increase the success rate of mangrove growth and facilitate the monitoring and management of mangrove plants. The success of mangrove planting activities is strongly influenced by environmental conditions such as water quality, hydrological flow systems, and muddy soil substrate conditions that support mangrove growth (Fauzi *et al.* 2022). However, mangrove ecosystem management in the coastal area of Brebes also faces various threats from human activities. These threats include environmental destruction, waste disposal, and unsustainable coastal development due to increasing population demand and the conversion of mangrove land (Phong 2024). If not managed properly, these threats can lead to unsustainable mangrove use and potentially lead to long-term degradation of the mangrove ecosystem.

Resource units (RU)

The resource units component describes the various resources produced by the mangrove ecosystem and utilized by the surrounding community. The mangrove ecosystem in the coastal area of Brebes has an abundance of resources that can be utilized as the primary resource unit for coastal communities. One of the main resources utilized is fishery resources such as crabs, mullet, and milkfish (RU1), which are a source of livelihood for the fishing community in the area. In addition to fishery resources, the mangrove ecosystem also provides economic value through various activities such as fishery cultivation, ecotourism activities, and the production of mangrove seedlings for rehabilitation activities. The economic value of commercial fish resources (RU2) and the quality of brackish mangrove waters (RU3) are important factors in supporting fishery productivity in the area. Utilization of the mangrove ecosystem is also developing through ecotourism activities that attract tourists (RU4). These tourism activities contribute to increasing community income through the provision of tourism services, the sale of local products, and other economic activities. In addition, the community also utilizes mangroves as a source of raw materials in the production of mangrove seedlings (RU5) used in rehabilitation activities. On the other hand, communities have also developed various mangrove-based processed products that provide added economic value (RU6), such as mangrove batik, boiled salt, and various mangrove-based food products. This diversity of uses demonstrates the vital role of mangrove ecosystems in supporting the economic sustainability of coastal communities.

Resource actors dan resource governance (RA dan RG)

Mangrove ecosystem management in the coastal areas of Brebes involves various actors with roles and interests in managing mangrove resources. These actors include fisheries and forestry extension workers, village officials, community leaders, mangrove management groups, fishermen, fish farmers, women's groups, and non-governmental organizations (RA1–RA8). The existence of mangrove management groups is a crucial factor in supporting mangrove rehabilitation activities in the research area. These groups play a role in coordinating rehabilitation activities, such as mangrove seedling nursery, mangrove planting, and mangrove monitoring and maintenance activities. The formation of these community groups demonstrates a high level of community awareness of the mangrove ecosystem in the coastal areas of Brebes. In addition to community involvement, mangrove management is also supported by a governance system involving various government institutions as well as support from the private sector and state-owned enterprises (SOEs). The involvement of local government agencies, SOEs, and private companies (RG1–RG3) provides support in the form of funding, mangrove rehabilitation programs, and community empowerment activities. Mangrove management in this area is also supported by various formal regulations governing the protection and sustainable use of mangrove ecosystems (RG4). The existence of this policy is the basis for more targeted mangrove management and supports mangrove ecosystem conservation efforts in the coastal area of Brebes.

Table 1. Components and variables of the social-ecological system (SES) of mangrove rehabilitation in Brebes Regency.

Category	Variable Code	Variable Name	Description
Resources System (RS)	RS1	Mangrove Ecosystem	The primary ecological system being managed and utilized.
	RS2	Sediment	The condition or rate of sedimentation affects the mangrove ecosystem.
	RS3	Mangrove Planting Patterns	Methods or patterns applied for planting mangrove trees.
Resources Units (RU)	RU1	Value of Tourism	The economic potential and attractiveness of mangrove tourism activities.
	RU2	Value of Mangrove	Direct and indirect benefits derived from the presence of the mangrove ecosystem.
	RU3	Fish Stock	The availability or population of fish around the mangrove ecosystem.
	RU4	Fish Prices	The market value or selling price of fish affects economic dynamics.
	RU5	Fish Production Dynamics	Volume and yield dynamics of fish catching or aquaculture activities.
	RU6	Added Value of Mangrove	The additional value gained from processing mangrove raw materials into products.
Resources Governance (RG)	RG1	Regulations	Rules, policies, or formal legal frameworks underlying mangrove management.
	RG2	Private Companies	Private-sector entities are involved through investment, utilization, or CSR programs.
	RG3	State-Owned Enterprises (SOEs)	State-owned companies supporting funding or environmental governance.
Resources Actors (RA)	RA1	Tourism Managers	Operators or managers of the mangrove ecotourism area.
	RA2	Conservation Groups	Local community groups focused on environmental conservation efforts.
	RA3	Forest Farmer Groups	Community forest groups manage the mangrove area.
	RA4	Extension Officer	Field officers providing technical guidance in fisheries or forestry.
	RA5	Women's Household Groups	Groups of housewives involved in utilizing or processing mangrove products.
	RA6	Fisherman	Traditional capture fishermen utilize the mangrove waters.
	RA7	Aquaculture Farmers	Fish or shrimp farmers operate ponds around the mangrove area.
	RA8	NGOs	Non-governmental organizations assisting in community development and conservation.
Interaction (I)	I1	Government	Government institutional interactions in policy making and coordination.
	I2	Multi-Stakeholder Collaboration	Cross-sector collaboration between the government, the private sector, the community, and NGOs.
	I3	Capacity Building	Activities aimed at improving the skills and capabilities of actors/communities.
	I4	Promotion	Activities to market and promote mangrove tourism or local products.
	I5	Women's Empowerment	Efforts to empower women in social and economic activities.

Table 1. (Continued).

Category	Variable Code	Variable Name	Description
Interaction (I)	I6	Mangrove Utilization	Direct utilization activities of the mangrove ecosystem by the community.
	I7	Fishing Activity	Capture fishing activities conducted by fishermen.
	I8	Educational Tourism	Eco-tourism activities focused on environmental education about mangroves.
	I9	Research Activity	Scientific research and studies regarding mangrove ecosystem conditions.
	I10	Mangrove Seedling Nursery	Cultivation and nursery activities for mangrove seeds.
	I11	Mangrove Ecosystem Monitoring	Routine monitoring activities to check the health status of the ecosystem.
	I12	Silvo-fishery	An integrated mangrove-aquaculture system combining pond culture and conservation.
	I13	Aquaculture Activity	Fish or shrimp culture practices in the coastal ponds.
	I14	Mangrove Planting	Reforestation or planting activities of mangrove seedlings along the coast.
Outcomes (O)	O1	Mangrove Growth Success	The survival and growth rate of the planted mangrove seedlings.
	O2	Income	Financial revenue and economic well-being received by the local community/actors.
	O3	Mangrove Ecosystem Health	The overall health, density, and viability of the mangrove ecosystem.
	O4	Ecosystem Quality	The environmental quality status resulting from a healthy ecosystem.
External Factors (EF)	EF1	Tides	External factors of high and low sea tides affecting mangrove growth.
	EF2	Climate Change	Global climate change impacts on the dynamics of coastal ecosystems.

Interaction (I)

Interactions within the mangrove social-ecological system in the coastal area of Brebes are demonstrated through various mangrove utilization and rehabilitation activities carried out by the community and stakeholders. These activities include mangrove ecosystem utilization, mangrove seedling nurseries, mangrove planting, fishing activities, and fishery cultivation activities (I1–I5). Furthermore, mangrove ecotourism activities are also developing as a form of mangrove resource utilization that provides economic benefits to the community (I6). Interactions between actors are also evident in multi-actor collaboration activities, mangrove ecosystem monitoring, and research activities conducted by various educational institutions and non-governmental organizations (I7–I11). Mangrove rehabilitation activities carried out by the community are also supported by a mangrove seedling nursery program managed independently by community groups with assistance from government extension workers. The mangrove seedlings used in planting activities are generally in the form of propagules, which are considered more effective in the growth process because they have adapted to the environmental conditions of the mangroves in the area.

Outcomes (O)

The various interactions occurring within the mangrove social-ecological system on the Brebes coast have resulted in several important outcomes in mangrove ecosystem management. One of the main outcomes is improved mangrove ecosystem health (O1), demonstrated by successful mangrove growth and improved coastal ecosystem quality (O1.1 and O1.2). Furthermore, mangrove rehabilitation and utilization activities have also had a positive impact on increasing community income (O2). Utilization of mangroves through cultivation, ecotourism, and the production of processed mangrove products provides alternative livelihoods for coastal communities and improves overall community welfare.

Related ecosystem (ECO)

External factors also influence the dynamics of the mangrove social-ecological system in the coastal area of Brebes. One of the main factors is climate change and seasonal dynamics (ECO1), which can affect coastal environmental conditions, such as increased extreme tidal waves that can cause tidal flooding and coastal erosion (Salgueiro-Otero and Ojea 2020). Furthermore, tidal dynamics (ECO2) also affect sedimentation processes and the hydrological flow system that plays a role in supporting mangrove growth. Therefore, strengthening governance and the stability of coastal development policies are crucial factors in maintaining the sustainability of the mangrove ecosystem in the coastal area of Brebes.

Analysis of interactions between social-ecological systems (SES) in mangrove ecosystem rehabilitation

Based on the basic conceptual diagram of the social-ecological system of mangrove ecosystem rehabilitation on the coast of Brebes, it can be seen that there are many variables that have relationships or connections with other variables in a complex network (Figure 2). The Sankey diagram depicts the flow of interactions of 19 types of social-ecological interactions, such as actions, rules, scientific basis, support, capacity, natural processes, and pressures, which connect 22 implementing actors (sources) with 17 target outcomes (targets) in the mangrove rehabilitation system. These interactions are carried out by various actors such as the government, non-governmental organizations (NGOs), forest farmer groups (KTH), extension workers, researchers, silvofishery actors, and promotion and planting units, each of which plays a role in encouraging the restoration process, capacity building, monitoring, and strengthening the economic and ecotourism value of mangroves. This flow of interactions then culminates in target outcomes in the form of ecosystem sustainability, increased income of coastal communities, fish stock recovery, sediment stabilization, and strengthening the conservation and tourism value of mangroves. The basic network model of the social-ecological system for mangrove rehabilitation on the Brebes coast demonstrates a complex overall system consisting of 58 components (nodes) and 141 relationships (links) (Figure 3). This complexity emphasizes that mangrove ecosystem rehabilitation efforts require a comprehensive understanding that represents the interrelationships between systems as nodes and links within each social-ecological component, ensuring effective and sustainable rehabilitation strategies (Felipe-Lucia *et al.* 2022).

The social-ecological system of mangrove rehabilitation on the coast of Brebes has a structure that is not only complex but also layered in terms of the roles and functions of nodes. Nodes with high degree values, such as PemdaMng and KTH, act as interaction centers, connecting multiple components while ensuring a consistent flow of information, regulations, and actions. However, when viewed from a bridging connectivity perspective, other nodes emerge that act as cross-dimensional connectors, such as Silvofishery with the highest contribution value (≈0.09 degrees), which bridges the relationship between ecological dimensions (sediment, fish stocks) and socio-economic dimensions (income, sustainability). Furthermore, ValMang (≈0.08 degrees) emphasizes the importance of the economic value of mangroves as a connecting node between local actors, policies, and economic outcomes, while AistPen (≈0.07 degrees) demonstrates the role of community capacity interactions in connecting the rehabilitation process with tangible results. KTH (≈0.06 degrees) again emerges as a strategic node, strengthening its position not only as an interaction center but also as a connector between actors. Regulation (≈0.05 degrees) serves to maintain governance connectivity, and sediment (≈0.04 degrees), despite its lower value, remains an important ecological indicator linking natural processes to rehabilitation success (Figure 4). However, this quantitative narrative shows that the success of mangrove rehabilitation in Brebes depends not only on central actors with a high degree but also on connecting nodes with high bridging connectivity values that are able to bridge the social, economic, and ecological dimensions. This complexity emphasizes the need for a management strategy that not only strengthens dominant actors but also optimizes connecting nodes so that the social-ecological system can function integratively and sustainably.

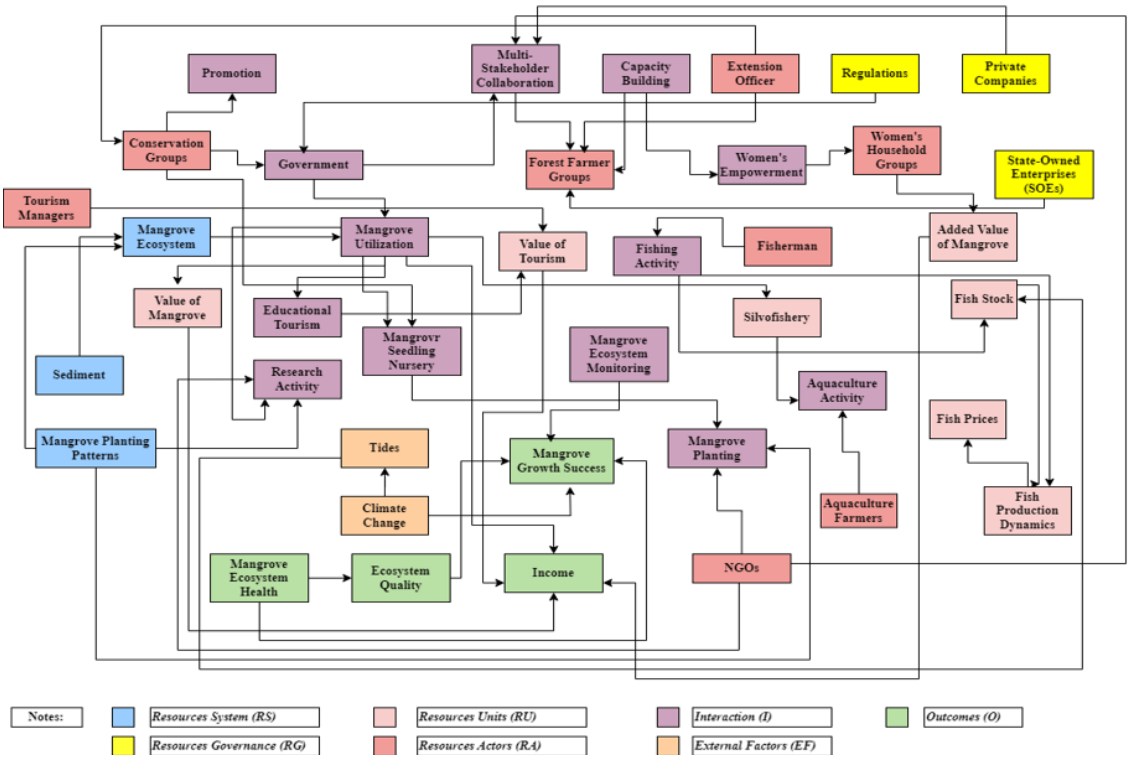

Figure 2. Conceptual diagram of interactions (directed) between variables in the social-ecological system of mangrove rehabilitation on the coast of Brebes.

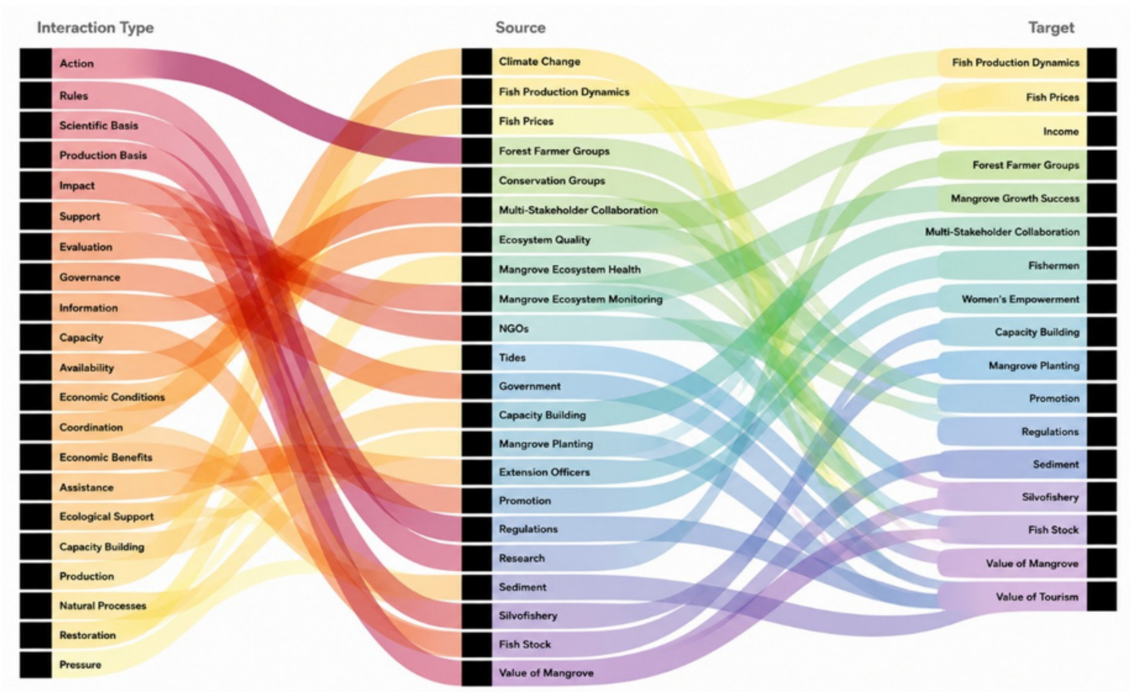

Figure 3. Social-ecological system network of mangrove rehabilitation on the Brebes coast based on the relationship between social and ecological components.

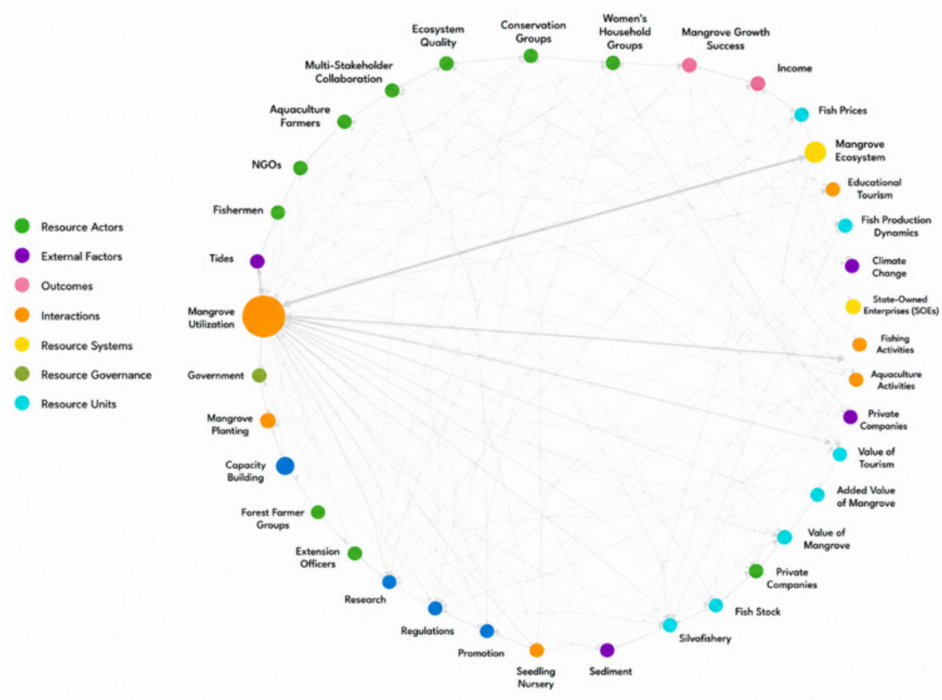

Figure 4. Visualization of core nodes and connectivity in the social-ecological system network of mangrove rehabilitation on the coast of Brebes.

CONCLUSION

The social-ecological systems (SES) approach in this study maps the complexity of multidimensional relationships between social actors, ecological systems, resource units, governance, external factors, and outcomes in the mangrove rehabilitation program in Brebes Regency. The characteristics of the network model formed show system dynamics based on field practices and resource units, where the intercropping component (silvofisheries) and the direct benefit value of the mangrove ecosystem (value of mangrove) are the dominant nodes with the highest level of connectivity. In the context of long-term sustainability, this study confirms that resource actor (RA) managers hold the most crucial position as the central component (core of the network) that drives all rehabilitation activities in the coastal areas of Brebes Regency. The central role of these management actors is the main factor linking the orientation of resource utilization with conservation efforts. Therefore, future policy orientation needs to be directed at optimizing an integrated SES by strengthening the capacity of resource actors (RA) managers. This needs to be supported by the synergy of the roles of all other actor elements and the strengthening of governance instruments such as regulations. This cross-actor collaboration and integration can transform the system to be more adaptive, resilient, and sustainable. The mangrove rehabilitation program will not only be successful in optimizing the coastal ecological function, but will also be able to provide social and economic added value that will have a real impact on the community.

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