

The dynamics model of sustainable mangrove management as a source of ecosystem services

Sjaifuddin Sjaifuddin^{1*}, Susiyanti Susiyanti², Suroso Mukti Leksono³

¹ Department of Environmental Studies, Universitas Sultan Ageng Tirtayasa, Kota Serang, Banten, Indonesia

² Department of Agricultural Sciences, Universitas Sultan Ageng Tirtayasa, Kota Serang, Banten, Indonesia

³ Department of Science Education, Universitas Sultan Ageng Tirtayasa, Kota Serang, Banten, Indonesia

* Corresponding author's e-mail: sjaifuddin@untirta.ac.id

ABSTRACT

Mangrove ecosystems provide essential ecosystem services that support human livelihoods, yet their overexploitation has led to significant ecological degradation. This study aims to develop a dynamic management model for mangrove ecosystems to ensure the sustainability of their ecosystem services. A system dynamics approach was applied to construct a simulation model that evaluates three management strategies: (1) a zero-action strategy, with no intervention in existing mangrove conditions; (2) a single-aspect strategy, focusing on one sectoral policy without integration; and (3) a composite strategy, involving integrated cross-sectoral management. The model simulates the ecological and socio-economic impacts of each strategy over time. Simulation results reveal that the composite strategy performs best across ecological and socio-economic indicators. Compared with the other scenarios, this strategy led to a 70.44% increase in fisheries production, a 20% improvement in benefits from environmental disturbance prevention, a 277% rise in water quality maintenance benefits, a 104.3% enhancement in carbon sequestration benefits, a 268.46% increase in ecological restoration, and a 100% reduction in both chronic poverty and the ecological risk index. These findings suggest that integrated management can effectively balance conservation and human welfare. The model relies on simulation assumptions that may differ from real-world dynamics; therefore, empirical validation is necessary for future applications. This model can assist policymakers and local stakeholders in designing adaptive and sustainable mangrove management strategies. The study provides a novel system-dynamics-based framework for evaluating trade-offs among ecological, economic, and social dimensions of mangrove management, contributing to evidence-based sustainable coastal governance.

Keywords: dynamics model, sustainable mangroves management, ecosystem services, environmental disturbance prevention, carbon sequestration, ecological risk index.

INTRODUCTION

Mangroves are wetland ecosystems located at the confluence of the ocean and land. These ecosystems are diverse, rich, and complex (Queiroz et al., 2017). Mangroves have very high productivity and contribute 2/3 of the total ecosystem services available in nature (Islam et al., 2020). Because of their ability to absorb carbon, along with salt marshes and seagrasses, mangroves are often referred to as blue forests (blue carbon ecosystem) (Himes-Cornell et al., 2018). Mangroves are also very important in biogeochemical cycles, acting as

sustainable supplier of nutrients to terrestrial and marine ecosystems (Hussain and Badola, 2008).

Ecosystem services are the benefits provided by ecosystems to humans and will be needed forever to ensure survival (Ashournejad et al., 2019). Mangroves not only provide direct benefits to the community such as timber and fishery products, but also indirect benefits such as coastal protection, water filtration, research and education, recreation, and carbon sequestration (Wang et al., 2018). Ecosystem services is a concept that is used as an important instrument in decision making in the field of environmental management (Pearson

et al., 2029). Ecosystem services provided by mangroves to humans are often measured through economic assessments. For example, the benefits of mangroves support functions for water quality maintenance USD 5820 ha⁻¹ year⁻¹, environmental disturbance prevention USD 1193 ha⁻¹ year⁻¹, carbon sink 155 kg C ha⁻¹ day⁻¹ (Walters et al., 2008), heavy metal retention USD 73 ha⁻¹ year⁻¹, nutrient retention USD 145 ha⁻¹ year⁻¹ (Wang et al., 2018), nursery ground for fish USD 164,22 ha⁻¹ year⁻¹, biodiversity richness USD 674.51 ha⁻¹ year⁻¹, education and research USD 4.6 ha⁻¹ year⁻¹ (Owuor et al., 2019). In the last few decades, most mangroves ecosystem services have declined due to irresponsible exploitation (Sannigrahi et al., 2020).

Besides having an important role, the great pressure on this ecosystem has driven mangroves to be categorized as an endangered ecosystem (Kumar et al., 2017). The important role of mangroves turns out to be inversely proportional to human treatment of this ecosystem. The ability of mangroves to provide various needs for human life has actually degraded the function of this ecosystem in the long term. On a global scale, currently the mangrove ecosystem has shrunk drastically (Andrieu et al., 2020). In the second half of the 20th century, deforestation has caused rapid loss of mangroves (1–2% area per year) (Worthington et al., 2020). Indonesia has lost more than 200 thousand ha of mangroves in the late 1960s. In just 30 years, the loss of mangroves in Indonesia has increased to more than 800 thousand ha due to the policy of expanding ponds and increasing timber production (Ilman et al., 2016). Over the past 3 decades, more than 50,000 ha (4% of the area of mangroves) in Brazil have been converted to aquaculture, urban, and industrial land (Ferreira and Lacerda, 2016). Australian mangroves (the third largest in the world after Indonesia and Brazil), are continuing to shrink, and the trend will continue, even worse due to the population explosion (Rogers et al., 2016). Countries within the Tropical Eastern Pacific zone (e.g., Ecuador) have also lost more than 40% of their mangrove cover in the last 40 years (Tanner et al., 2018).

This study focuses on Banten Bay, Indonesia, where mangroves are under severe threat from anthropogenic pressures such as overexploitation, pollution, reclamation, and conversion into industrial land. The complexity of these problems is compounded by fragmented coastal management, unintegrated land-sea planning, and limited stakeholder participation. Previous studies

on mangrove management have largely focused on static evaluations such as mapping ecosystem services or economic valuations without addressing dynamic interdependence among ecological, economic, and social variables. Moreover, few models provide integrated cross-sectoral management frameworks capable of simulating policy impacts over time. Hence, a knowledge gap exists in developing a system-based model that captures feedback interactions and long-term sustainability outcomes of mangrove management strategies. Therefore, this study aims to develop a dynamic model for sustainable mangrove management as a source of ecosystem services. Specifically, it seeks to (1) simulate the dynamic interactions between ecological and socio-economic variables in mangrove ecosystems; (2) evaluate alternative management strategies-zero-action, single-aspect, and composite approaches; and (3) identify the most effective strategy for achieving long-term sustainability. The study hypothesizes that an integrated cross-sectoral management strategy (composite strategy) will produce superior ecological and socio-economic outcomes compared to partial or non-intervention strategies. It is expected that this model will not only advance theoretical understanding of ecosystem service dynamics but also offer a practical decision-support tool for sustainable coastal governance.

BACKGROUND

System dynamics

Sustainable management of mangroves needs to pay attention to an in-depth study of comprehensive policies through system modeling. System dynamics (SD) is a simulation technique that meets these criteria because it has a high level of abstraction and is capable of simulating complex system behavior (Ali et al., 2020). SD is very powerful when used to understand various dynamic issues and interdisciplinary studies such as sustainable development (Tan et al., 2018). In policy formulation, SD is used to explore the relationship between ecological, social, economic and technological systems that involve the decisions of stakeholders (Melkonyan et al., 2020). There are 3 main characteristics of SD (Selvakkumaran and Ahlgren, 2020): 1) feedback loop that illustrates the causal relationship between variables, feedback, and delays; 2) computer simulation to

understand non-linear system behaviour; 3) involving mental models through abstraction in the constructed model. One of SD's strengths is its ability to accommodate the feedback loops inherent in complex systems and its usefulness for designing policies effectively (Xie et al., 2020). Development of a complete dynamic model is carried out through 7 steps: 1) conceptualization; 2) development of modeling ideas; 3) formulation; 4) simulation; 5) validation; 6) policy analysis; 7) model utilization (Aliani et al., 2018).

There are two important stages of SD model development (Jiang et al., 2020; Lu et al., 2019): 1) development of a causal loop diagram (CLD) which is used to qualitatively analyse the relationship between variables in the system; 2) development of a simulation model using flow diagrams (FD). In the causal loop diagram, the interaction between variables is described by a plus sign (+) on the arrowhead for a unidirectional relationship, and a minus sign (-) for an opposite relationship (Ketzer et al., 2020). The relationship between variables produces positive and negative loops. A positive loop (also called a reinforcing loop (R)) occurs when the relationship between variables results in an increasingly strong change, while a negative loop (also called a balancing loop (B)) results in a balance change (Daneshezand et al., 2019; Kontogiannis and Malakis, 2019). Flow diagrams are designed using a quantitative approach. The diagram illustrates a logical relationship, feedback mechanisms, and system controls (Li et al., 2020). Flow diagrams are constructed from several components: state (level), rate (flow), and auxiliary (converter) (Zhong, 2018). Besides that, there are also constants and connectors. State (level) is a variable that shows the accumulation of information in the system, rate (flow) represents the flow of information from or into the system, while the auxiliary describes the accumulation of temporary information before the information is processed in the next phase (Sjaifuddin et al., 2019). It is known that there are many SD softwares that can be used to create system dynamics modelling such as Analytica, Vensim, Stella/iThink, InsightMaker, AnyLogic, and Powersim (Honti et al., 2019). This research uses Powersim software. By using Powersim, a model developer is able to evaluate the dynamic behaviour of a system from social, economic, ecological and technological aspects in a more effective and efficient manner (Babamiri et al., 2020).

Sustainable forest management

The world is currently focusing on dealing with forest degradation that occurs in tropical and sub-tropical countries (Gunn et al., 2019). Forest degradation is interpreted as a decrease in the capacity of forests to provide goods and services to fulfil human needs (Miettinen et al., 2014). According to the sustainable development goals report (SDGs Report) 2020 no. 15 (UN, 2020), each year (during 2015–2020), 10 million hectares of forest were destroyed, and two billion hectares of land degraded. This condition causes high rates of species extinction and increases the rate of climate change. The report also states that out of 113 countries in the world, only a third have been able to achieve the national target of integrating biodiversity into national development planning. The following data are in line with the SDGs Report: 1) despite being designated as a world heritage site, the Belize Barrier Reef Reserve System (BBRRS), in Central America has lost 89 ha of mangrove forest from 1996–2017. This condition is indeed better when compared to the estimated loss of 2.703 ha outside BBRRS in the same period (Cherrington et al., 2020); 2) as a result of high exports of logs and conversion to agricultural land, Indonesia's forest loss increased significantly from the 1970s to the mid-1990s. The high demand for world timber has also increased illegal logging in Indonesian forests from the mid-1990s to 2015 (Cadman et al., 2019); 3) nearly 40% of forests in northern New England (Vermont, New Hampshire, and Maine) are already in an understocked condition and lack the density of stands of species that are urgently needed in the future (Gunn et al., 2019); 4) In Cerrado, a biome most threatened in South America, deforestation has resulted in increased soil loss due to surface erosion, loss of natural land cover, increased surface temperature (albedo), and increased pressure on river ecosystems (Garcia and Ballester, 2016).

Facing severe challenges and pressures resulting from forest degradation, currently experts around the world are continuously discussing various methods and actions that can be taken towards sustainable forest management (SFM) efforts (Yamada, 2018). The Brundtland report (WCED 1987) had a major influence on this concept and prompted a massive public debate that led to various interpretations of the concept of sustainability (Sutterlüty et al., 2018). In this context, SFM has two important dimensions: 1)

forest management that integrates biodiversity conservation, carbon sequestration, water and soil protection, and other forest uses, 2) forest management that prioritizes balancing the fulfillment of various needs for goods and ecosystem services for present and future generations (Sotirov et al., 2017). According to the United Nations Conference on Environment and Sustainable Development (UNCED) held in Rio de Janeiro in 1992, SFM has 4 groups of criteria, where each criterion is supported by a number of indicators that show the success of these criteria in achieving goals (Köhl et al., 2020): 1) forest resources, the indicators are: changes in forest area, timber production, and forest characteristics; 2) environment, the indicators are: the vitality and health of forest ecosystems, biodiversity, water conservation, soil conservation, contribution to global ecological cycles, and ecosystem productivity; 3) socio-economic, the indicators are: multiple economic benefits and long-term social benefits; 4) institutional and legal, the indicators are: legislation, infrastructure, and institutions. SFM planning is carried out based on programs implemented through six criteria which aim to maintain, conserve, and enhance: 1) forest ecosystem health; 2) forest protection function (soil and water); 3) contribution of forest to carbon cycle; 4) biodiversity of ecosystems; 5) function of forest production; 6) socio-economic function of forest (Riccioli et al., 2020). There are 3 important criteria towards achieving SFM: 1) supporting legal and institutional governance; 2) protection against anthropogenic and natural factors; 3) good governance of the socio-economic function of forest (Jafari et al., 2028).

Mangrove ecosystem

Mangroves are group of woody plants, living in intertidal zones, complemented by the forest communities: microbes, animals, fungi, and other plants. Mangroves dominate tropical and subtropical coastal zones, having adapted to salinity, high temperatures, and anaerobic substrates (Zaldivar et al., 2000). Mangroves differ from tropical rainforests, primarily in the ability to: 1) developing aerial roots; 2) survive in water with high salt content; 3) canopy production speed; 4) viviparous embryos; 5) propagules that are dispersed by the tides (Yessoufou and Stoffberg (2016). Mangrove ecosystems are characterized by several factors: 1) become a place for accumulation of nutrients,

sediment, carbon, and various contaminants; 2) high productivity and diversity of ecological processes; 3) provide suitable habitat for many species (Berlanga-Robles et al., 2029). Ecologically, mangroves are characterized by salt regulation and photosynthesis. Mangroves can reduce the salt load through a metabolic combination of salt excretion and accumulation. Mangroves also have a specific rate of photosynthesis that varies depending on inter-and intraspecific aspects and is largely determined by genetic factors (Farooqui and Dangi, 2017).

Mangroves are complex ecosystems and play an important role in maintaining the balance of coastal ecosystems (Liu et al., 2020). Ecosystem function is related to the ability to guarantee the sustainability of ecological processes, while ecosystem services relate to the ability to provide services and goods that are beneficial to human life (Chu et al., 2020). Mangroves play an important role in ensuring the ongoing biogeochemical cycles (for example: the production of dissolved oxygen, nutrient uptake, and their contribution to the food web) (Hussain and Badola, 2008). Mangroves also provide various ecosystem services such as regulating services (erosion control, climate regulation, and storm protection), provisioning services (food, fuel, building materials), cultural services (spiritual enrichment, recreation), and supporting services (nutrient cycling) (Wang et al., 2018). Some important examples of ecosystem services played by mangroves: 1) protecting the geographic zone behind the mangroves forest so that it suffers relatively little damage from the tsunami (Oyana et al., 2009); 2) play an important role in climate regulation because they absorb carbon efficiently, have high carbon sediment capture rates and primary productivity, and low decomposition rates (Geoghegan et al., 2020); 3) provide organic matter, good hydrobiological factors, and nutrients for fisheries so that mangroves are the best feeding, nursery, and breeding ground (Hoque et al., 2015). Mangroves provide a variety of economic, social, and ecological benefits (Wang et al., 2017). Thus, community involvement in mangroves conservation is very important, because the community has a strong symbolic relationship with mangroves (Queiroz et al., 2017). Mangrove conservation is important because of the high potential for extinction so that mangroves are included in an endangered ecosystem (Kumar et al., 2017).

METHOD

As a complex ecosystem that plays a vital role in maintaining coastal balance, mangroves must be managed through intersectoral integration, interdisciplinary approaches, and attention to ecological linkages. The management of mangroves as a source of ecosystem services involves numerous interconnected variables. In this study, these variables were categorized into three main dimensions: (1) ecosystem services, (2) community empowerment, and (3) ecological risk.

Research design and framework

This study employed a SD approach, which conceptually analyzes how changes in system components or subsystems affect the overall behavior of the system (Sjaifuddin, 2020a). The framework integrates the three dimensions mentioned above by linking seven key variables: four related to ecosystem services (fisheries production, benefits of environmental disturbance prevention, benefits of carbon sequestration, and benefits of water quality maintenance), two to community empowerment (chronic poverty and ecological restoration), and one to ecological risk (ecological risk index). Each dimension was developed into a sub-model that interacts dynamically within the system.

Research steps

The study was carried out in five main steps (Figure 1): 1) Problem articulation and system

boundary definition. Identification of key issues and variables influencing mangrove ecosystem services in Banten Bay, Indonesia. The variables were derived from literature review, expert judgment, and field observation; 2) Formulation of dynamic hypotheses. The causal relationships among variables were mapped through causal loop diagrams (CLD) to visualize reinforcing (R) and balancing (B) feedback loops that explain system behavior; 3) Development of a simulation model. Based on CLD, flow diagrams (FD) were constructed to represent stocks (levels), flows (rates), auxiliary variables, and constants (Lara et al., 2023). The model structure was developed using Powersim Studio software, which allows simulation of dynamic interactions over time; 4) Model validation. Structural and behavioral validation was performed using the unit consistency test, sensitivity analysis, and historical data comparison to ensure that the model accurately represents real-world mangrove dynamics. Historical data were collected from regional environmental and fisheries agencies (2010–2022) and field measurements in Banten Bay; 5) Scenario design and evaluation. Three management strategies were simulated: a) zero action scenario: no intervention on existing mangrove conditions; b) single aspect strategy: implementation of isolated sectoral policies; c) composite strategy: implementation of integrated cross-sectoral policies (Tan et al., 2018). Each scenario was run for a 10-year simulation period (2020–2030), and outputs were compared using percentage change across seven variables to identify the most effective management strategy.

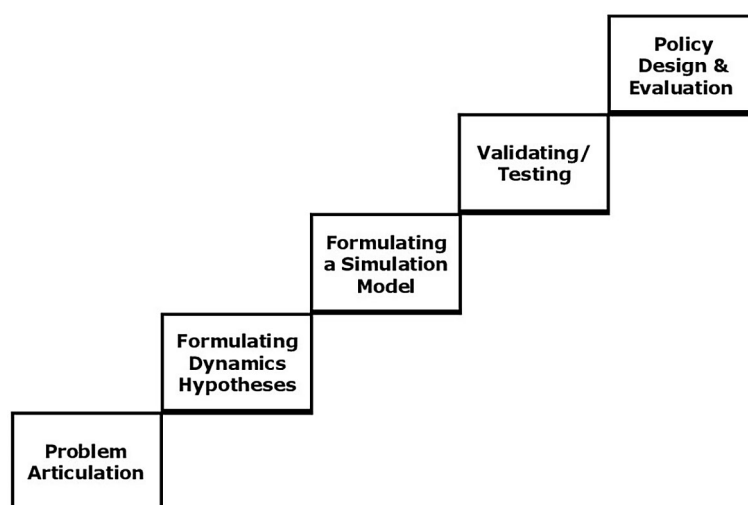


Figure 1. The steps for system dynamics (Yusaf et al., 2022)

System dynamics is equipped with CLD and FD to describe the feedback function that connects various variables in the system (Sjaifuddin, 2020b). Qualitatively, CLD is a representation that can be used to analyse the structure of the system. The direction of the relationship between variables in CLD is described by the letters R (reinforcing loop) and B (balancing loop). R occurs when the variables change in the same direction so that they reinforce each other, whereas B occurs when the variables change in opposite directions so that they weaken each other. Figure 2a illustrates the relationship between variables that strengthen each other, while Figure 2b weakens each other. FD was developed based on the CLD that had been designed. In a simple FD there were four (4) main components: level, rate, auxiliary, and constant. Within the system, level is a variable that represents the main information accumulation. Rate represents the flow of information to the level; the flow can increase or decrease the accumulation of information. Auxiliary is an intermediate variable for various calculations of changes in accumulated information. Constant is a fixed value that can affect a variable. Connector is a link in the system structure. The various components in a simple FD are presented in Figure 3.

Model interpretation and output analysis

Simulation results were analyzed by comparing the trend behavior of each variable under different scenarios. Emphasis was placed on identifying the direction, rate, and equilibrium point of system change. The performance of each strategy was evaluated based on ecological resilience, socio-economic benefits, and reduction of ecological risks. The results were then used to design adaptive policy recommendations for sustainable mangrove management.

RESULTS AND DISCUSSION

Causal loop diagram

The complexity of the relationship between variables in sustainable mangrove management can be identified through CLD. Based on Figure 4, there is a CLD for sustainable management of mangrove as a source of ecosystem services.

This CLD is equipped with 4 R and 1 B. A mutually corroborating relationship at R1 is shown by mangrove ecosystem services and fisheries production. The higher the quality of mangrove ecosystem services, the better the mangrove support function for fisheries, in such a way that the nursery ground will be better. A better nursery ground will encourage better fisheries production in such a way that mangrove ecological restoration will increase. Increased mangrove ecological restoration will lead to increased mangrove ecosystem services as well.

A mutually confirming relationship at R2 is shown by mangrove ecosystem services and carbon sequestration. The higher the quality of mangrove ecosystem services, the better the mangrove support functions to carbon sequestration, such that the carbon sequestration will be better. The better carbon sequestration will encourage mangrove ecological restoration to increase in such a way that mangrove ecosystem services will be better.

A mutually toughening relationship at R3 is shown by mangrove ecosystem services and water quality maintenance. The better the mangrove ecosystem services, the better the mangrove support functions to water quality maintenance, such that the biofiltering process will be more effective. The more effective biofiltering process will have an impact on the better water quality maintenance. This will encourage increased mangrove

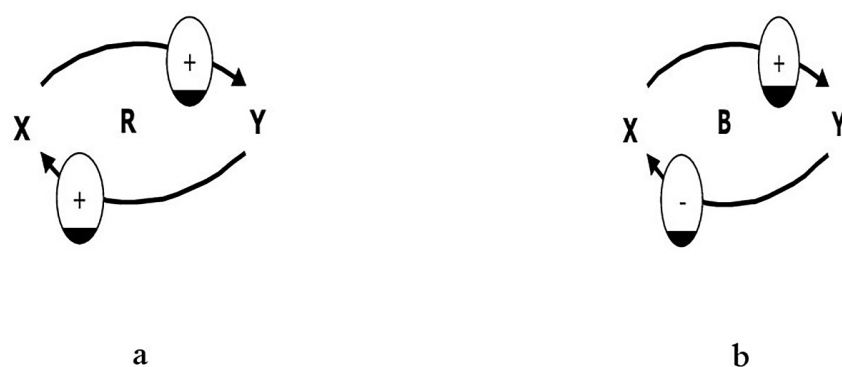


Figure 2. Causal loop diagrams: a) reinforcing loop; b) balancing loop

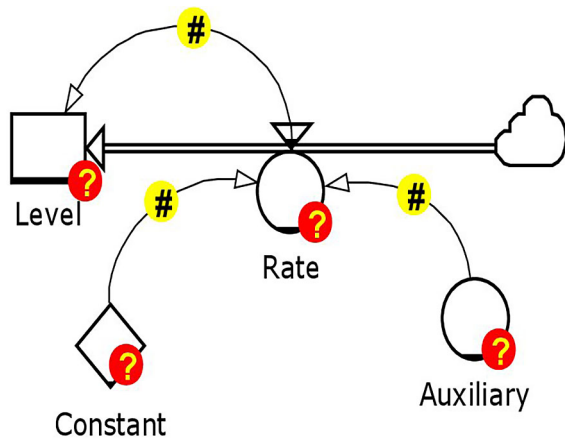


Figure 3. The components of a flow diagram

ecological restoration in such a way that mangrove ecosystem services will also increase.

A mutually amplifying relationship at R4 is shown by mangrove ecosystem services and storm, flood, and erosion control. The better the mangrove ecosystem services, the better the mangrove support functions for environmental disturbance prevention. This will result in better storm, flood and erosion control, in such a way that mangrove ecological restoration will increase. Better mangrove ecological restoration will improve mangrove ecosystem services.

A mutually countervailing relationship at B1 is shown by mangrove ecosystem services and ecological risk index. The better the mangrove ecosystem services, the better the mangrove support functions to reduce metal contamination. This will reduce the ecological risk index and encourage mangrove ecological restoration. The better restoration will lead to increased mangrove ecosystem services.

Flow diagram

Based on the CLD in Figure 4, then the FD is designed in Figure 5. This FD is called the mangrove ecosystem services model (MESM). There are 3 sub-models in MESM: ecosystem services sub-model (black), community empowerment sub-model (red), and ecological risk sub-model (blue). The main model is the ecosystem services sub-model. This sub-model has 4 levels: ‘fisheries production’, ‘benefits of environmental disturbance prevention’, ‘benefits of carbon sequestration’, and ‘benefits of water quality maintenance’. As the co-model is the community empowerment sub-model which has 2 levels: ‘chronic poverty’ and ‘mangrove ecological restoration’. Another co-model is the ecological risk sub-model which has only 1 level: ‘ecological risk index’.

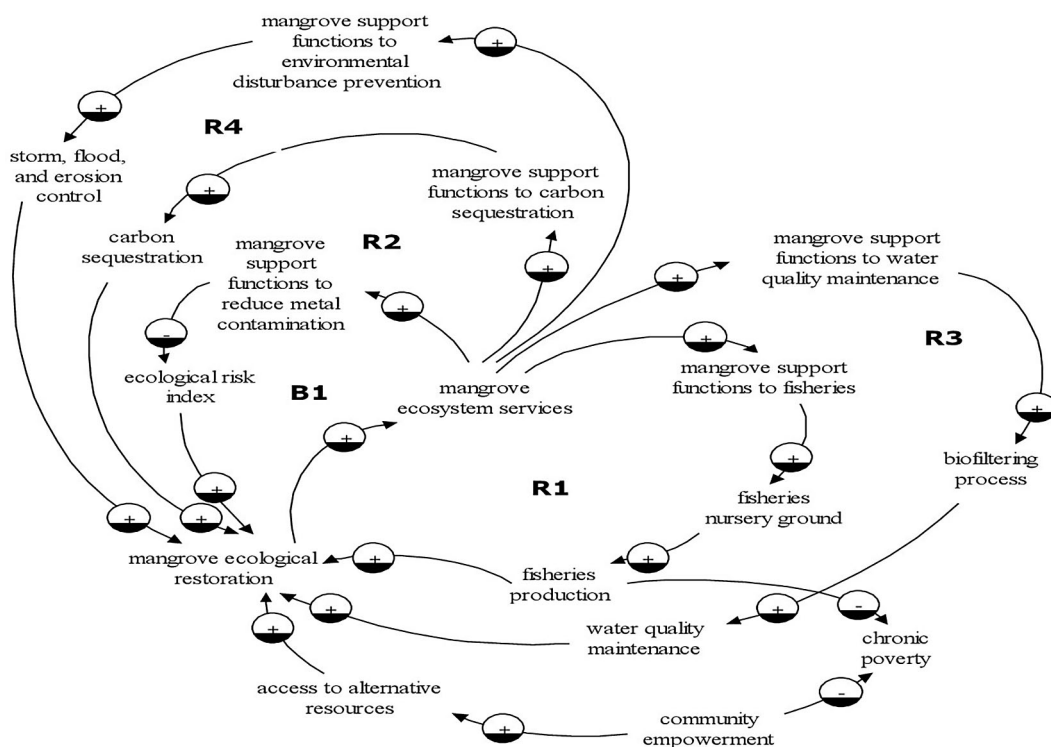


Figure 4. CLD for sustainable management of mangroves as a source of ecosystem services

Fisheries production

Figure 5 shows that ‘fisheries production’ is a level that has an initial value: 5.798 tons. ‘Rate of production’ is a flow that improves ‘fisheries production’ through the equation: ‘ecological risk on fisheries production’*‘fisheries production’*‘fisheries nursery ground’*‘factor of production’. ‘Fisheries nursery ground’ is a graph function with an equation: GRAPHCURVE(‘mangrove support functions to fisheries’;0;0,1;{0,1, 0,14;0,24;0,34;0,54;0,71;0,73;0,79;0,89;0,92//Min:0;Max:1//}). ‘Mangrove support functions to fisheries’ is an auxiliary that has an equation: ‘mangrove ecosystem services’*‘factor of nursery ground’*‘mangrove forest area’. ‘Ecological risk on fisheries production’ is also an auxiliary that has an equation: ‘factor of ecological risk on fisheries production’*‘rate of risk’. There are 3 constants in this sub-model: ‘factor of production’ which has a value of 0.0012 year^{-1} , ‘factor of nursery ground’ which has a value of $0.2 \text{ hectares}^{-1}$, and ‘factor of

ecological risk on fisheries production' which has a value of 0.39. Table 1 shows the equations and values associated with 'fisheries production'.

Benefits of environmental disturbance prevention

Based on Figure 5 it is known that ‘benefits of environmental disturbance prevention’ is a level that has an initial value of USD 918.380. ‘Rate of prevention’ is a flow that improves ‘benefits of environmental disturbance prevention’ through the equation: ‘benefits of environmental disturbance prevention’*‘factor of prevention’*‘storm flood and erosion control’. ‘Storm, flood and erosion control’ is a graph function with an equation: GRAPHCURVE(‘mangrove support functions to environmental disturbance prevention’;0;0,1;{0,1; 0,15;0,207;0,32;0,427;0,71;0,82;0,86;0,91;0,93//Min:0;Max:1//}). ‘Mangrove support functions to environmental disturbance prevention’ is an auxiliary that has an equation: ‘factor of environmental disturbance’*‘mangrove

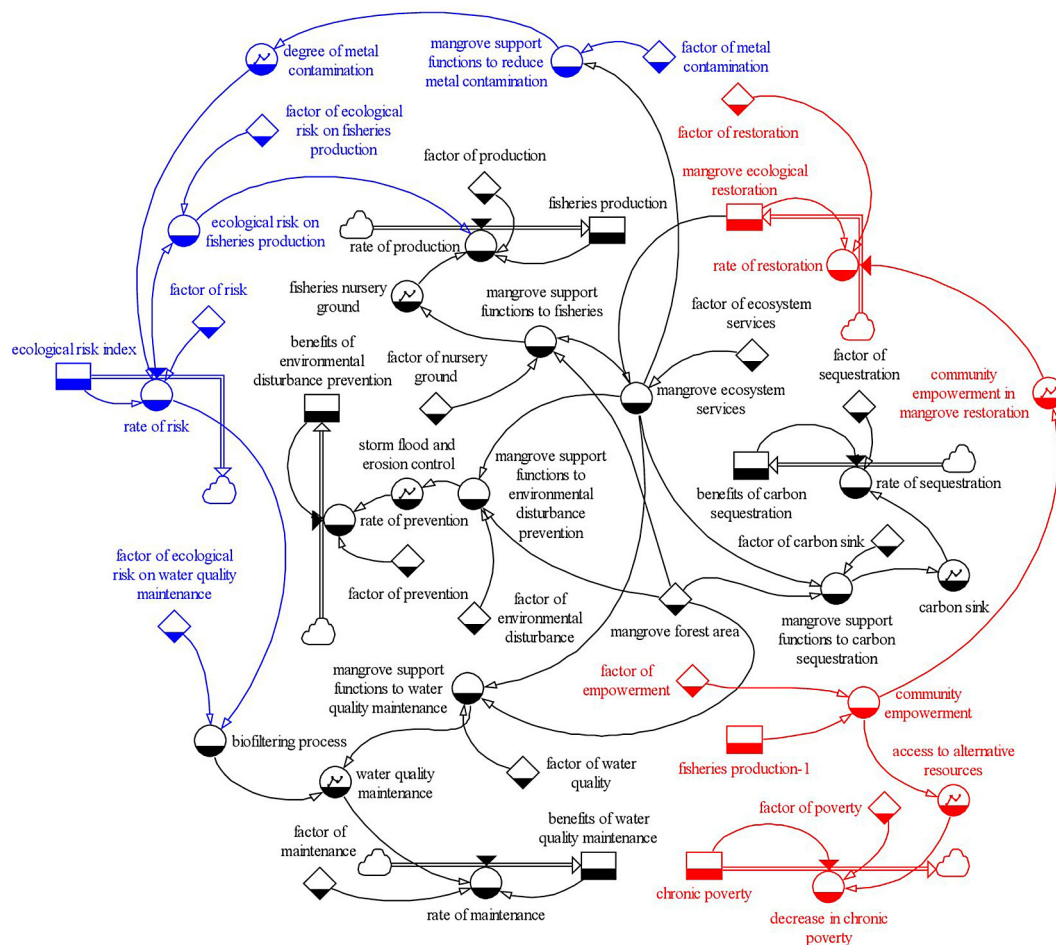


Figure 5. The mangrove ecosystem services model (MESM)

Table 1. The equations and values associated with ‘fisheries production’

Components	Values	Equations
Fisheries production (level)	5798 tons	
Rate of production (flow)		‘Ecological risk on fisheries production’*‘fisheries production’*‘fisheries nursery ground’*‘factor of production’
Factor of production (constant)	0.0012 year ⁻¹	
Fisheries nursery ground (graph function)		GRAPHCURVE(‘mangrove support functions to fisheries’; 0;0,1;{0,1;0,14;0,24;0,34;0,54;0,71;0,73;0,79;0,89;0,92//Min:0;Max:1//})
Mangrove support functions to fisheries (auxiliary)		‘Mangrove ecosystem services’*‘factor of nursery ground’*‘mangrove forest area’
Factor of nursery ground (constant)	0.2 hectares ⁻¹	
Ecological risk on fisheries production (auxiliary)		‘Factor of ecological risk on fisheries production’*‘rate of risk’
Factor of ecological risk on fisheries production (constant)	0.39	

forest area’*‘mangrove ecosystem services’. ‘Mangrove ecosystem services’ is also an auxiliary that has an equation: ‘mangrove ecological restoration’*‘factor of ecosystem services’. There are 3 constants in this sub-model: ‘factor of prevention’ which has a value of 0.0002 year⁻¹, ‘factor of environmental disturbance’ which has a value of 0.3 hectares⁻¹, and ‘factor of ecosystem services’ which has a value of 0.2%⁻¹. Table 2 shows the equations and values associated with ‘benefits of environmental disturbance prevention’.

Benefits of water quality maintenance

Figure 5 shows that ‘benefits of water quality maintenance’ is a level that has an initial value of USD 1137228. ‘Rate of maintenance’ is a flow that improves ‘benefits of water quality maintenance’ through the equation: ‘benefits of water quality maintenance’*‘water quality maintenance’*‘factor of maintenance’. ‘Water quality maintenance’ is a graph function with an equation: GRAPHCURVE (‘mangrove support functions to water quality maintenance’ ;0;0,1;{0,11;0,25;0,36;0,44;0,507;0,56;0,627;0,7;0,8;0,84//Min:0;Max:1//})*‘bio-filtering process’. ‘Mangrove support functions to water quality maintenance’ is an auxiliary that has an equation: ‘mangrove ecosystem services’*‘factor of water quality’*‘mangrove forest area’. ‘Biofiltering process’ is an auxiliary that has an equation: ‘rate of risk’*‘factor of ecological risk on water quality maintenance’. There are 4 constants in this sub-model: ‘factor of maintenance’ which has a value of 0.04 year⁻¹, ‘factor of water quality’ which has a value of 0.3 hectares⁻¹, ‘factor of ecological risk on water quality maintenance’ which has a value of 0.01, and ‘mangrove forest area’ which

has a value of 195.4 hectares⁻¹. Table 3 shows the equations and values associated with ‘benefits of water quality maintenance’.

Benefits of carbon sequestration

According to Figure 5 it is known that ‘benefits of carbon sequestration’ is a level that has an initial value of 30287 kg C. ‘Rate of sequestration’ is a flow that improves ‘benefits of carbon sequestration’ through the equation: ‘benefits of carbon sequestration’*‘factor of sequestration’*‘carbon sink’. ‘Carbon sink’ is a graph function with an equation: GRAPHCURVE (‘mangrove support functions to carbon sequestration’;0;0,1; {0,1;0,147;0,54;0,647;0,67;0,67;0,687;0,77;0,81;0,85//Min:0;Max:1//}). ‘Mangrove support functions to carbon sequestration’ is an auxiliary that has an equation: ‘mangrove ecosystem services’*‘factor of carbon sink’*‘mangrove forest area’. There are 2 constants in this sub-model: ‘factor of sequestration’ which has a value of 0.021 year⁻¹ and ‘factor of carbon sink’ which has a value of 0.002 hectares⁻¹. Table 4 shows the equations and values associated with ‘benefits of carbon sequestration’.

Chronic poverty

Figure 5 shows that ‘chronic poverty’ is a level that has an initial value of 84 %. ‘Decrease in chronic poverty’ is a flow that reduces ‘chronic poverty’ through the equation: ‘chronic poverty’*‘factor of poverty’*‘access to alternative resources’. ‘Access to alternative resources’ is a graph function with an equation: GRAPHCURVE(‘community empowerment’ ;0;0,1;{0,227;0,18;0,21;0,287;0,35;0,47;0,57;0,727;0,86;0,887//

Table 2. The equations and values associated with ‘benefits of environmental disturbance prevention’

Components	Values	Equations
Benefits of environmental disturbance prevention (level)	USD 918380	
Rate of prevention (flow)		'Benefits of environmental disturbance prevention'*'factor of prevention'*'storm flood and erosion control'
Factor of prevention (constant)	0.0002 year ⁻¹	
Storm flood and erosion control (graph function)		GRAPHCURVE('mangrove support functions to environmental disturbance prevention';0;0,1;{0,1;0,15;0,207;0,32;0,427;0,71;0,82;0,86;0,91;0,93//Min:0;Max:1//})
Mangrove support functions to environmental disturbance prevention (auxiliary)		'Factor of environmental disturbance'*'mangrove forest area'*'mangrove ecosystem services'
Factor of environmental disturbance (constant)	0.3 hectares ⁻¹	
Mangrove ecosystem services (auxiliary)		'Mangrove ecological restoration'*'factor of ecosystem services'
Factor of ecosystem services (constant)	0.2 % ⁻¹	

Table 3. The equations and values associated with ‘benefits of water quality maintenance’

Components	Values	Equations
Benefits of water quality maintenance (level)	USD 1137228	
Rate of maintenance (flow)		'Benefits of water quality maintenance'*'water quality maintenance'*'factor of maintenance'
Factor of maintenance (constant)	0.04 year ⁻¹	
Water quality maintenance (graph function)		GRAPHCURVE('mangrove support functions to water quality maintenance';0;0,1;{0,11;0,25;0,36;0,44;0,507;0,56;0,627;0,7;0,8;0,84//Min:0;Max:1//})**'biofiltering process'
Mangrove support functions to water quality maintenance (auxiliary)		'Mangrove ecosystem services'*'factor of water quality'*'mangrove forest area'
Factor of water quality (constant)	0.3 hectares ⁻¹	
Biofiltering process (auxiliary)		'Rate of risk'*'factor of ecological risk on water quality maintenance'
Factor of ecological risk on water quality maintenance (constant)	0,01	
Mangrove forest area (constant)	195.4 hectares ⁻¹	

Min:0;Max:1//}). ‘Community empowerment’ is an auxiliary that has an equation: ‘fisheries production-1’*‘factor of empowerment’. ‘Fisheries production-1’ is a level that has an initial value of 5798 tons. There are 2 constants in this sub-model: ‘factor of poverty’ which has a value of 0,1 year⁻¹ and ‘factor of empowerment’ which has a value of 0,004 tons⁻¹. Table 5 shows the equations and values associated with ‘chronic poverty’.

‘Mangrove ecological restoration’

According to Figure 5 it is known that ‘mangrove ecological restoration’ is a level that has an initial value of 26 %. ‘Rate of restoration’ is a flow that improves ‘mangrove ecological restoration’ through the equation: ‘community empowerment

in mangrove restoration’*‘mangrove ecological restoration’*‘factor of restoration’. ‘Community empowerment in mangrove restoration’ is a graph function with an equation: GRAPHCURVE(‘community empowerment’;1;0,1; {0,2;0,08;0,08;0,12;0,26;0,43;0,667;0,81;0,87;0,89//Min:

0;Max:1//}). There is only one constant in this sub-model: ‘factor of restoration’ which has a value of 0,031 year⁻¹. Table 6 shows the equations and values associated with ‘mangrove ecological restoration’.

‘Ecological risk index’

Based on Figure 5 it is known that ‘ecological risk index’ is a level that has an initial value of 27.94. ‘Rate of risk’ is a flow that reduces

Table 4. The equations and values associated with ‘benefits of carbon sequestration’

Components	Values	Equations
Benefits of carbon sequestration (level)	30287 kg C	
Rate of sequestration (flow)		'Benefits of carbon sequestration'*factor of sequestration*'carbon sink'
Factor of sequestration (constant)	0.021 year ⁻¹	
Mangrove support functions to carbon sequestration (auxiliary)		'Mangrove ecosystem services'*factor of carbon sink*'mangrove forest area'
Carbon sink (graph function)		GRAPHCURVE('mangrove support functions to carbon sequestration'; 0;0,1;{0,1;0,147;0,54;0,647;0,67;0,67;0,687;0,77;0,81;0,85//Min:0;Max:1//})
Factor of carbon sink (constant)	0.002 hectares ⁻¹	

Table 5. The equations and values associated with ‘chronic poverty’

Components	Values	Equations
Chronic poverty (level)	84%	
Decrease in chronic poverty (flow)		'Chronic poverty'*factor of poverty*'access to alternative resources'
Factor of poverty (constant)	0.1 year ⁻¹	
Access to alternative resources (graph function)		GRAPHCURVE('community empowerment'; 0;0,1;{0,227;0,18;0,21;0,287;0,35;0,47;0,57;0,727;0,86;0,887//Min:0;Max:1//})
Community empowerment (auxiliary)		'Fisheries production-1'*factor of empowerment'
Factor of empowerment (constant)	0.004 tons ⁻¹	
Fisheries production-1(level)	5798 tons	

‘ecological risk index’ through the equation: ‘degree of metal contamination’*‘ecological risk index’*‘factor of risk’. ‘Degree of metal contamination’ is a graph function with an equation: GRAPHCURVE(‘mangrove support functions to reduce metal contamination’; 0;0,1;{0,2;0,2;0,227;0,287;0,427;0,57;0,72;0,82;0,9;0,922//Min:0;Max:1//}). ‘Mangrove support functions to reduce metal contamination’ is an auxiliary that has an equation: ‘factor of metal contamination’*‘mangrove ecosystem services’. There are 2 constants in this sub-model: ‘factor of risk’ which has a value of 0.003 and ‘factor of metal contamination’ which has a value of 0.2%⁻¹. Table 7 shows the equations and values associated with ‘ecological risk index’.

Model simulation

Model simulation is useful for representing the real conditions. In this research, simulations were carried out using Euler method (fixed step) at the 1st order, starting from 2020 to 2030. Simulation of three strategies of mangrove management and their impact on fisheries production is shown in Figure 6. In the zero-action strategy, fisheries production declined sharply, so that at the end of

the simulation, fisheries production was only 486 tons (a decrease of 91.62% from production at the beginning of the simulation). Different conditions occur in the single aspect strategy. In this scenario, fisheries production increases by 16.98% (from 5798 tons at the beginning of the simulation to 6783 tons at the end of the simulation). In the composite strategy, the increase in fisheries production is much higher. In this strategy, fisheries production increases by 70.44% (to 9.882 tons at the end of the simulation). Thus, the composite strategy is the best scenario to increase fisheries production. This cross-sectoral policy integration is able to ensure that the mangrove ecosystem remains in the best condition. The combination of integrated policies with local knowledge in mangrove conservation and restoration efforts can also be used as option (Carrasquilla-Henao et al., 2019). Thus, mangroves can remain good nursery habitats and breeding grounds for many fish species (Anneboina and Kavi Kumar, 2017). Research in Gujarat, India shows that overall, mangrove restoration has succeeded in increasing fisheries production by USD 0.57 billion per year (Das, 2017), where the part of the mangrove that was restored contributed benefits of almost a quarter of the part of the natural mangrove.

Table 6. The equations and values associated with ‘mangrove ecological restoration’

Components	Values	Equations
Mangrove ecological restoration (level)	26%	
Rate of restoration (flow)		'Community empowerment in mangrove restoration'* 'mangrove ecological restoration'*factor of restoration'
Community empowerment in mangrove restoration (graph function)		GRAPHCURVE('community empowerment'; 1;0,1;{0,2;0,08;0,08;0,12;0,26;0,43;0,667;0,81;0,87;0,89//Min:0;Max:1//})
Factor of restoration (constant)	0.031 year ⁻¹	

Table 7. The equations and values associated with ‘ecological risk index’

Components	Values	Equations
Ecological risk index (level)	27.94	
Rate of risk (flow)		'Degree of metal contamination'*'ecological risk index'*factor of risk'
Factor of risk (constant)	0.003	
Degree of metal contamination (graph function)		GRAPHCURVE('mangrove support functions to reduce metal contamination';0;0,1;{0,2;0,2;0,227;0,287;0,427;0,57;0,72;0,82;0,9;0,922//Min:0;Max:1//})
Mangrove support functions to reduce metal contamination (auxiliary)		'Factor of metal contamination'*mangrove ecosystem services'
Factor of metal contamination (constant)	0.2% ⁻¹	

Research in Peam Krasaop, Cambodia shows that the estimated catch of fish by fishermen in areas associated with mangroves is higher (about 85%) compared to other locations (Seary et al., 2020).

Simulation of three strategies of mangrove management and their impact on the benefits of environmental disturbance prevention is shown in Figure 7. In the zero-action strategy, the benefits of environmental disturbance prevention decrease by 3% (from USD 918 thousand at the beginning of the simulation to USD 886 thousand at the end of the simulation). In the single aspect strategy, the benefits of environmental disturbance prevention increased by 12.3% (from USD 918 thousand at the beginning of the simulation to USD 1031 thousand at the end of the simulation). The highest increase (20%) occurred in the composite strategy (from 918 thousand USD at the beginning of the simulation to 1102 thousand USD at the end of the simulation). Thus, the composite strategy is the best scenario because it integrates several cross-sectoral policies. This scenario will maintain the mangrove ecosystem at a high performance to be able to provide benefits of environmental disturbance prevention. This is very important because of the following arguments: 1) by using geospatial techniques,

Islam et al. (2020), pointed out that during a cyclone disaster, mangroves are an ecosystem that is relatively less damaged when compared to agricultural land, riparian forest, and sandy beach. 2) The important role of mangroves in protecting the coast during the 2004 tsunami: coastal zones that have good mangrove cover are relatively protected from damage compared to other coastal zones (Oyana et al., 2009). Mangroves provide valuable ecosystem services however these ecosystems are highly vulnerable to disturbance. Thus, adaptation plans must be designed to minimize the negative impact of these disturbances (Mafi-Gholami et al., 2020).

Simulation of three strategies of mangrove management and their impact on the benefits of water quality maintenance is shown in Figure 8. In the zero-action strategy, the benefits of water quality maintenance decrease by 23.3% (from USD 1137 thousand at the beginning of the simulation to USD 872 thousand at the end of the simulation). In the single aspect strategy, the benefits of environmental disturbance prevention increased by 54.5% (from USD 1137 thousand at the beginning of the simulation to USD 1757 thousand at the end of the simulation). The highest increase (277%) was seen in the composite strategy (from

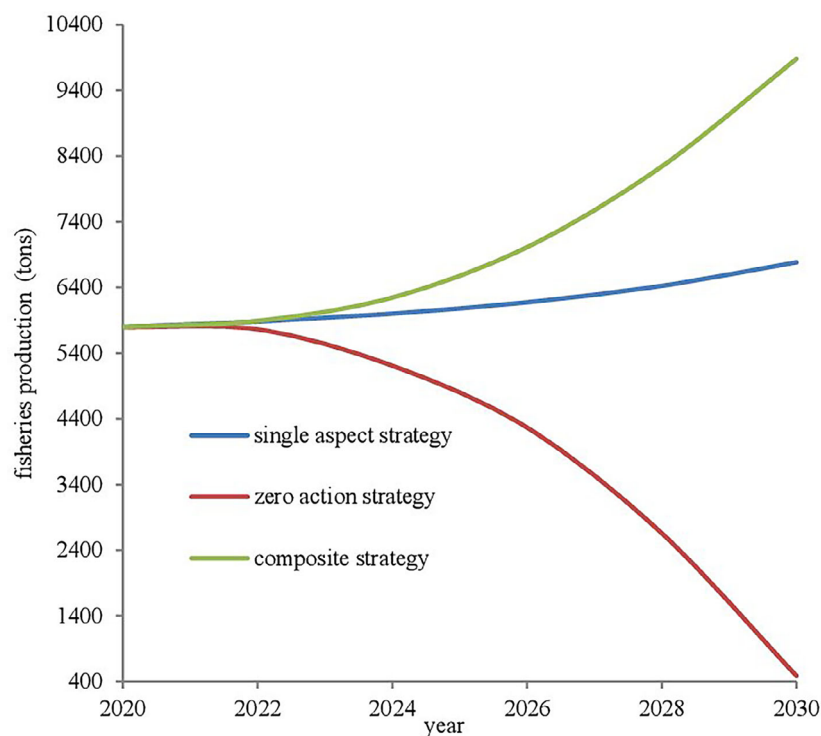


Figure 6. Simulation of three mangrove management strategies and their impact on the fisheries production

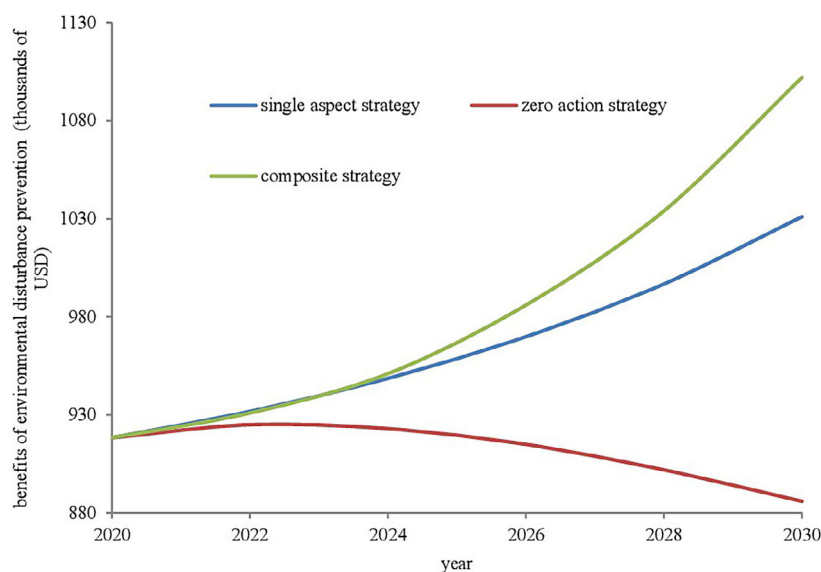


Figure 7. Simulation of three mangrove management strategies and their impact on the benefits of environmental disturbance prevention

USD 1137 thousand at the beginning of the simulation to USD 4286 thousand at the end of the simulation). This scenario will maintain the mangrove ecosystem at its best in maintaining water quality. Mangroves can provide suitable environmental conditions for transforming contaminants in the water. The mechanism takes place through sedimentation, filtration, microorganism activity,

and absorption by mangroves (Wang et al., 2020). In various parts of the world and especially in Asia, mangrove ecosystems have been heavily contaminated with heavy metals: mercury (Hg), lead (Pb), arsenic (As), and cadmium (Cd). The mangrove ecosystem functions as a sink to trap these heavy metals under normal circumstances (Samsudin, et al., 2019). Mangroves have good

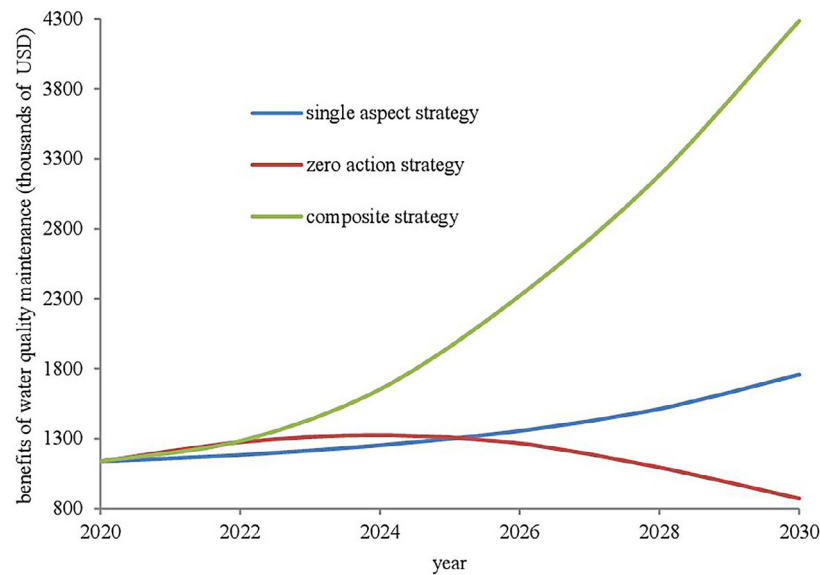


Figure 8. Simulation of three mangrove management strategies and their impact on the benefits of water quality maintenance

phytoremediation capabilities so that organic and inorganic materials as well as other pollutants from domestic, agricultural, and industrial waste can be absorbed through the root system. Mangroves are also capable of denitrification so that the process of enriching nitrate and phosphate in the environment can be controlled (Lotfinasabasl et al., 2018).

Simulation of three strategies of mangrove management and their impact on the benefits of carbon sequestration is shown in Figure 9. In the zero-action strategy, the benefits of carbon sequestration decrease by 24.8% (from 30.29 thousand kg C at the beginning of the simulation to 22.78 thousand kg C at the end of the simulation). In the single aspect strategy, the benefits of carbon sequestration increased by 50.35% (from 30.29 thousand kg C at the beginning of the simulation to 45.54 thousand kg C at the end of the simulation). The highest increase (104.3%) was seen in the composite strategy (from 30.29 thousand kg C at the beginning of the simulation to 61.89 thousand kg C at the end of the simulation). The composite strategy provides opportunities for better carbon sequestration and storage. Carbon absorption will increase along with increasing levels of nutrients, silt, moisture, and clay; conversely it will decrease if there is an increase in bulk density, temperature, volume of sand in the soil, pH, and salinity (Kandasamy et al., 2021). As they get older, mangroves have higher carbon sequestration capabilities. The mangrove species that has

the most potential to absorb carbon is *Xylocarpus mekongensis* (Sahu and Kathiresan (2019).

Simulation of three strategies of mangrove management and their impact on chronic poverty is shown in Figure 10. In the zero-action strategy, chronic poverty increases by 18.31% (from 84% at the beginning of the simulation to 99.38% at the end of the simulation). The decline in chronic poverty occurs in 2 other scenarios. In the single aspect strategy, chronic poverty decreased by 61.78% (from 84% at the beginning of the simulation to 22.22% at the end of the simulation). The sharpest decrease (100%) occurred in the composite strategy (from 84% at the start of the simulation to 0% at the end of the simulation). In the zero-action scenario, mangroves are highly degraded. Case studies in Indonesia show that for every 1% increase in mangrove loss, fishing households decrease their annual income by 5.3–9.8% (Yamamoto, 2023). In the composite strategy, the main consideration in managing mangroves is the importance of poverty alleviation and creation of mangrove-friendly jobs so that mangroves are no longer the main source of livelihood (Damastuti et al., 2022). Composite strategy provides broad opportunities for the community to actively participate in sustainable management of mangroves.

Simulation of three strategies of mangrove management and their impact on mangrove ecological restoration is shown in Figure 11. In the zero-action strategy, mangrove ecological restoration

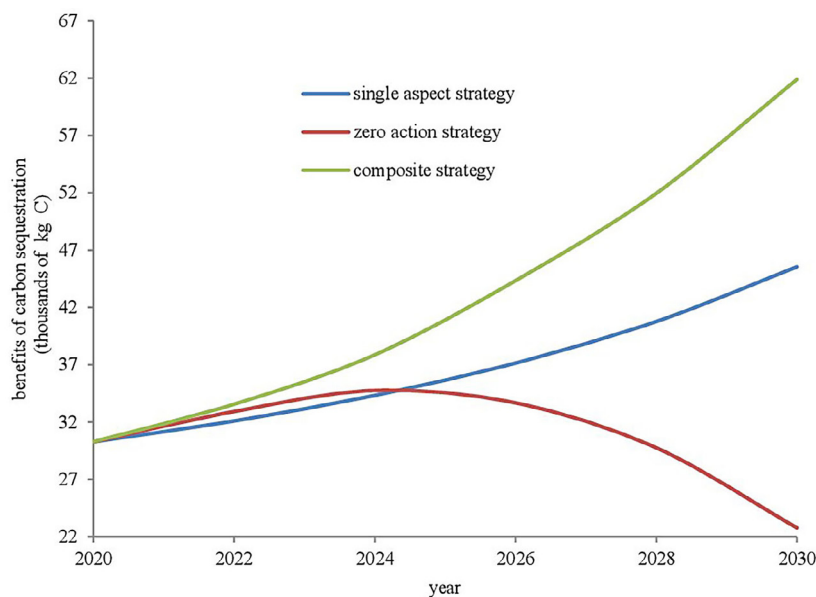


Figure 9. Simulation of three mangrove management strategies and their impact on the benefits of carbon sequestration

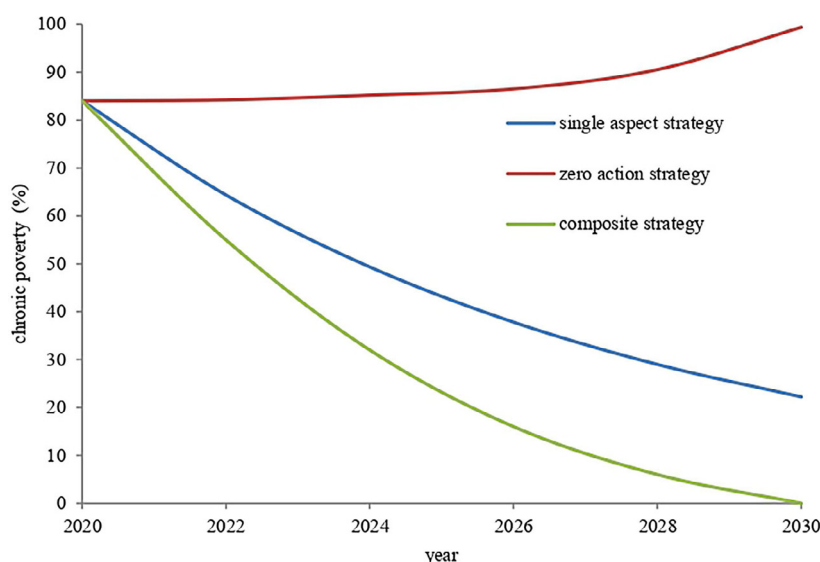


Figure 10. Simulation of three mangrove management strategies and their impact on chronic poverty

decreases drastically (98.46%) (from 26.0% at the beginning of the simulation to 0.4% at the end of the simulation). Increased mangrove ecological restoration occurs in 2 other scenarios. In the single aspect strategy, mangrove ecological restoration increased by 194.23% (from 26.0% at the beginning of the simulation to 76.5% at the end of the simulation). The sharpest increase (268.46%) occurred in the composite strategy (from 26.0% at the beginning of the simulation to 95.79% at the end of the simulation). Community Based Ecological Mangrove Restoration (CBEMR) is the most

effective type of restoration (Rodríguez-Rodríguez et al., 2021). Through CBEMR, mangrove restoration programs in Latin America were able to achieve 69% mangrove cover at a cost of 4115 US\$/ha. CBEMR has also been able to increase the income of the fisheries sector in Gujarat by USD 0.75 billion per year through the improvement of nursery grounds and habitat services (Das, 2017).

Simulation of three strategies of mangrove management and their impact on the ecological risk index is shown in Figure 12. In the zero-action strategy, ecological risk index increases

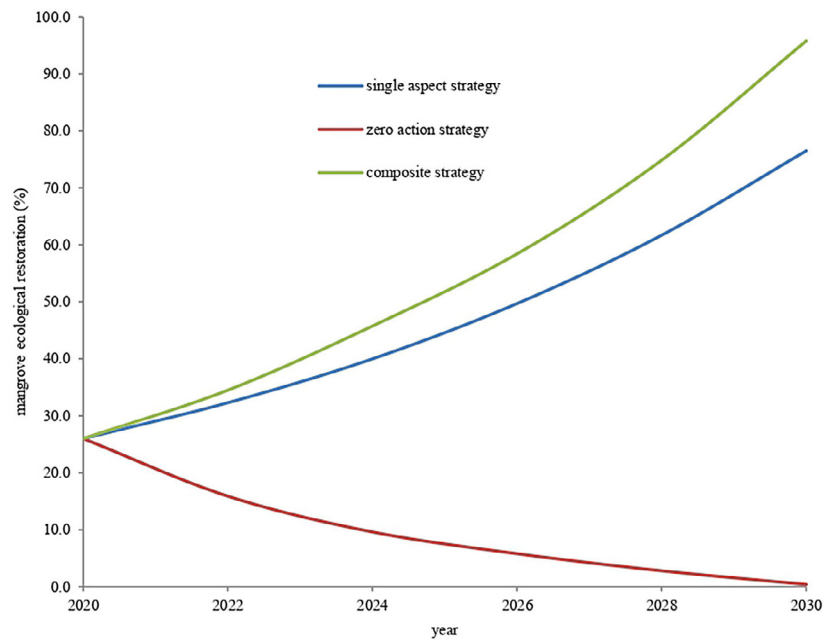


Figure 11. Simulation of three mangrove management strategies and their impact on mangrove ecological restoration

drastically (174.95%) (from 27.94 at the beginning of the simulation to 76.82 at the end of the simulation). The decline of ecological risk index occurred in 2 other strategies. In the single aspect strategy, ecological risk index decreased by 32.96% (from 27.94 at the beginning of the simulation to 18.73 at the end of the simulation). A sharp decrease (100%) occurred in the composite strategy (from 27.94 at the beginning of the simulation to 0 at the end of the simulation).

Ecological risk assessment is very important to determine the toxicity, bioaccumulation, and perseverance of heavy metals (Wang et al., 2023). Mangrove ecosystems are very vulnerable to heavy metal bioaccumulation. This ecosystem then acts as a metal sink in coastal areas. Consequently, the population of microorganisms in mangrove sediments then develops various mechanisms of tolerance and adaptation to the metal toxicity (Puthusseri et al., 2021).

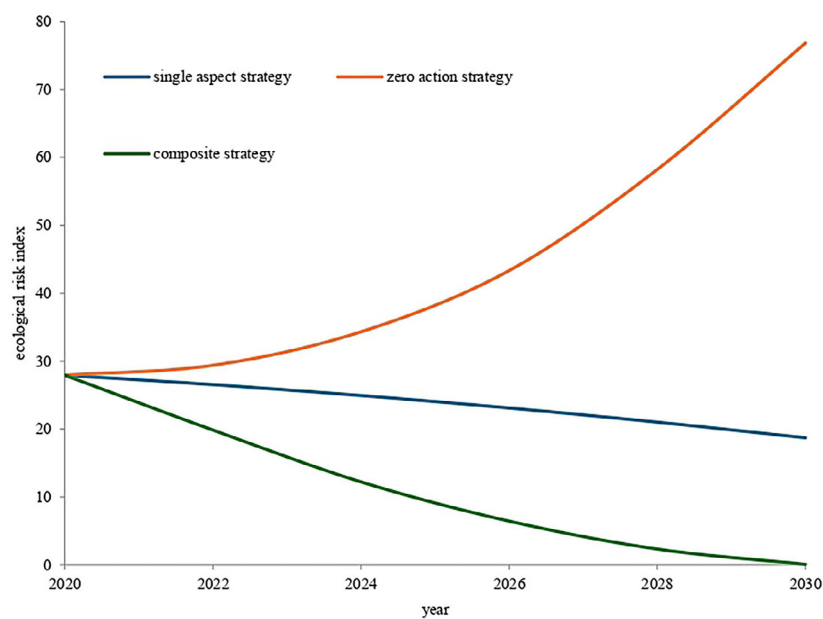


Figure 12. Simulation of three mangrove management strategies and their impact on ecological risk index

Model validation

Model validation is used to provide confidence that the model built can describe the real situation. This research uses a construction validity test which aims to show the fulfilment of the basics of logic in the structure of the model being built. The simulation shows that mangrove management through a composite strategy can significantly increase fisheries production (Figure 6) which results in reduced poverty rates (Figure 10). The composite strategy is also capable of providing benefits of environmental disturbance prevention (Figure 7), benefits of water quality maintenance (Figure 8), and benefits of carbon sequestration (Figure 9). Composite strategy can increase mangrove ecological restoration (Figure 11) and reduce the ecological risk index (Figure 12). These conditions indicate that the simulation has followed the logical thinking pattern of composite strategy-based mangrove management and is relevant to the basics of the system archetype. The simulation also shows that after 10 years, unmanaged mangrove ecosystems (zero action strategy) will reduce fisheries production (Figure 6) so that it will have an impact on increasing poverty (Figure 10). The zero-action strategy significantly reduces the benefits of environmental disturbance prevention (Figure 7), the benefits of water quality maintenance (Figure 8), and the benefits of carbon sequestration (Figure 9). The zero-action strategy also reduces mangrove ecological restoration (Figure 11) and increases the ecological risk index (Figure 12).

CONCLUSIONS

This study successfully achieved its objective of developing a dynamic model for sustainable mangrove management as a source of ecosystem services. By applying a System Dynamics approach, the model integrated seven key variables within three main dimensions-ecosystem services, community empowerment, and ecological risk-into an interactive and holistic simulation framework. The research demonstrated that system dynamics modeling is an effective tool for analyzing long-term interactions and feedback mechanisms that determine mangrove sustainability under different policy scenarios.

The findings revealed that the composite management strategy, which integrates cross-sectoral

policies, produced the most optimal outcomes compared to the zero-action and single-aspect strategies. Over the ten-year simulation period, the composite strategy resulted in substantial improvements across ecological and socio-economic indicators: a 70.44% increase in fisheries production, a 20% rise in environmental disturbance prevention benefits, a 277% improvement in water quality maintenance benefits, a 104.3% increase in carbon sequestration benefits, a 268.46% enhancement in mangrove ecological restoration, and a 100% reduction in both chronic poverty and the ecological risk index. These results confirm the initial hypothesis that integrated, multi-dimensional management can simultaneously enhance ecological resilience and social welfare.

This study contributes a new scientific insight by developing a dynamic and integrative framework that links ecological processes with socio-economic outcomes, filling an important gap in previous mangrove management research that primarily relied on static or single-sector analyses. The proposed model advances theoretical understanding of ecosystem service dynamics and provides a decision-support tool for policymakers to evaluate alternative management scenarios quantitatively and holistically.

Although the model achieved its intended goals, it is based on simulated data that depend on parameter assumptions. Therefore, future studies should incorporate empirical calibration and field validation to improve model reliability. The dynamic framework developed here opens new prospects for applying system-based approaches to other coastal ecosystems, enabling the design of adaptive management strategies that balance conservation objectives with community development goals.

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