Exploring Livelihood Dynamics and Policy Interventions in Mangrove Social-Ecological Systems with Agent-Based Modeling: A Mesa Framework Approach

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Abstract

Mangrove ecosystems represent critical interfaces between human societies and natural systems, providing essential ecological services, vital resources, and economic sustenance to coastal livelihoods. While Agent-Based Modelling (ABM) based on Socio-Ecological Systems (SES) theory have advanced the understanding of such dynamic interactions, current approaches have rarely explored the possibility of designing optimal policy interventions using modeling techniques. We employ MESA, a flexible and computationally efficient Python-based framework, to model the socio-ecological dynamics of an area in the Sundarbans, the largest mangrove forest in the world. Our model description follows the ODD (Overview, Design concepts, Details) protocol to ensure transparency and reproducibility. Through simulations, we demonstrate that more dynamic and adaptive policies have greater potential in promoting ecological stability, while widespread non-compliant behavior among agents undermines the effectiveness of even the most robust intervention strategies. The model implementation and analysis code are made available as open-source software to facilitate replication and extension of this work.

Keywords: Mangrove Ecosystems, Socio-Ecological Systems (SES), Agent-Based Modeling (ABM), MESA (Python Framework), Dynamic Policy Interventions, Ecosystem Management

1. Introduction

Mangrove ecosystems are of significant ecological and economic importance to coastal populations and natural resources. They are one of the prominent and productive ecosystems that provide habitats for numerous species and economic support for human beings. Mangroves play a vital role in ecological balance and protection from natural calamities, such as cyclones, tsunamis, flow tides, and so on. They compose carbon as biomass, providing nutrient cycling and export to neighborhood ecosystems. Mangroves provide human livelihood and sustainability simultaneously as a supplier of woodland, food, fuel, medicine, etc. Thus, mangroves, having a total area of 15,000,000 ha, include material and energy flow for the natural habitats as well as livelihood for the living organisms. Mangroves thus establish stable human-natural interactions that integrate socio-ecological systems (SES)[1][2][3][4].

Over several decades, Social-Ecological Systems (SES) theory has evolved to comprehend and solve complex human-natural system interactions. Early mid- to late 20th century foundational work separated social and ecological systems, with little integration in scientific inquiry. As scholars recognized the connection between humans and nature, systems thinking helped them understand these systems.

Berkes and Folke's 1998 study conceived SES as complex adaptive systems, formalizing SES as a field. Defying the artificial separation between social and natural systems, this framework paved a new way of thinking. SES study was based on the concept that human actions affect ecological outcomes and vice versa. The paradigm also included resilience and adaptive management, which would dominate the sector. This work laid the groundwork for SES research in sustainability science [5]. The Stockholm Resilience Center and other research centers helped the SES field grow in the early 2000s. During this time, resilience thinking and other frameworks showed how SES can adapt to disruptions and maintain function. Walker and colleagues (2004) highlighted SES's adaptability, broadening the field's conceptual environment. Interdisciplinary and transdisciplinary techniques facilitated the analysis of the interactions between the natural and social sciences. The interactions between natural resources and human beings are controlled by several external factors like institutional policies and the choice of particular occupations for livelihood. Different approaches to the operationalization of the SES theory in diversified systems can be found in literature[6][7].

In recent days, Agent-based Modeling (ABM) has become a widely used tool to comprehend complex ecosystems and their interaction with environmental factors.[8][9][10] ABM allows the simulation of autonomous agents that interact with one another leading to emergent behavior and other associated applications for analyses. It shows high effectiveness in modeling urban evacuations, spread of diseases, Geographic Information System (GIS), consumer behavior, transportation, emergency management, and other affiliated domains involving complex interactions. Literature includes review and comparisons among widely used agent-based modeling tools like Netlogo, Anylogic, MATSim, and Repast[11][12][13][14]. While Anylogic is suited for commercial purposes mostly, MATSim and Repast are useful tools for large-scale transportation and social simulations. Netlogo is often highlighted as an ABM modeling tool over the existing ones because of its user-friendly interface, interactive visualizations, and large-scale community. However, we chose to implement our agent-based modeling of the socio-ecological ecosystems using MESA, an open-source ABM framework in Python, which offers more modularity, extensibility, and flexibility over the others[15][16]. MESA supports computationally efficient large-scale simulations taking advantage of parallel computing and high-performing libraries. Being a Python framework, it allows seamless integration with Python's vast ecosystem of scientific computing and machine learning libraries facilitating research purposes. Moreover, MESA offers the opportunity of probing the simulation output continuously with a web socket, thereby allowing the development of robust web applications with custom visualization and interactive interface. Considering these advantages, we implemented the modeling of mangrove socio-ecological systems in MESA and analyzed the interactions of SES components involved there.

While the observable macro characteristics of an SES naturally evolve over time, strategic policy interventions from authoritative bodies can play a crucial role in managing and preserving depleting natural resources.[17][18] Although agent-based modeling has long been used for simulating ecological systems, their potential in identifying optimal intervention strategies remains underexplored. We examine the impacts of three different policies regarding the extraction of Golpata in mangroves and demonstrate that policies that take more dynamic, adaptive decisions accounting for a broader range of possibilities tend to promote greater stability in the ecosystem.

Policy interventions, however, do not guarantee that the enforced rules will be universally abided by. A portion of the population may commit mischievous deeds defying the restrictions imposed by the authority. We analyze the impact of the presence of such a population. Our analysis reveals that even the most well-crafted policy fails to retain its positive impact with an increasing proportion of the rogue population.

2. Materials and Methods

2.1. Model Description: ODD Protocol

We describe our agent-based model following the ODD (Overview, Design concepts, Details) protocol [19] to ensure clarity, replication, and structural realism. The complete model code is available at [GitHub repository URL to be added upon acceptance].

2.1.1. Purpose and Patterns

The model aims to understand how livelihood dynamics in the Sundarbans mangrove ecosystem respond to environmental changes and policy interventions. Specifically, it explores: (1) resource extraction patterns by different livelihood groups, (2) occupation switching behaviors under economic stress, (3) the effectiveness of different policy mechanisms, and (4) the impact of non-compliance on system sustainability.

2.1.2. Entities, State Variables, and Scales

The model consists of the following entities:

Agents:

- **Bawalis:** Extract Golpata (Nypa fruticans) from the mangrove forest
- **Mangrove Fishers:** Fish within the mangrove ecosystem
- **Household Fishers:** Engage in small-scale fishing near their homes
- **Farmers:** Cultivate crops in agricultural lands

Environment:

- Golpata stock (measured in metric tons)
- Fish stock (implicit in the model)
- Agricultural land productivity

Spatial Scale: The model is non-spatial, representing the Gabura union as a single unit.

Temporal Scale: Each time step represents one year, with simulations typically running for 90 years to observe long-term dynamics.

2.1.3. *Process Overview and Scheduling*

The model follows a discrete time-step approach with the following sequence each year:

1. Environmental conditions update (natural growth, hazard impacts)
2. Agents assess their current state and make extraction/production decisions
3. Resource extraction and production occur
4. Economic outcomes are calculated
5. Agents update their capacities and may switch occupations
6. Policy interventions are applied if conditions are met

2.1.4. *Study Area Description*

The study area involves Sunadarbans, the world's largest mangrove forest. Our study is specifically focused on Gabura union under Shayamnagar upazila of Satkhira District in Bangladesh.[20]. Mangrove area provides essential livelihood and ensures environmental protection during natural calamities to the coastal area and the people residing there. The mangrove forest (Sundarbans) covers an area of over 6,017 km^2 in Bangladesh of its total area of about 10,000 km^2. Several natural elements of the Mangrove area are contributing to the enrichment of its diversity and helping a diversified community fit into this livelihood system.

2.1.5. *SES Components and Agents*

Golpata(*Nipa fruticans*), being one of the most abundant species around the mangrove areas, constitute a significant part of the livelihood of the mangrove region. They provide economic growth by offering a variety of usage as raw materials[21]. This palm tree lacks a trunk and has tall, upright leaves and a dense root system. It thrives in riverbanks and streams that have a moderate to high salt concentration. It is prevalent in the southern regions of Bangladesh, specifically in Patuakhali, Bagerhat, Khulna, and Satkhira.However.the amount and extent of Golpata are shrinking with time making a threat to the coastal areas population in regard to their existence and income source[22]. Golpata palm fronds are used to make roofs, headgear, containers, shade devices, and floor coverings. Palm inflorescence sap may be used to produce vinegar, alcohol, and brown sugar. Edible seed endosperms that are not fully developed are consumable. Annually, a total of 2,100 metric tons of Sundarbans Golpata leaves are collected, providing employment for a workforce of 19,000 individuals. Particularly for its people who rely on forests [23][24], the area's economy is quite dependent on this renewable resource. However, the existence Golpata is being threatened due to natural as well as human causes. Cyclones, high salt levels, overharvesting, and habitat degradation have all contributed to a declining Golpata population. The reduction of this resource puts the survival and financial demands of the indigenous people depending on it in danger [23]. Maintaining Golpata's sustainability requires tremendous effort in protection and maintenance. Local non-governmental organizations (NGOs) and research institutes are improving their management strategies and growing Golpata in specialist nurseries to ensure their supply. Implementing sustainable harvesting and habitat restoration among other sensible conservation practices will help to maintain this vital resource for the next generations [23].

The World Heritage Site spans over 1,400 km^2, of which 490 km^2 are submerged underwater. A sizable portion of the population depends on fishing, and the Sundarbans' fisheries are regarded as the foundation of the SRF economy. The Sundarbans mangroves have been slowly declining since the 1970s. Their ecology is changing since the dry season brings less freshwater entering their habitat. More problems are illegal hunting and agricultural invasion. Nonetheless, the fisheries of the Sundarbans present several difficult problems influencing sustainability, biodiversity, and the way of life for fish resources and fishermen. Among these problems are pollution, careless shrimp seed collecting, illicit fishing, inadequate post-harvest and associated infrastructure, and cyclonic waves—natural calamities. Direct results of the growing shrimp farming along Bangladesh's coast include the higher need for natural shrimp seed, which performs better than hatchery seed. As a result, there is extreme pressure on shrimp fry collection from Sundarbans water, which is a serious worry. Notwithstanding these issues, there is a considerable chance that the fisheries of the Sundarbans will grow in tandem with interior capture and coastal aquaculture[25]. Fishes of the Sundarbans represent 322 species belonging to 217 genera, 96 families, and 22 orders [26].

Agriculture is a significant means of subsistence that has been present in mangrove regions up to now. The agriculture in the Sundarbans is significantly influenced by the unique natural characteristics of the region as well as social factors. The area, which shares borders with both Bangladesh and India, is distinguished by tidal surges, frequent cyclones, and increasing soil salinity, all of which pose significant challenges to traditional agricultural practices. The aftermath of events like Cyclone Aila in 2009 has resulted in persistent consequences, such as the formation of salt deposits in agricultural areas that, even after a decade, have not fully regenerated. Numerous farmers have been compelled to abandon their agricultural lands, thereby prompting their migration to urban areas in pursuit of alternative means of livelihood. Farmers in the Sundarbans are utilizing innovative agricultural practices to adjust to the challenging weather conditions. Utilizing harvested rainwater for irrigation, integrated agricultural techniques that combine aquaculture and rice farming mitigate the impact of saline water intrusion. Enhancing soil health and productivity may be achieved by activities such as cultivating a variety of crops, using dry straw as mulch, and shaping the ground into ridges and furrows. However, the move to shrimp farming has led to significant environmental degradation and financial losses for some farmers due to its high profitability. Local non-governmental organizations (NGOs) and academic institutions are working to recover traditional agricultural expertise and support sustainable farming practices thereby guaranteeing the continuing sustainability of farming in this delicate ecosystem.[27][28][29][30] .

Agent-Based Models (ABM) are composed of agents, the main entities identified by traits and qualities. These agents perform their actions according to the rules defined to interact with their surroundings. These agents have dynamic states that change with time depending on their interactions and decision-making procedures. Agents can change their behavior depending on their experiences; so, they can adapt and pick fresh knowledge. Though it is not directly involved, the surroundings clearly affect human activities and interactions. Several fields, including social sciences to study social events, economics to examine market dynamics, and epidemiology to replicate the spread of illnesses, apply this modeling approach.[31][32][33].

This study, using simulation, examines the interactions between important groups that depend on mangrove ecosystems, including both individual and group participants. When necessary, the related authorities and decision-makers oversee these activities. Thus, the study assigns Bawalis, Fishers, and Farmers as the main livelihood groups—assumed as agents in the Agent-Based Model (ABM).

Livelihood Agents

- Bawalis
- Fishers - Types of Fishers:
  - Mangrove Fishers - Operate within the mangrove ecosystem.
  - Household Fishers - Engage in small-scale fishing near their homes.
- Farmers

These agents interact with all the natural components stated beforehand with some specified mathematical equations defined in our model. We also analyze the impact of the interventions from law enforcement agencies and concerned authorities in respective necessities.

2.1.6. Design Concepts

Basic Principles: The model is based on the concept of coupled human-natural systems where agent decisions are driven by economic necessities and constrained by resource availability and regulations.

Emergence: System-level patterns emerge from individual agent decisions, including resource depletion, occupation switching dynamics, and loan participation rates.

Adaptation: Agents adapt by:

- Adjusting extraction/production capacities based on previous year's performance
- Switching occupations when economic thresholds are crossed
- Taking loans when capacity falls below critical levels

Objectives: Agents aim to maintain positive extraction/production capacity and avoid excessive debt.

Learning: Agents do not explicitly learn but adapt their capacities based on success/failure.

Prediction: Agents do not predict future conditions but respond to current state.

Sensing: Agents sense their own economic state, resource availability, and regulatory constraints.

Interaction: Agents interact indirectly through resource competition.

Stochasticity: Natural hazard impacts and initial agent distributions include stochastic elements.

Collectives: No explicit collective behavior, though agents belong to occupational groups.

Observation: Model tracks resource stocks, agent capacities, occupation distributions, and loan participation over time.

2.1.7. *Initialization*

The model initializes with:

- 300 Bawali agents
- 200 Mangrove Fisher agents
- 100 Household Fisher agents
- 200 Farmer agents
- Initial Golpata stock: 50,000 metric tons
- Agent capacities drawn from specified distributions

2.1.8. *Input Data*

The model uses time-series data for natural hazards and can accept CSV files for parameter values. Key parameters include extraction costs, growth rates, and policy thresholds.

2.1.9. *Submodels*

The underlying mathematical architecture of the model is founded on the empirically derived linear equations in [20]. Agents are primarily assigned to a particular occupation. Under unfavorable circumstances, however, they are allowed to switch to other occupations as well for a certain period of time.

Golpata (*Nypa fruticans*) forms a major part of the flora of the Sundarbans. A certain group of people named *Bawalis* primarily depends on extracting Golpata throughout the year. To prevent the Golpata stock from diminishing abruptly, each *Bawali* is granted permission to extract a certain maximum amount of *Golpata*. Moreover, the own financial condition of the *Bawali* gives rise to an extraction capacity which puts another limit to the actual extraction amount. In case the extraction capacity of a *Bawali* falls below the minimum allowed capacity, he switches to farming in the following year. If the agent's permitted amount happens to be zero, he is expected not to perform any extraction that year, which in turn leads to a decline in his extraction capacity for the next year. However, a certain portion of the population turns out to be pilferers. They violate these restrictions and extract *Golpata* even if they are not granted to do so. Each year, natural hazards result in a loss of *Golpata* stock, which the authority tries to replenish by enhancing the conservation rate.

Mangrove Fishers and Household Fishers form another major part of the livelihood in the Sundarbans. A fisher's financial state together with the expenditure for movement determines the catching capacity of the Mangrove Fishers for that year. The capacity of the Household Fishers, however, is affected by the cost to produce fish in their vicinity. If the capacity falls below zero, the fisherman takes out a loan, which leads to a slight increase in his capacity. Depending on the amount of catching throughout the year, the fisher's capacity enhances or declines for the subsequent year. If the capacity crosses a certain threshold, the fisher pays back the loan and regains a portion of the catching capacity.

Natural factors, such as, natural hazards, crop productivity of lands, and human factors like the financial condition of farmers together control the state of farming. Similar to the previously described occupations, a farmer is also assigned a crop production capacity. If it surpasses the minimum required capacity, a certain amount of crop is produced based on the land productivity and natural hazards. Depending on the production amount, the capacity increases or decreases by a certain percentage of the current capacity. Unless the condition is favorable, the farmer takes out loan, leading to a increase in his capacity. He pays back the loan once he regains the required capacity.

Finally we investigate the impact of three different policy interventions on maintaining the ecological stability and also visualize the effect of rogue population when we apply the policy that performs best as per the experiments.

2.2. *Simulation Experiments*

We conducted three sets of simulation experiments to investigate system dynamics:

1. Scenario Analysis: We tested three environmental scenarios (favorable, moderate, critical) varying key parameters such as natural hazard intensity, resource growth rates, and extraction costs. Each scenario was run for 90 time steps with multiple replications.

2. Policy Intervention Analysis: We evaluated three policy designs:

- Policy 1: Single threshold with strict enforcement
- Policy 2: Two-tier system with graduated responses

- Policy 3: Three-tier system with flexible enforcement

3. Compliance Analysis: We varied the percentage of non-compliant (rogue) agents from 0% to 100% to assess the impact on resource sustainability.

2.3. Model Implementation

The model is implemented in Python using the Mesa framework. Mesa provides a modular structure for agent-based modeling with built-in scheduling, data collection, and visualization capabilities. The code repository includes:

- Core model files implementing agent behaviors and environment dynamics
- Parameter configuration files
- Visualization dashboard for real-time monitoring
- Analysis scripts for processing simulation outputs

The complete source code, documentation, and example runs are available at: [GitHub repository - to be added upon acceptance].

3. Results and Discussions

We first reproduce the results obtained in [20] by tracking several parameters in case of three different scenarios distinguished by input parameter values. Then we evaluate the impacts of three different policy interventions and compare them in terms of ecological stability. Finally, we present the negative impact of non-compliant population who violates the rules imposed by the policies.

3.1. Different Cases and Outcomes

Three SES cases are selected to examine system performance and agent behavior within a feasible variable range. These cases focus on the variation in the catching capacity of both types of fishers, crop production capacity of farmers, and the permitted golpata amount for the Bawalis. The model variables that distinguish these cases are listed in Table 1.

- **Case 1** features a high Golpata permit for Bawalis, low catching capacities for both types of fishers, and high crop production capacity.
- **Case 2** includes moderate Golpata permits, moderate catching capacities for fishers, and low crop production capacity.
- **Case 3** presents comparatively low Golpata permits, high catching capacities for fishers, and moderate crop production capacity.

Table 1 summarizes the variable values for each case, showing the metrics for Golpata permits, catching capacities, and crop production.

Additionally, global variables affecting agent behavior as positively and negatively, also play a role in determining how the ecosystem responds under different conditions.

Case Number	Variable	Value (Unit)
Case 1	golpata_permit	125
	catching_capacity_M	2.3
	catching_capacity_H	2.3
	crop_production_capacity	5
Case 2	golpata_permit	120
	catching_capacity_M	2.4
	catching_capacity_H	2.4
	crop_production_capacity	4.75
Case 3	golpata_permit	115
	catching_capacity_M	2.5
	catching_capacity_H	2.5
	crop_production_capacity	4.5

Table 1: Variable values for the three cases

Three scenarios are chosen to simulate each case:

- **Favorable scenario:** This scenario considers the highest values of global variables that have a positive impact and the lowest values for those with a negative impact, as configured in the MESA framework sliders.
- **Moderate scenario:** This scenario assumes moderate values for all global variables.
- **Critical scenario:** This scenario selects the highest values for global variables with a negative impact and the lowest values for those with a positive impact.

The global variable values for each scenario are as follows:

Global variable (unit)	Favorable	Moderate	Critical
Movement cost for Bawali	10	14.75	20
Golpata conservation growth rate	150	125	100
Golpata natural growth rate	75	62.5	50
Natural hazard loss	50	75	100
Ice cost	0.25	0.375	0.5
Movement cost for Fishermen_M	0.25	0.375	0.5
Production cost of fish	0.25	0.5	0.75
Natural hazard loss (crops)	0.5	0.75	1
Fertilizer cost	0.5	0.75	1
Extraction control efficiency	4	3	2
Regulatory efficiency	2	1.5	1

Table 2: Global variable values for each scenario.

3.2. Behaviour of Agents in Different Scenarios

3.2.1. Favourable Condition:

The detailed figures and tables illustrating the changes in outcomes associated with the livelihood agents over time under favourable circumstances are provided in the Supplementary Material (Figures S1-S6 and Tables S1-S6). We can conduct a comprehensive assessment of these elements over a prolonged period. The X-axis represents each year, and the graphs show data for a maximum of 90 years, giving a thorough overview of long-term trends.

The condition of the "Golpata Stock," which holds enormous importance for the *Bawali* people, acts as a crucial gauge of resource sustainability. The trends identified in these plots provide essential insights about the resilience and availability of this crucial resource. The plots labelled "Mangrove Fishers in Loan" and "Catching Capacity Mangrove" are essential for understanding the behaviours and results of mangrove fishers. These graphs offer valuable information on how these communities manage financial borrowing and resource allocation under favourable circumstances. The plots labelled "Household Fishers in Loan" and "Catching Capacity Household" are of enormous significance to household fishermen. This data illustrates the changing patterns within these communities, particularly the fluctuations in loan acquisition and resource capacity over time. Furthermore, the plots headed "Farmers in Loan" and "Crop Production Capacity" are crucial in illustrating farmers' adaptive methods and their efficient use of resources. To do a thorough examination, statistical measures have been calculated for each individual case, mirroring the approach used for the moderate conditions. These measurements facilitate a direct and accurate comparison of the three scenarios, allowing us to examine similarities and differences with precision. The data not only reinforces the observed patterns in the plots but also ensures a full and lucid explanation of the comparison results for each livelihood agent. Detailed statistical analyses are presented in Supplementary Tables S1-S6.

3.2.2. Moderate Condition:

The detailed analyses for moderate conditions are provided in the Supplementary Material (Figures S7-S12 and Tables S7-S13). Comparable to the study conducted for the favorable condition, these show the fluctuations in outcomes connected to the livelihood agents throughout time in the designated somewhat demanding environment. Every graph shows data for up to 90 years; the X-axis shows one year.

In this regard, the "Golpata Stock" is still very important for the Bawali people since it shows the existence of resources in moderate conditions. For mangrove fishermen as well, the stories "Mangrove Fishers in Loan" and "Catching Capacity Mangrove" remain indispensable since they show their responses to unfavorable circumstances. For household fishermen, the plots "Household Fishers in Loan" and "Catching Capacity Household" still hold great relevance since they show the changing loan and resource patterns. Moreover, the plots "Farmers in Loan" and "Crop Production Capacity" remain absolutely vital for farmers since they show their capacity to adapt under somewhat limited conditions.

The statistical indicators, including those used to evaluate favorable conditions, let one easily compare the three scenarios. These steps together with the graphs guarantee a clear and unambiguous understanding of the variations noted under various conditions. Detailed analyses are presented in Supplementary Tables S7-S13.

3.2.3. Critical Condition:

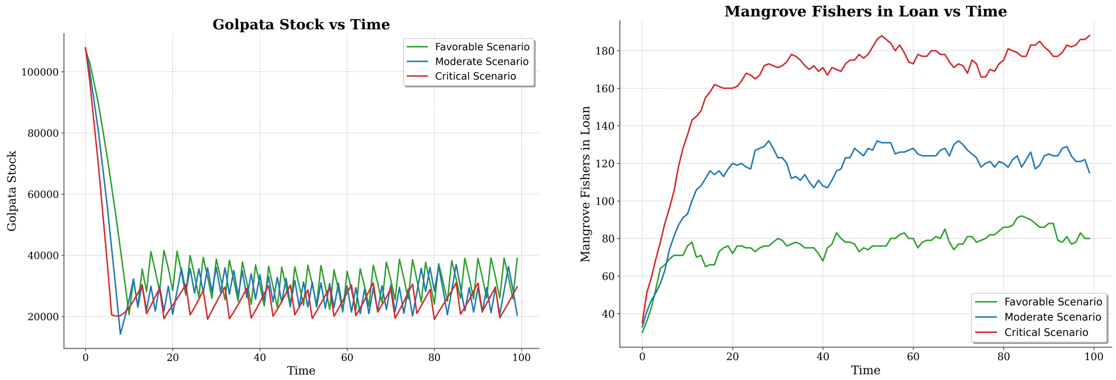
The detailed analyses for critical conditions are provided in the Supplementary Material (Figures S14-S19 and Tables S14-S20). These depict the significant differences in outcomes observed among individuals whose livelihoods depend on critical circumstances compared to those in more favourable and moderate settings. The X-axis remains constant, denoting a single year per unit, whereas the data in each graph covers a time span of up to 90 years.

Under these circumstances, the "Golpata Stock" (shown in Supplementary Figure S14) shows increasing degree of instability, which emphasizes the critical need of resource management for the Bawali people in handling progressively difficult circumstances. The supplementary figures "Mangrove Fishers in Loan" and "Catching Capacity Mangrove" show the great difficulties mangrove fishermen face in adjusting to difficult conditions marked by changing resource availability over time.

The capacity of the plots "Household Fishers in Loan" and "Catching Capacity Household" (see Supplementary Material) to fairly reflect the difficulties encountered by household fishermen determines their relevance. These graphs show a variable pattern, implying a shortage of resources and hence more challenges keeping constant loans and capacity. Furthermore, the statistics presented in the supplementary material under "Farmers in Loan" and "Crop Production Capacity," illustrate the difficulties encountered by farmers in adapting to stringent environmental or regulatory constraints, resulting in significant volatility.

The statistical indicators (see Supplementary Tables S14-S20) illustrate the heightened volatility in the critical situation in comparison to both the favourable and moderate situations. A comprehensive comparison can be carried out among the three samples by incorporating these markers into the time-series plots. This analysis illustrates the significant disparities observed among the three distinct situations, emphasising that more challenging circumstances result in larger variations, unpredictability, and potential inefficiencies among all the individuals and organisations involved in supporting their livelihoods.

3.3. Analyses of Livelihood Agents for Critical, Moderate and Favorable Scenarios



(a) Golpata Stock

(b) Mangrove Fishers in Loan

Figure 1: Key system indicators across Critical, Moderate and Favorable Scenarios. (a) Golpata stock levels showing resource availability under different conditions; (b) Mangrove fishers' loan participation indicating economic stress levels. Additional metrics available in Supplementary Material.

As shown in Figure 1, the analysis of the three scenarios—favorable, moderate, and critical—reveals distinct trends in ecological and social dynamics. The favorable scenario is characterized by strong resource sustainability and economic stability, with Golpata stock stabilizing at higher levels (panel a) and lower fisher loan participation (panel b). Effective conservation and resource management create a balance between environmental preservation and livelihood activities, with minimal economic stress for all agent groups.

In contrast, the critical scenario demonstrates the consequences of ineffective management and aggressive resource extraction. Golpata stock levels are significantly lower, indicating rapid depletion. Fishers experience increasing debt levels, as evidenced by the higher number of fishers taking loans. The capturing capacity for both mangrove and household fisheries becomes more variable and generally lower, reflecting the volatility from decreased resource availability and increased competition.

The moderate scenario represents an intermediate state—a functional but less ideal system. Small-scale conservation initiatives slow but cannot completely prevent resource depletion. Fisher loans show a steady increase but remain within manageable ranges, indicating a pressured but still functional economic environment.

These findings emphasize the importance of proactive resource management and appropriate conservation policies for maintaining both ecological health and socioeconomic stability. While the favorable scenario demonstrates how controlled resource utilization can support long-term sustainability, the critical scenario highlights the dangers of unregulated exploitation. Even the moderate scenario shows signs of gradual degradation, suggesting that only well-designed management strategies can ensure both ecological and economic sustainability in the long term.

3.4. Effect of Policy Interventions

We define a policy as a set of conditions and corresponding actions. For a clear presentation of the conditions and actions, we define three variables gf, zf, rf. The definitions of these variables are as follows:

gf: The fraction of the initial Golpata stock that is currently present. Therefore,

$$gf = \frac{\text{current stock of Golpata}}{\text{initial stock of Golpata}}$$

zf: The fraction of Bawalis whose Golpata collection permission will be withdrawn completely. Therefore,

$$zf = \frac{\text{number of Bawalis with zero permission}}{\text{total number of Bawalis}}$$

rf: The fraction of maximum permitted amount that will be allowed for the rest of the Bawalis. Therefore,

$$rf = \frac{\text{permitted amount for rest of the Bawalis}}{\text{maximum permitted amount}}$$

A condition will be denoted as a relational expression involving gf and the corresponding action will be fully described by the pair (zf, rf). To elucidate, if a condition is expressed as $0.25 \leq gf < 0.5$, $zf = 0.1$, and $rf = 0.8$, it means, when the Golpata stock falls between 25% and 50% of the initial Golpata stock, 10% of the Bawalis will be denied the permission completely and the rest of the Bawalis will be permitted an amount that is 80% of the maximum extraction permission.

Name	**Condition**	zf	rf
Policy 1	$gf < 0.25$	0.2	0.2
Policy 2	$gf < 0.25$	0.5	0.1
	$0.25 \leq gf < 0.5$	0.1	0.8
Policy 3	$gf < 0.25$	0.5	0.1
	$0.25 \leq gf < 0.33$	0.3	0.5
	$0.33 \leq gf < 0.5$	0.1	0.8

Table 3: Definitions of three experimental policies

Table 3 shows the three policies that we experiment with. The first policy consists only one (condition, action) pair while the third contains three such pairs.

Our analysis of policy impacts (detailed in Supplementary Material) shows that applying Policy 1 significantly reduces the mean Golpata stock (31,764 metric tons) compared to Policies 2 and 3 (approximately 55,000 metric tons each). Policy 1 also results in greater fluctuations in stock over time, with a coefficient of variation of 45.2

Next, we analyze the effects of policy interventions on the switching of professions, which further confirms these findings.

The analysis of Bawali occupation counts (see Supplementary Material) further substantiates the volatility arising from the imposition of Policy 1. While the count of Bawalis tends to be turbulent in the case of Policy 1 (coefficient of variation = 21.1

Therefore, the results corroborate the notion that policies with greater flexibility and smooth courses of actions perform better than those with stricter actions and single cut-off conditions in terms of maintaining ecological equilibrium.

3.5. Analyses of Rogue Population

We investigate the effect of rogue population in case of applying Policy 3, the policy that performed best in terms of stability as per the above results.

Our analysis of rogue population impacts (detailed in Supplementary Material) reveals a substantial negative effect on ecological balance. When applying Policy 3 (our best-performing policy), the mean Golpata stock drops by almost 28

In the scenario where half the population is non-compliant, Golpata stock appears more stable in the first few decades but eventually declines to a more turbulent state over time. These results emphasize that even if a carefully curated policy is applied, ecological challenges may still persist if compliance rates are low, highlighting the critical importance of enforcement mechanisms alongside well-designed policies.

4. Summary and Conclusions

This study presents a comprehensive agent-based model of the Sundarbans social-ecological system using the Mesa framework, following the ODD protocol for transparency and reproducibility. Our model captures the complex interactions between three livelihood groups (Bawalis, Fishers, and Farmers) and their environment, incorporating resource dynamics, economic pressures, and adaptive behaviors.

Our results demonstrate several key findings:

1. Environmental conditions significantly impact system stability. Under favorable conditions, all livelihood groups maintain stable outcomes with minimal variability. However, moderate and critical conditions lead to increased volatility, frequent occupation switching, and higher loan dependency.
2. Mathematical modeling can successfully capture the dependence of the observable characteristics of a Mangrove ecosystem on a multitude of environmental and socio-economic factors. Among the proposed policy interventions for Golpata conservation, Policy 2 and 3 offered greater ecological stability over time, thereby proving the necessity of crafting dynamic and adaptive policies that vary their decisions based on a broader range of conditions.
3. Multi-tiered, flexible policies (Policies 2 and 3) significantly outperform rigid single-threshold approaches (Policy 1) in maintaining ecological balance. The graduated response mechanisms reduced Golpata stock volatility from 45.2% to below 17.6%.
4. The presence of a considerable amount of rogue population can, however, wipe away the benefits of the most promising policy interventions. Even with well-designed policies, increasing rogue populations from 0% to 100% resulted in a 28% decline in mean resource stocks, emphasizing the importance of enforcement mechanisms.

Our findings have important implications for managing complex social-ecological systems. Effective policies must be flexible, accounting for heterogeneous agent behaviors and varying environmental conditions. Future work should explore spatial dynamics, more detailed agent learning mechanisms, and integration with empirical data from the Sundarbans region.

The open-source implementation using Mesa facilitates extension and adaptation to other social-ecological systems, contributing to the growing toolkit for sustainability science.

Code and Data Availability

The complete model code, documentation, and analysis scripts are available at: [GitHub repository URL - to be provided upon acceptance]. The repository includes detailed installation instructions, parameter configurations, and example simulations following the ODD protocol specification.

Author Contributions

The first author (Anik Saha) prepared the basic code base and contributed to the preparation of the manuscript. The second author (H.M. Shadman Tabib) contributed to modifications of the codes for further processes and wiriting of the manuscript. The third author (Dr. M. Sohel Rahman) supervised the entire project from start to finish.

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