An Agent Based Model of Mangrove Social-Ecological System for Livelihood Security Assessment

Abstract [200 words max]

Ecosystem services and livelihood security are strongly interrelated in any social-ecological system (SES), and their interdependence should be assessed using an integrated framework. Overexploitation of ecosystem resources may undermine the ecosystem services while restrictions on resource extraction may hamper the dependent livelihoods. We examine these interrelationships for the mangrove SES in Bangladesh using an Agent Based Model (ABM), a useful tool for integrated assessment of human behavior and natural processes. The model simulates the dynamics of ecosystem pressure and livelihood security by linking the supply and expenditure of ecosystem resources, exploited and/or regulated by five primary agents, viz. Bawalis, Farmers and Fishers (livelihood agents), and Forest office and UP office (institutional agents). We find that the livelihood activities can be considerably influenced, both favorably and adversely, by the ecosystem characteristics and the institutional efficiencies. Sustainability of the livelihood activities is indicated by a change in the number of livelihood groups being able to continue their activities in the long term. This will require sound institutional policy for conservation of the ecosystem, preventing overexploitation, and supporting production of provisioning ecosystem services. Supporting optimum levels of livelihood activities and ensuring sustainability of ecosystem resources will help avert their tipping points.

Keywords

Social-ecological system, Livelihood sustainability, Agent based model, Ecosystem service, Mangrove.

1. Introduction

1.1 Mangrove social-ecological system and ecosystem services

Mangroves provide essential ecosystem services to the coastal population and natural environment. These services include provisioning (e.g. food and water), regulating (e.g. climate and disease control), supporting (e.g. nutrient cycling and pollination), and cultural (e.g. recreational and spiritual) dimensions that define the services. While the ecosystem services ensure material and energy flows, leading to economic flow, human actions and interventions often stress the ecosystem and affect its services to varying extents. The cultural dimensions influence the way the social groups act and perform. A systems view of the coupled human-natural processes is thus useful in the analysis of sustainability of the ecosystem services and resilience of the ecosystem, society and institutions. This concept of a dynamically coupled human and natural system (CHANS) can therefore be applied more specifically to an integrated social-ecological system (SES) of the mangrove ecosystem and its dependent population.

The SES framework emerged from the concepts of common pool resources and integrated social-ecological processes (Ostrom 1990, Ostrom et al. 2007). A SES is an integrated and adaptive system representation of the social and ecological components and processes, and broadly represents the human and natural domains of the system (see Figure 1). The complex dynamics of the integrated system, particularly in different dimensions and scales, however, are yet to be fully understood and operationalized through analytical methods and tools. Virapongse et al. (2016) present a framework to translate the SES theory into practice for improved environmental management by defining the key components and processes in the system. Interaction of processes in the human and natural domains of the SES gives rise to a set of management decisions and adaptation choices, while the system and its sub-domains are influenced by external factors such as political, economic and biogeochemical conditions. Other approaches to operationalization of the SES theory and representation of the nonlinear system properties and dynamics are found elsewhere in the literature (Cole et al. 2019, Forrester et al. 2014, Schlüter et al. 2012, Schlüter et al. 2014).

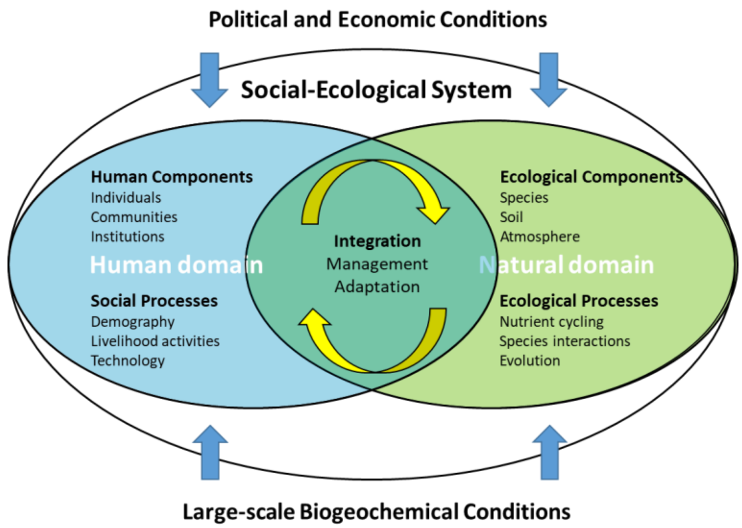


Figure 1: Components and processes in a social-ecological system [adapted from Virapongse et al. (2016)]

1.2 Livelihood security and dependency

The Sundarbans mangroves are rich sources of livelihood resources such as timber, mangrove palm, fish, shrimp, crab, and honey. Rice is also grown in the fringe areas of the mangroves. Household income and food security of the communities living in and around the mangroves depend much on these resources. Although the households are clustered and known by their main livelihood activities, household members are often engaged in multiple livelihoods to maximize the household income. Also, different livelihood groups in a community are connected and interdependent through various social and economic activities.

Local-level institutions, such as the Forest Office, regulate resource extraction to prevent overexploitation of resources and preserve ecosystem health, and undertake other measures for ecosystem conservation and growth. Other institutions, such as the Union Parishad, the lowest tier local government institution, provide support to the livelihood groups through subsidies, training, and awareness campaign. Thus, sustainability of the mangrove-dependent livelihoods depends not only on the natural resources, but also on the institutional policies and broader economic, political, and environmental conditions.

1.3 SES tipping points

Sustainability of both the ecosystem and the dependent livelihoods is ensured when the resource extraction and ecosystem growth are balanced. This equilibrium can be achieved through regulatory policy and participatory decision making. However, environmental hazards or overexploitation often lead to negative feedback loops in the system forcing it to reach a tipping point. For example, overexploitation of fish increases household income, but rapidly depletes the fish availability, eventually leading to an overall decline of the SES sustainability. The tipping point is the 'point of no return' beyond which the SES can no longer be brought back to the previous equilibrium even by lowering the fish catch. Examples of SES feedback loop, ecosystem service trade-off, food security and livelihood sustainability are given in Miyasaka et al. (2017), Acosta et al. (2018),Dobbie et al. (2018)and Yan et al. (2019).

1.4 Agent based modeling for SES analysis

Agent based models (ABM) can help develop a simplified understanding of the complex and dynamic interaction among the ecosystem components, human actors and institutions. This understanding is essential for sustainable environmental management and livelihood security. ABMs idealize the SES as a composition of autonomous, decision-making agents that are able to follow their goals, based on a set of rules. These agents may range from plant species to fish and animals, to households, livelihood groups and institutions (Schulze et al. 2017, Rounsevell et al. 2012, Macal and North 2009). ABMs can also analyze the complexities such as heterogeneity, nonlinearity and feedback in a CHANS or integrated SES, support geospatial simulation or participatory modeling of the SES, explore the system behavior across scales, and clarify the system dynamics in varying conditions (An 2012, An et al. 2014, Castle and Crooks 2006, Voinov et al. 2018, Lippe et al. 2019, Martin and Schlüter 2015, Hossain et al. 2017).

In this paper, we present an ABM application to analyze the mangrove SES-based livelihood processes, simulate the dynamics of livelihood activities and ecosystem responses, determine the efficiency of institutions in SES management, and explore how livelihood decisions and tipping points vary in different scenarios. In particular, we assess the ecosystem pressure in response to the livelihood activities, and how restrictions on resource extraction impact the livelihoods.

2. Study Area and Methods

2.1 Study area description

SES components and linkages

Gabura union under Shyamnagar upazila of Satkhira district and its surrounding areas of the Sundarbans is selected as the study area (Figure 2). Since the life and livelihoods of people in Gabura are strongly dependent on the mangrove resources, the study area is an excellent example of a SES. The mangrove forest (Sundarbans) covers an area over 6,017 km^2 in Bangladesh of its total area of about 10,000 km^2. This world heritage site provides natural protection against cyclones and storm surges. The fertile soils of this area have been used intensively in agriculture for centuries and the fringes of this ecoregion have been converted for intensive agriculture thereby decreasing the forest area alarmingly. This transition region between freshwater from the Ganges and saline water of the Bay of Bengal provides a brackish environment rich in biodiversity.

Golpata or mangrove palm (*Nypa fruticans*) is a very common palm species of the Sundarbans which grows in abundance here naturally, mainly in the less saline zone but can also grow in the moderate saline zone. Golpata is of high demand as an economically important product for its widespread domestic and commercial use. However, the golpata stock in the Sundarbans has been severely decreasing because of both licensed and unauthorized extraction in excessive amounts, and due to the lack of proper forest management.

Fishes of the Sundarbans represent 322 species belonging to 217 genera, 96 families and 22 orders (Habib et al. 2020), with at least 150 species of commercially important fish (Wikipedia 2021). The forest also supports the habitat for economically significant mud crabs or mangrove crabs (Banglapedia 2021).

Fishing and collecting fish and crab seedlings from the mangrove and nearby offshore waters for fish farming are very common livelihoods of the people living in and around the Sundarbans. Many people are also engaged in fish farming and household fishing. Overfishing and excessive seedling collection to meet the increasing domestic and commercial demands has become a threat for the sustainability of the ecosystem services of the Sundarbans (Hoq 2007).

Figure 2: Location and physical features of the mangrove social-ecological system under study

Physical and hydro-climatic and settings

Gabura union is situated on the bank of the Kholpetua River, which separates this union from the Sundarbans (Figure 2). The Kopotakkho River flows on the east side of this union, bordering with Dakshin Bedkasi union of Koyraupazila of Khulna district. Gabura is also adjacent to Padmapukur union on the north and is 27 km and 82 km away from the upazila headquarter and Satkhira district headquarter, respectively.

Gabura is one of the few areas near the Sundarbans that have been frequently affected by cyclones and storm surges. Climate change is believed to have increased the frequency of these high-energy cyclones.

Fresh water availability has been severely limited in Gabura, which becomes acute after every cyclone. The brackish water is useful for the fish farms, but adversely affects crop production and freshwater habitats. Criss-crossed with a network of rivers and canals, the area suffers from sediment deposition in the water bodies.

Primary and alternative livelihoods

The major livelihoods in this area include crab fattening, shrimp farming, agriculture, fishing, golpata and honey collection, day labor, van/auto bike pulling, and small business. About 42% of the people in the study area are involved in aquaculture, especially crab fattening for their livelihoods, while approximately 19% are dependent on forest resources, 16% are involved in shrimp farming and 23% engage in agricultural activities, mainly paddy cultivation (http://www.gaburaup.satkhira.gov.bd).The primary mangrove-dependent livelihoods are fishing in mangrove water bodies and household ponds, extracting golpata and paddy cultivation. Golpata extraction is possible only in winter in mid-March to mid-May; therefore, the Bawalis, i.e. the golpata collectors, do fishing as an alternative livelihood. Mangrove-dependent fishers of this area go into the mangroves for fishing, with a small group of them also doing fishing in household ponds. These fishers do not take other livelihood options although they are required to stop fishing in the mangroves due to fishing ban for one month of the year usually in July. Other fishers do fishing in household ponds only.

2.2 Agent Based Model for Mangrove SES

The important steps for developing an ABM for the Mangrove SES include selecting important agents, developing a conceptual model delineating how the agents interact with each other and their environment, and defining the rules mathematically how the agents would behave, interact and take decisions autonomously. The conceptual framework and the rules for different agents were based on review of secondary literature on Sundarban-based livelihood systems (e.g. Mallick et. al. 2021, Kabir et.

al. 2019, Mozumder et. al. 2017, Getzner and Islam 2013, Sarker 2012 and https://www.ccec-bd.org › files › reports), direct mobile communication with few representatives of the primary agents (e.g. fishermen, Bawalis), and expert judgement. Some baseline data were collected from the Bangladesh Bureau of Statistics (BBS) database (http://www.bbs.gov.bd/).

The model can be considered exploratory at this stage. The conceptual model and the rules for agent behavior will require detailed verification and validation in the field with the primary agents (which was limited during this study because of the prevailing COVID situation) before the ABM for the mangrove SES can be used as a fully robust model. Nevertheless, the approximations made in the formulation are considered reasonable, if not fully accurate, and hence the model should be able to provide useful early insights.

2.2.1 Agent selection for ABM

Agents are individual actors or actor groups of a SES who can interact with each other and their environment by autonomous decision-making based on specific rules. This study simulated the interrelations of the main mangrove-dependent livelihood groups (both individual actors and actor groups) with each other and with the environment of the SES. The livelihood activities are also linked with the regulations by the Union Parishad Office (UPO) and Forest Office (FO). For this reason, three main livelihood groups of this study area: Bawalis, Fishers and Farmers, and these two institutions have been considered as the agents in the ABM model. The agent classification and model environment are given in Table 1.

Table 1: Agents and model environment

Class of Agents	Name of Agents	Model Environment
Livelihood Agent	Bawalis	Mangrove Socio-Ecological System
	Fishers	
	Farmers	
Institutional Agent	Union Parishad Office(UPO)	
	Forest Office (FO)	

2.2.2 Conceptual model

Following the agent descriptions and attributes discussed earlier, Figure 3 shows a conceptual model of interactions among the agents of the mangrove SES. Golpata is a primary source of livelihoods of the Bawalis. The Bawalis mainly extract golpata from the Sundarbans with a permit from the FO to extract a maximum fixed amount. The extraction amount of the Bawalis depends on their extraction capacity and the permitted extraction amount. The FO gives permission till the golpata stock of the patches in the forest reaches a threshold maximum amount after which the permission ceases. Also, the Bawalis need to attain a threshold capacity to go to the forest for extracting golpata even if they get a permit. Otherwise, they do mainly fishing or farming to support household activities and increase their extraction capacity gradually. Golpata grows and dies in a natural way at a net growth rate, while the golpata stock decreases due to natural hazards at an average rate. For each extraction trip, the Bawalis need to spend a portion of resources, which is subtracted from their actual extraction amount. A fraction of the remaining extracted amount contributes to increasing the extraction capacity for the next trip. Rest of the extracted amount is spent for household living and other purposes. The FO stops giving permits if the golpata stock reaches a minimum threshold amount when the FO also starts conservation activities for golpata to grow rapidly.

Two types of fishers are considered in this study. The first type of fishers mainly goes to the mangroves to catch fish using boats after getting a permit from the FO. The FO generally stops giving fishing permits for one month per year to support fish breeding, during when these fishers remain jobless. For catching fish, they need to spend a portion of resources which is subtracted from their catching capacity in terms of the catch amount. A fraction of the catch amount contributes to increasing the catching capacity for the next year, which is proportional to the amount of fish caught in the current year. Rest of this amount is spent for household living and other purposes. They can take permits from the FO for many times in a year, with each permit valid for one week. Although the catch amount during a trip is uncertain, these fishers can generally catch a good amount for 7 months, a satisfactory amount for 2 months and small amounts for the rest of the year. Their expenditure, mainly on living, slightly increases if they can achieve a certain threshold of catching capacity. If their catching capacity goes down below a minimum threshold, they need to take loan for continuing fishing. They must pay back the loan with interests at a higher rate. Some of these fishers also do fishing in their household ponds.

The second type of fishers only grows fish in their own household ponds. They need to bear the production cost which is subtracted from their catching capacity. A fraction of the production increases the catching capacity for the next year and the remaining amount is used for household living and other purposes. The procedures for taking loan and repayment are similar to the first type of fishers. Fishes in the mangroves and household ponds increase due to breeding and decrease due to death and catching. Besides, if the fishes increase at a certain maximum threshold rate, a certain population of the fish dies naturally.

Farmers grow crops (mainly paddy) according to their crop production capacity and crop productivity of the agricultural land. They need to bear fertilizer cost to produce paddy which is subtracted from their crop production capacity. Crop productivity of the land decreases due to natural hazards, mainly soil salinization from storm surges. The actual production amount of paddy depends on the remaining crop production capacity and crop productivity. A fraction of this actual amount increases the crop production capacity of the farmers for the next year. The remaining amount is used for living and other expenses at the household level. Farmers need to achieve a minimum crop production capacity to produce paddy; otherwise, they take loan to achieve it. The loan is repaid later at a higher rate with interest.

The UPO performs regulatory functions in the study area to support financial security of the livelihood groups. It also coordinates with the FO for forest conservation. The efficiency of providing the financial security depends on the capacity of livelihood activities of the livelihood groups. For example, if the number of active Bawalis decreases to a certain minimum, it indicates the lack of efficiency of the UPO in supporting their financial security. Similarly, if the number of fishers and farmers who have loans to pay increases to a certain maximum, it indicates a lower efficiency of the UPO in supporting their financial security.

The FO regulates extraction in mangroves for mangrove protection and conservation. When the natural hazard loss exceeds a certain amount, and the conservation growth rate remains low at the same time, it indicates low forest conservation efficiency. Since the livelihood groups depend on ecosystem resources directly for their livelihood activities, they produce pressure on the ecosystem. Such pressures produced by each livelihood group are calculated from the Net Primary Productivity (NPP) (from the net carbon gain) supply of the ecosystem and the NPP consumed by the livelihood group.

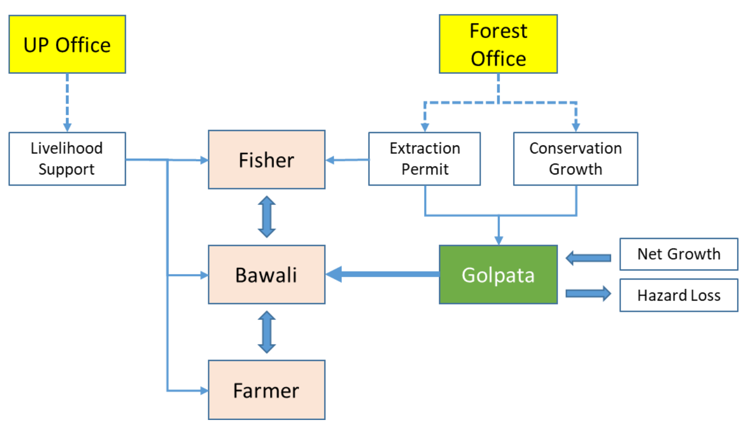


Figure 3: Conceptual model of the mangrove social-ecological system showing the agents and their livelihood interactions

2.2.3 Mathematical descriptions

Mathematical formulation of the model follows an agent-wise rule-based approach where the agents follow their own procedures according to the rules and behave autonomously while they interact with each other and with their environment. The pressures produced by the livelihood groups are calculated from the NPP supply on the ecosystem and the NPP consumed by each livelihood group where the NPP is estimated from the net carbon gain. The multipliers with variables and subtractors from variables in the equations are taken hypothetically considering logic where multipliers are numbers and subtractors have the same unit of associated variables.

Rules related to Bawalis

The rules for the Bawalis are defined in terms of their extraction capacity, actual extraction amount, new actual extraction amount, golpata permit, golpata stock, their cost of movement, natural growth rate of golpata, conservation growth rate of golpata and natural hazard loss of golpata. All these components are expressed in Metric tons.

1. If permit for golpata extraction remains active, then the Bawalis need to have a minimum capacity to extract golpata and they can extract the amount of golpata according to the amount permitted by the FO and their capacity for extraction. If their capacity is higher than the permitted amount, they need to extract the amount equal to the permitted amount, otherwise they can extract equal to their capacity which is their actual extraction amount.
2. They need to spend for their movement to the mangroves and it reduces some units of their actual extraction amount as follows:

$$\text{new actual extraction amount} = \text{actual extraction amount} - \text{movement cost of bawali} \quad (1)$$

3. A fraction of this increases the extraction capacity of Bawali for the next year. So, their increased capacity becomes:

$$\text{extraction capacity} = \text{extraction capacity} + (0.01 \times \text{new actual extraction amount}) \quad (2)$$

4. If the permit remains off and they have the minimum necessary capacity for extraction, then they lose some units of their extraction capacity as follows:

$$\text{extraction capacity} = \text{extraction capacity} - 10 \quad (3)$$

5. If they do not have the minimum capacity, then they increase their capacity by some units for extraction in the next year by doing fishing or farming as follows:

$$\text{extraction capacity} = \text{extraction capacity} + 2 \quad (4)$$

6. If golpata stock of patches has a certain maximum unit of golpata, then the golpata stock changes by the following equation:

$$\text{golpata stock} = \text{golpata stock} + \text{golpata natural growth rate} - \text{natural hazard loss} \quad (5)$$

7. If the golpata stock of patches reaches at a certain minimum amount, FO starts conservation. In this case,

$$\text{golpata stock} = \text{golpata stock} + \text{natural growth rate} + \text{conservation growth rate} - \text{natural hazard loss} \quad (6)$$

Rules related to Fishers

Rules for the fishers are defined in terms of their apparent and actual catching capacity, amount of loans they take, cost of ice for fish preservation, their movement cost, and fish production cost. All these components are expressed in Metric Tons.

1. Fishers who catch fishes in mangrove water area need to spend movement cost for fishing in mangroves and for carrying ice to protect fishes. It decreases some units of their capacity. So, their actual catching capacity becomes:

$$\text{actual catching capacity} = \text{catching capacity} - \text{movement cost} - \text{ice cost} \quad (7)$$

2. If they can catch a good amount of fishes for at least seven months per year, it increases their catching capacity by some units as follows:

$$\text{catching capacity} = \text{catching capacity} + (0.05 \times \text{actual catching capacity}) \quad (8)$$

Otherwise,

$$\text{catching capacity} = \text{catching capacity} - 0.075 \quad (9)$$

3. If they can catch a moderate amount of fishes for at least two months per year, it increases their catching capacity by some units as follows:

$$\text{catching capacity} = \text{catching capacity} + 0.075 \tag{10}$$

Otherwise,

$$\text{catching capacity} = \text{catching capacity} - 0.1 \tag{11}$$

4. If they can catch a small amount of fishes for a maximum of two months per year, it increases their catching capacity by some units as follows:

$$\text{catching capacity} = \text{catching capacity} + 0.05 \tag{12}$$

Otherwise,

$$\text{catching capacity} = \text{catching capacity} - 0.03 \tag{13}$$

5. Fishing in mangroves remains stopped for one month, and the fishers become jobless at this time. In this case,

$$\text{catching capacity} = \text{catching capacity} - 0.125 \tag{14}$$

6. If their catching capacity becomes greater than 2.5 Metric ton, they increase additional expenses and therefore:

$$\text{catching capacity} = \text{catching capacity} - 0.25 \tag{15}$$

7. If their catching capacity becomes less than 2 Metric ton, they need to take loan to increase some units of their catching capacity by the following equation,

$$\text{catching capacity} = \text{catching capacity} + 0.1 \tag{16}$$

8. After achieving a catching capacity greater than 2.5 Metric ton after taking loan, they pay back their loan at a slightly increased amount, which is given by the following equation:

$$\text{catching capacity} = \text{catching capacity} - 0.2 \tag{17}$$

9. Some of these fishers also do household fishing and thus increase some units of their catching capacity for fishing in mangroves by,

$$\text{catching capacity} = \text{catching capacity} + 0.005 \tag{18}$$

10. Fishers who grow fishes in household ponds need to spend a production cost and therefore their actual catching capacity becomes:

$$\text{catching capacity} = \text{catching capacity} - \text{fish production cost} \tag{19}$$

11. If the production is good for most of the year, then their catching capacity increases as:

$$\text{catching capacity} = \text{catching capacity} + (0.1\ \times \text{actual catching capacity}) \tag{20}$$

12. If their fish production for the year is moderate, then:

$$\text{catching capacity} = \text{catching capacity} + (0.075\ \times \text{actual catching capacity}) \tag{21}$$

13. If they produce a small amount of fishes in the year, they cannot increase their catching capacity.
14. If they produce a very low amount of fish which is not noticeable, their catching capacity decreases as follows:

$$\text{catching capacity} = \text{catching capacity} - 0.5 \tag{22}$$

15. If their catching capacity becomes greater than 2.7 Metric ton, they increase their other expenditure, and it reduces some units of their catching capacity as:

$$\text{catching capacity} = \text{catching capacity} - 0.25 \tag{23}$$

16. They need to take loan, if their catching capacity becomes less than 2 Metric ton, to increase their catching capacity as:

$$\text{catching capacity} = \text{catching capacity} + 0.1 \tag{24}$$

17. They pay back the loan after gaining a catching capacity greater than 2.5 Metric ton, which is represented by,

$$\text{catching capacity} = \text{catching capacity} - 0.2 \tag{25}$$

Policy

1. After which threshold, will farmer get a loan of which amount under which terms?

a) 20,30,50 b)10,20,40 c) d)

2.

Rules related to Farmers

Rules for the farmers are defined in terms of crop production capacity, actual production amount, loan, crop productivity, actual crop productivity, fertilizer cost and natural hazard loss of crops. All these components are expressed in Metric Tons.

1. Farmers' actual crop production depends on the actual crop productivity of their agricultural land and their own capacity. They need to also pay for fertilizer. The crop productivity of agricultural land decreases due to natural hazards. If their capacity is higher than half of the actual crop productivity of the land, their actual production amount then becomes half of the actual crop productivity of the land (since it is observed that two farmers produce in each land); otherwise, they produce the amount to their capacity.
2. They need a certain minimum capacity to produce crops.
3. If the actual crop productivity is greater than 15 Metric ton, then their capacity increases as:

$$\text{crop production capacity} = \text{crop production capacity} + (0.1 \times (\text{actual production amount} - \text{fertilizer cost})) \tag{26}$$

4. If the actual crop productivity is between 10 Metric ton and 15 Metric ton, the crop production capacity increases as:

loan

$$\text{crop production capacity} = \text{crop production capacity} + \left(0.05 \times (\text{actual production amount} - \text{fertilizer cost})\right) \tag{27}$$

10

5. If the actual crop productivity is less than 15 Metric ton, then crop production capacity becomes:

$$\text{crop production capacity} = \text{actual production amount} - \text{fertilizer cost} \tag{28}$$

6. They take loan if their crop production capacity is less than or equal to 2.5 Metric ton which is given by,

$$\text{crop production capacity} = \text{crop production capacity} + 1 \tag{29}$$

7. They pay back the loan when they regain their crop production capacity to greater than or equal to 4 Metric ton as below:

$$\text{crop production capacity} = \text{crop production capacity} - 1.25 \quad (30)$$

Rules related to UPO

1. If the mean extraction capacity of the Bawalis, mean catching capacity of both types of Fishers and mean crop production capacity of Farmers become less than 125, 2.3 and 4.5 Metric ton, respectively, and the number of active Bawalis becomes less than half of the total number of the Bawalis, then financial security efficiency (a dimensionless quantity or score) of the UPO will be 0.5; otherwise, it will be 1 for each of these 5 cases.
2. If the number of Fishers of both types and Farmers who have loans to pay is greater than their total number for each of these three types of livelihoods, then financial security efficiency of UPO will be 0.5; otherwise, it will be 1 for each of these 3 cases.
3. The efficiency of UPO is calculated by,

$$\text{efficiency of UP Office} = \text{regulatory efficiency} + \text{support of financial security efficiency} + \text{financial safety efficiency} \quad (31)$$

Rules related to FO

1. If for natural hazard, the loss of golpata becomes greater than 1 Metric ton, and in this case conservation growth rate of golpata remains less than 4 Metric ton, the forest conservation efficiency (dimensionless quantity or score) of the FO will be 2; otherwise, it will be 4.
2. The efficiency of FO is given by,

$$\text{efficiency of Forest Office} = \text{extraction control efficiency} + \text{forest conservation efficiency} \quad (32)$$

Pressure on the ecosystem

Pressure on the ecosystem is calculated by the following equation for all livelihood groups (Yan et al. 2019),

$$\text{pressure on ecosystem} = \frac{\text{NPP consumed}}{\text{NPP supply}} \tag{33}$$

Pressures on ecosystem are numbers as they are ratio of the amount of carbon.

2.3 Simulations using NetLogo

Based on the conceptual framework for the ABM, mathematical equations were set for formulating the computational framework. The NetLogo software (https://ccl.northwestern.edu/netlogo/) was used for simulations of the ABM (the interface is shown in Figure 4). NetLogo is a multi-agent programming language and modeling environment for simulating complex systems evolving over time (Tisue and Wilenski 2004).

NetLogo visualizes the model by a 'NetLogo world' (made up of agents). It has four types of agents:

Turtles: This type of agents can move around in the world.

Patches: This type of agents has fixed coordinates, and turtles can move over patches.

Links: Links are used to connect two turtles. Links are of two types - directed and undirected.

Observers: They do not have locations, and only give instruction to other agents.

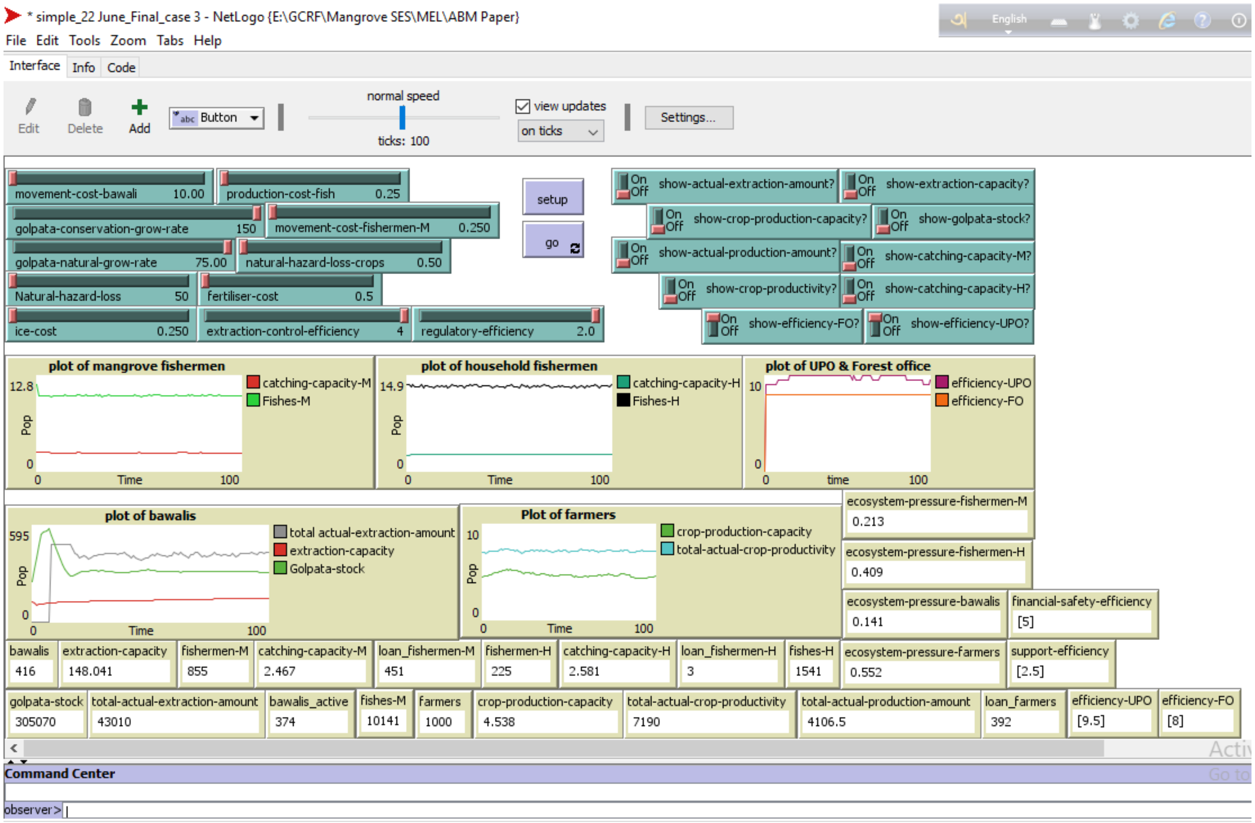


Figure 4: NetLogo 'Interface' of the model

Four livelihood breeds: Bawalis, Fishersmen_M (for mangrove fishermen), Fishermen_H (for household fishermen), and Farmers; and two institutional breeds: UPO and FO, are used in the NetLogo model. Three types of fish breeds for the mangrove area and three types of fish breeds for household ponds are included to represent different amounts of catches during a year. These breeds are referred to as "turtles" in NetLogo as defined earlier. The model uses four types of patch variables, which include golpata permit, golpata stock, crop productivity, and actual crop productivity. Global variables are used in the model controlled by the sliders (to define different scenarios, e.g. favorable, moderate and critical), which include movement cost of the Bawalis, golpata growth rate (natural and conservation rates), loss of golpata, fish and crops due to natural hazards, cost of ice for the fishermen, movement cost of fishermen, production cost of fish, fertilizer cost for the farmers, extraction control efficiency of the FO and the regulatory efficiency of the UPO.

3. Results

3.1 Cases and scenarios

Three cases of the SES are selected to explore the system performance and agent behavior within a feasible range of variables. These cases represent the variation in catching capacity of the two types of Fishers, crop production capacity of Farmers and permitted amount of golpata for the Bawalis. The model variables which define the differences among the three cases are described in Table 2. Case 1 represents comparatively high golpata permit for the Bawalis, comparatively low catching capacity for both mangrove and household fishers, and comparatively high crop production capacity, while Case 2 and Case 3 represent moderate and comparatively low golpata permits for the Bawalis, moderate and comparatively high catching capacities for both mangrove and household fishers, and moderate and comparatively low crop production capacity, respectively.

Table 2: Variable values for the three cases

Case Number	Variable	Value (Metric ton)
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

Additionally, different global variables also influence agent behavior; some influence positively while others cause negative effects. These variables also influence how the ecosystem responds positively or negatively in different conditions.

Three scenarios are selected for simulation in each case: (i) a *favorable scenario* considering the highest values in the NetLogo interface slider for the global variables with positive impact and the lowest values of global variables with negative impact; (ii) a *moderate scenario* considering moderate values of all these global variables; (iii) a *critical scenario* where the highest values of global variables in the slider with negative impact and the lowest values of global variables with positive impact are selected. These values of the global variables are given in Table 3.

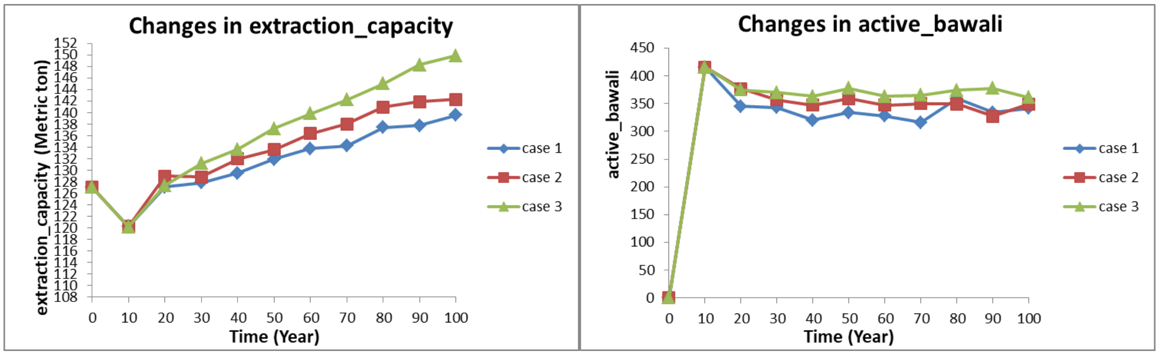
Table 3: Global variable values for the three scenarios

Global Variable	Scenario			Unit
	Favorable	Moderate	Critical	
movement_cost_bawali	10	14.75	20	Metric ton
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_fishermen_M	0.25	0.375	0.5	
production_cost_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	

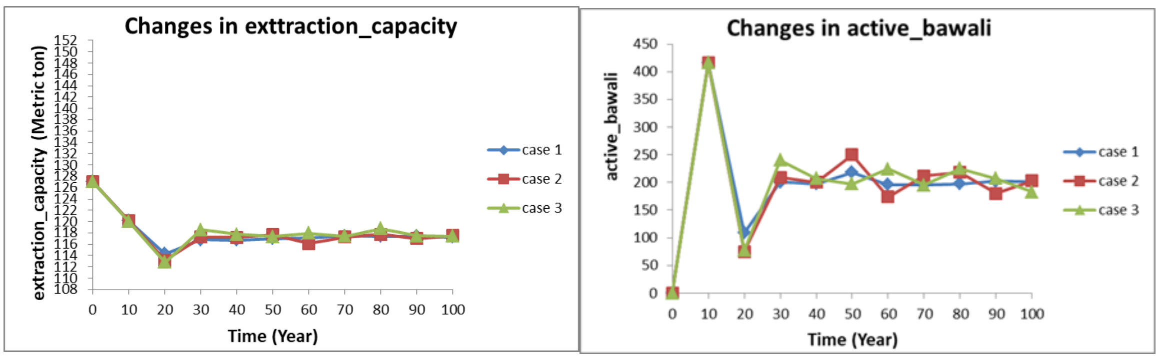
3.2 Agent behavior in different conditions

NetLogo simulations of the varying behavior of the agents in different cases and scenarios are shown in Figures 5-9. In Netlogo, time is arbitrarily represented as tics, whereas one tic is equivalent to a year in this model. The figures show how the agents perform in different ways in different conditions, i.e. one set of variables or condition may be favorable for certain agents while the same condition may be unfavorable for the others. Individual agent behaviors are shown in these plots.

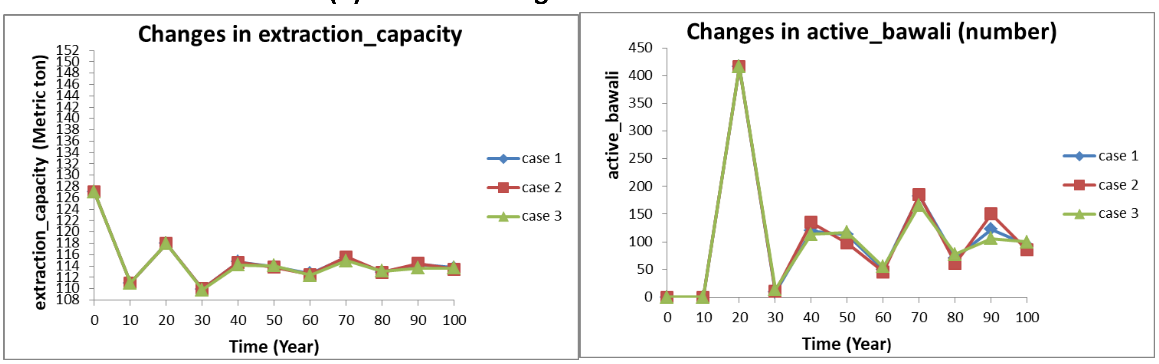
Figure 5 shows the behavior of Bawalis in different conditions. The initial extraction capacity of the Bawalis is only 127 metric ton in all scenarios for case 1, case 2 and case 3 with permit for golpata extraction 125, 120 and 115 metric ton respectively but in favorable scenario, increasing rapidly with time it reaches at almost 150, 142 and 140 Metric ton at the 100th year for case 3, case 2 and case 1 respectively. Above 365 bawalis can be active in most of the times for case 3 with extraction permit 115 Metric ton which is the best among all considered cases in this scenario. The Moderate scenario has also good extraction capacity ranges from almost 116 to 118 Metric ton and number of active Bawalis ranges from 180 to 240 in most of the times according to different cases. The best performance of this scenario is for case 3 where extraction capacity 117 Metric ton and number of active Bawalis 207 are almost constant in most of the times with lowest golpata permit of the three cases, which allows better conservation of golpata stock, and as such relatively high number of Bawalis can remain active for extraction in future. In critical scenario, almost constant extraction capacity 114 Metric ton and the number of active Bawalis below 100 in all cases indicate critical situation of Bawalis.



(a) Bawalis change of behavior in favorable scenario



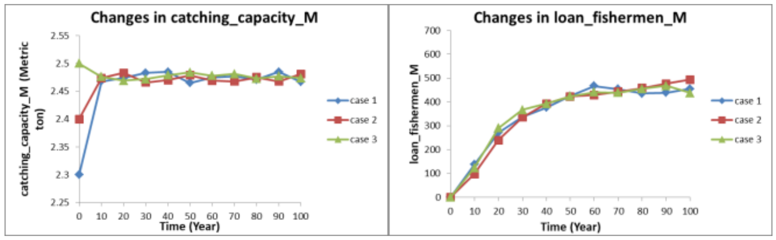
(b) Bawalis change of behavior in moderate scenario



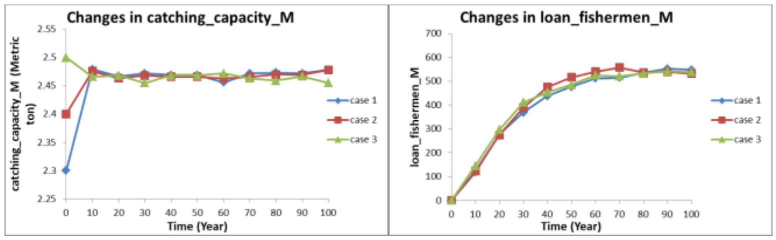
(c) Bawalis change of behavior in critical scenario

Figure 5: Behavior change of Bawalis. Case 1: comparatively high golpata permit (Metric ton); Case 2: moderate golpata permit (Metric ton); and Case 3: comparatively low golpata permit (Metric ton)

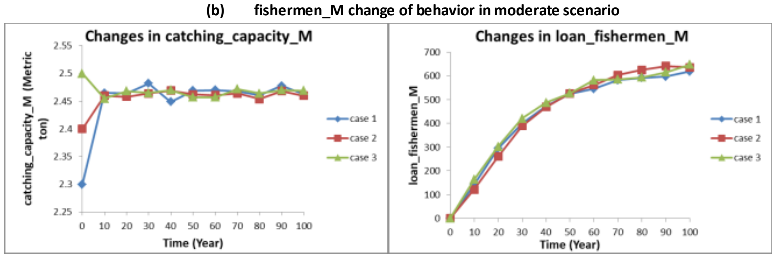
Figure 6(A) indicates that the catching capacity of the mangrove fishers remains constant with value above 2.45 Metric tons for all cases and scenarios. The number of this type of fishers who have to pay loan increases gradually with time for a long period of time and then becomes constant. This implies that the mangroves fishers struggle initially with repaying loan, but eventually overcome this with the attainment with stable catching capacity. The number is, however, the highest in the critical scenario of Case 2 (ranges from 122 to 641) and lowest in the favorable scenario of Case 2 (ranges from 123 t0 468) where catching capacity is moderate to comparatively high. In moderate scenario, the number of this type of fishers to pay loan has values ranges from 119 to 552, comparatively lower than critical scenario and comparatively higher than favorable scenario. This number in different times of the moderate scenario is the lowest for case 3 of all the cases and remains constant after 80^{th} years. Figure 6(B) indicates that catching capacity of household fishers for all cases does not change significantly with the scenarios (ranges between 2.55 and 2.6 Metric ton) but changes with time and this value remains constant most of the times for case 3 in favorable and moderate scenarios. The number of this type of fishers having loan remains very low in all scenarios (ranges from 1 to 8).



(a) fishermen_M change of behavior in favorable scenario

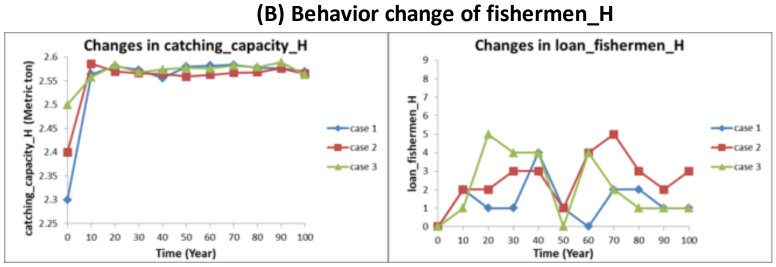


(b) fishermen_M change of behavior in moderate scenario

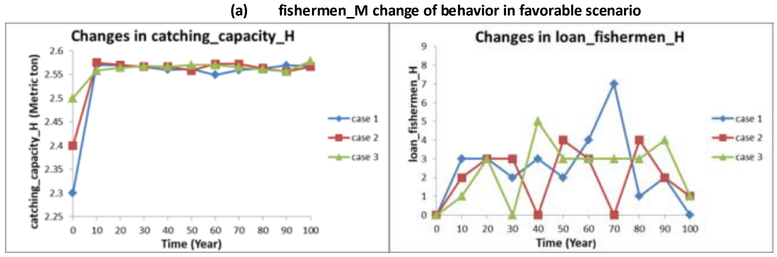


(c) fishermen_M change of behavior in critical scenario

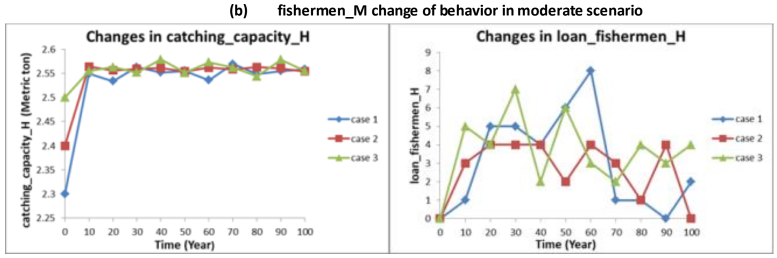
(B) Behavior change of fishermen_H



(a) fishermen_M change of behavior in favorable scenario



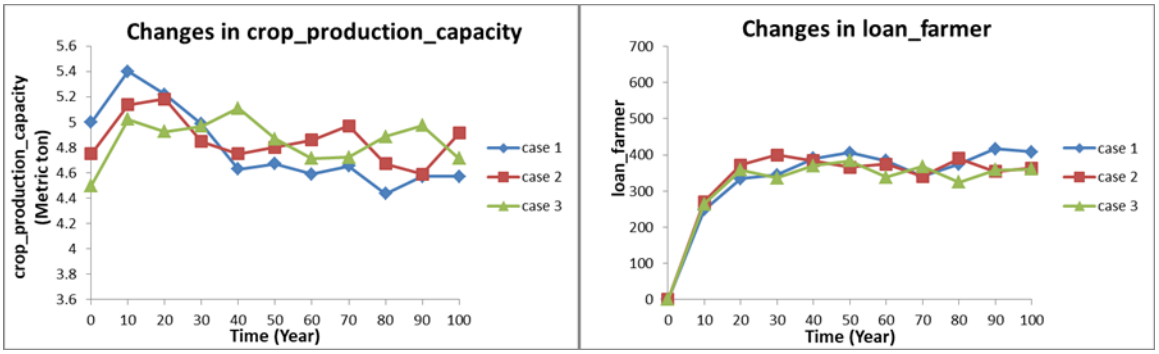
(b) fishermen_M change of behavior in moderate scenario



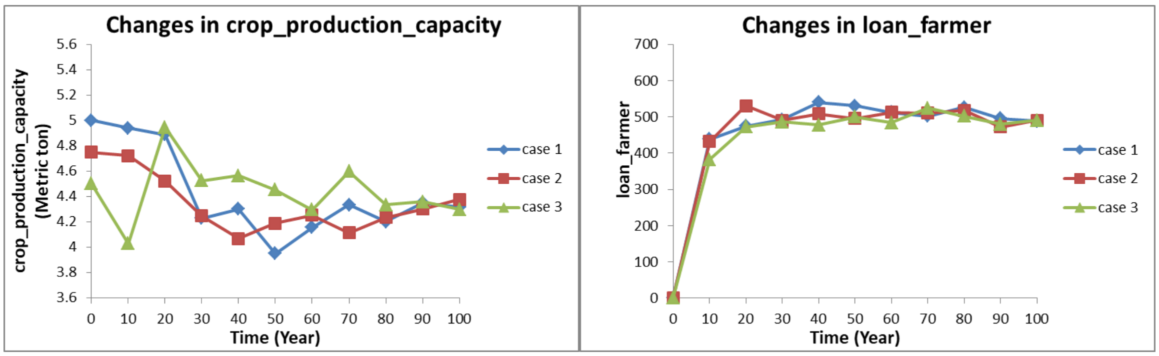
(c) fishermen_M change of behavior in critical scenario

Figure 6: Behavior change of Fishers. Case 1: comparatively low catching capacity; Case 2: moderate catching capacity; Case 3: comparatively high catching capacity

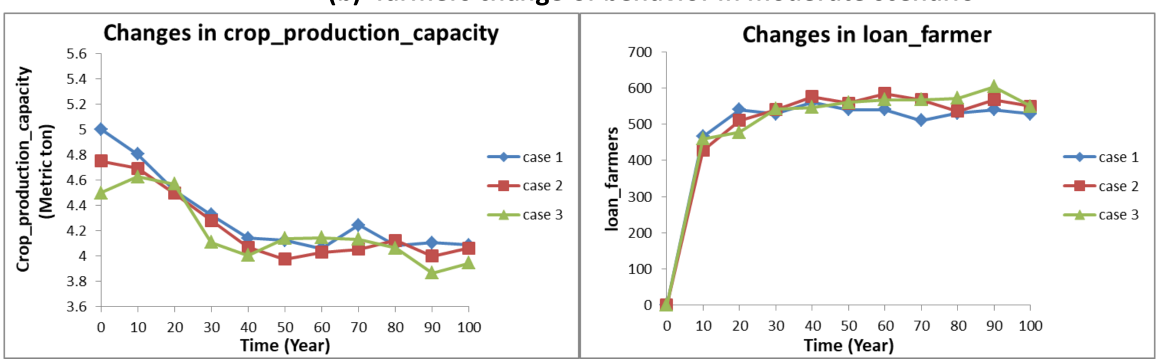
Figure 7 represents the behavior change of farmers for case 1, case 2 and case 3 with crop production capacity 5, 4.75 and 4.5 Metric ton respectively in favorable, moderate and critical scenario. From this it is noticed that crop production capacity of farmers remains the highest (above 4.7 Metric ton) in the favorable scenario in Case 3 with lowest number (below 400) of farmers having loan to pay of all conditions. In the critical scenario, crop production capacity indicates critical values (3.8 to 4.2 Metric ton) in most of the times for all cases. The number of farmers who have to pay loan is the lowest (below 450) in the favorable scenario and highest (above 500) in critical scenario for all cases for most of the times. The Moderate scenario of all cases indicates moderate number (about 500 to 525) of such farmers which does change significantly with time. In this scenario, Case 3 indicates the highest catching capacity whose values are above 4.3 Metric ton with lowest number of farmers having loan to pay whose maximum value is 500 in different times.



(a) farmers change of behavior in favorable scenario



(b) farmers change of behavior in moderate scenario



(c) farmers change of behavior in critical scenario

Figure 7: Behavior change of Famers. Case 1: comparatively high crop production capacity (Metric ton); Case 2: moderate crop production capacity (Metric ton); Case 3: comparatively low crop production capacity (Metric ton)

Figure 8 shows the efficiency change of FO and UPO for case 1 with extraction permit 125, catching capacity 2.3 and crop production capacity 5 metric ton respectively, case 2 with extraction permit 120, catching capacity 2.4 and crop production capacity 4.75 metric ton respectively and case 3 with extraction permit 115, catching capacity 2.5 and crop production capacity 4.5 metric ton respectively in favorable, moderate and critical scenario. Figure 8(A) shows that the FO works with the best efficiency 8 in the favorable scenario. The efficiencies are comparatively lower in the moderate and critical scenarios which are 7 and 6 respectively. This efficiency does not change according to cases. Figure 8(B) shows variations in efficiency of the UPO with different conditions. The efficiency is the best ranges from (9.5 to 10) in the favorable scenario. However, the efficiency remains at a reasonably satisfactory and constant level in the moderate scenario of Case 3 (ranges from 7.5 to 9). This efficiency is the lowest in the critical scenarios for all cases and has value 6.5 in most of the times.

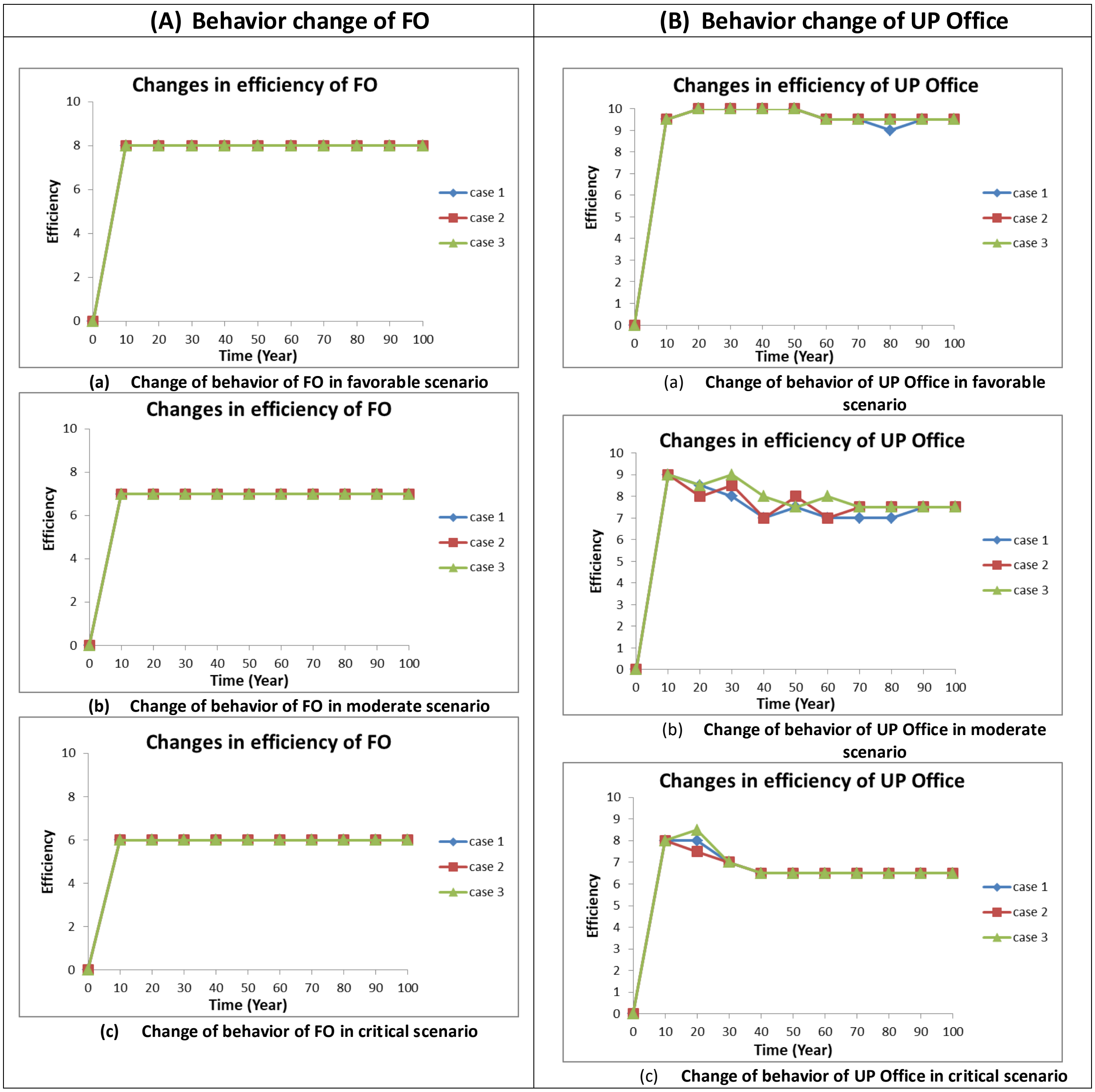


Figure 8: Behavior change of institutional agents: (A) Forest Office; (B) UP Office

3.3 Ecological and livelihood tipping points

Figure 9 shows the pressure on the ecosystem due to livelihood activities, and how the system reaches at an equilibrium condition (stable condition) or a tipping point (unstable condition) in different cases and scenarios. Figure 9(A) shows that in the favorable scenario of Case 3, the pressure on the ecosystem caused by the Bawalis increases rapidly and after 30th year its value remains almost constant with times. This value has the highest range (0.12 to 0.14), moderate range (0.06 to 0.08) in favorable scenario and moderate scenario respectively. In critical scenario, this value remains very low in most of the times but changes significantly with time. 9(B) shows that the mangrove fishers cause pressure constant with time and cases. The pressure is the lowest (below 0.17) in the critical scenario and the highest (above 0.21) in the favorable scenario, the moderate scenario indicates value almost 0.18. Figure 9(C) shows that the household fishers cause the minimum pressure in the critical scenario (below 0.35) and the maximum pressure in the favorable scenario (above 0.4) where this pressure is about 0.35 in moderate scenario. The pressure remains constant with time and cases. Figure 9(D) shows that the pressure caused by the farmers remains the highest for Case 3 (almost 0.6) in the favorable scenario for a long period of time. The pressure remains consistently moderate in Case 3 (ranges from 0.51 to 0.53). This pressure is about 0.5 for all cases of critical scenario.

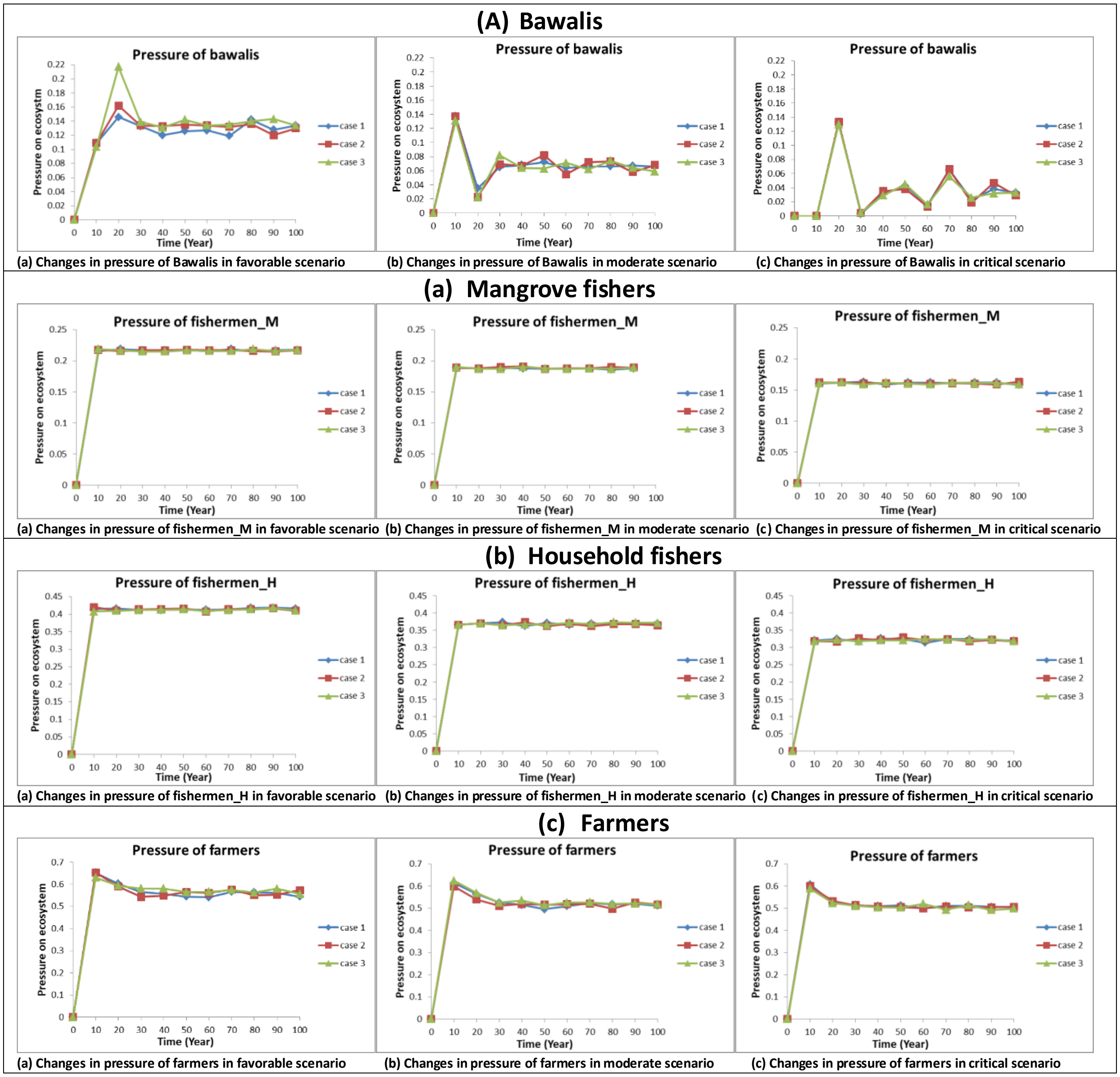


Figure 9: Pressure on the ecosystem in different conditions caused by: (A) Bawalis; (B) Mangrove fishers; (C) Household fishers; and (D) Farmers.

4. Discussion

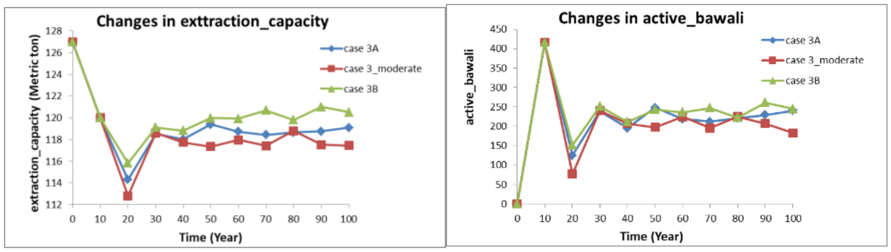
4.1 Sensitivity analysis

From the NetLogo simulation results it is clear that moderate scenario of case 3 is the best condition for livelihood activities by keeping balance with ecosystem pressure where favorable scenario gives the best livelihood performance by creating excessive pressure on ecosystem and critical scenario create the minimum pressure on ecosystem by giving poor livelihood performance. In this regard, we have tried to find out the conditions when livelihood performance will be better than moderate scenario creating lower pressure than favorable scenario considering case 3. To do this we have taken the same values for all global variables as considered for moderate scenario except only four most sensitive global variables and considered other 2 conditions under case 3 which are case 3A and case 3B. Since golpata_conservation_growth_rate has positive effect on livelihood activity, increased values than moderate scenario of case 3 (i.e. case 3_moderate) at the same rate has taken for case 3A and case 3B respectively. Again, movement_cost and fertilizer_cost have negative effect and therefore their decreased values than case 3_moderate have taken for case 3A and case 3B. The only global variable in this case related to fishermen_H is production_cost_fish. So, increased and decreased values at the same rate from case 3_moderate have taken for case 3A and case 3B respectively. The detailed values with variables name are given for different conditions in the Table 4.

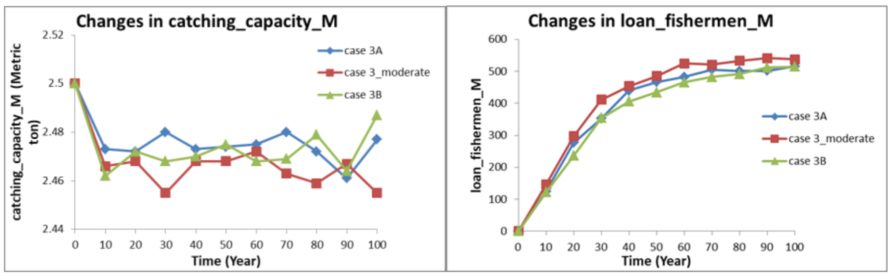
Table 4: Global variable values for the three conditions

Global variables	**case 3A**	**case 3_moderate**	**case 3B**	**Unit**
movement_cost_bawali	14.75	14.75	14.75	Metric ton
golpata_conservation_growth_rate	**137.5**	125	**150**	
golpata_natural_growth_rate	62.5	62.5	62.5	
natural_hazard_loss	75	75	75	
ice_cost	0.375	0.375	0.375	
movement_cost_fishermen_M	**0.3125**	0.375	**0.25**	
production_cost_fish	**0.625**	0.5	**0.375**	
natural_hazard_loss_crops	0.75	0.75	0.75	
fertilizer_cost	**0.625**	0.75	**0.5**	
extraction_control_efficiency	3	3	3	-
regulatory_efficiency	1.5	1.5	1.5	-

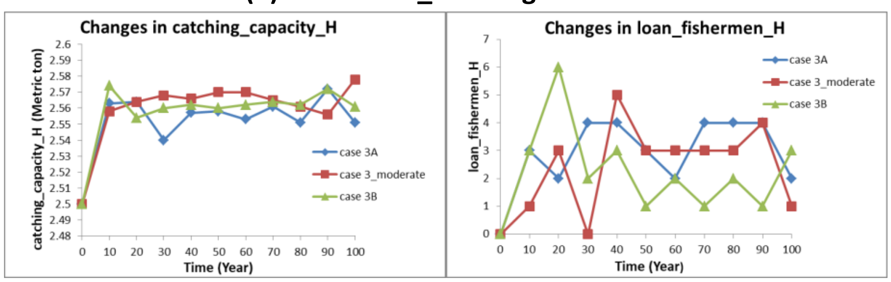
Figure 10 shows the changes of behavior of agents for different conditions with time comparing with moderate scenario of case 3 (case 3_moderate). From Figure 10(A), it is shown that the extraction capacity and number of active bewail increase rapidly with time for the case 3A and case 3B than case 3_moderate condition and case 3B give the best performance with extraction_capacity 122 Metric ton and 225 number of active bawali in most of the times. Figure 10(A) represent that catching capacity of mangrove fisher also increases than case 3_moderate condition for case 3A and case 3B but does not varies much for these conditions. But the number of mangrove fishermen who have to pay loan is the lowest for case 3B (highest 515). Figure 10(c) indicate that the values of catching capacity of household fishermen and number of household fishermen to pay loan do not changes significantly for case 3A and case 3B. From figure 10(d), it is noticed that crop production capacity and the number of farmers who have loan increase and decrease respectively from case 3_moderate for case 3A and case 3B and case 3 give the best performance. Again from Figure 10(e), it can be realized that efficiency of FO remain constant for all conditions where efficiency of UPO increase for case 3A and case 3B (values ranges from 8.5 to in most of the time) than case 3_moderate.



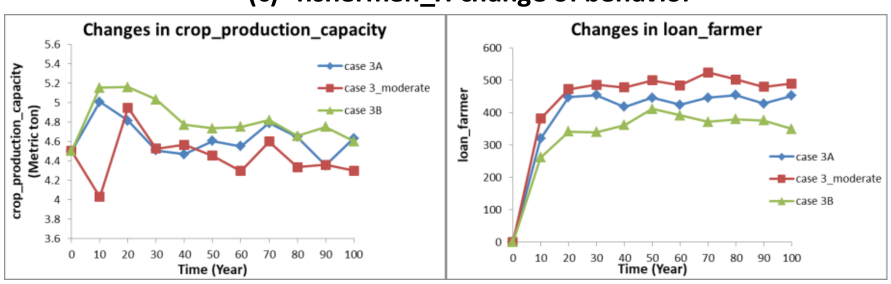
(a) bawalis change of behavior



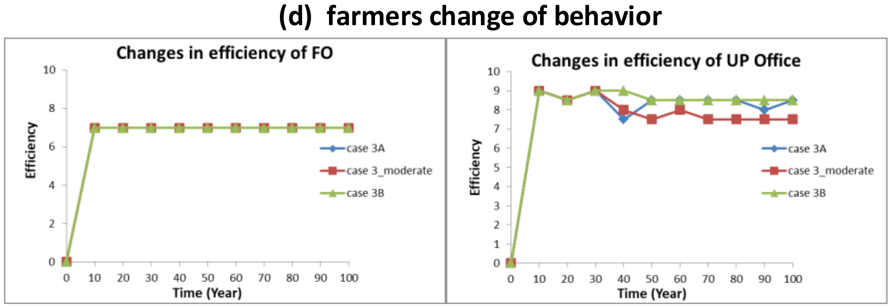
(b) fishermen_M change of behavior



(c) fishermen_H change of behavior



(d) farmers change of behavior



(e) Change of behavior of FO and UPO

Figure 10: Behavior change of agents: (A) Bawalis; (B) Mangrove fishers; (C) Household fishers; and (D) Farmers.

Figure 11 is for showing change of pressure on ecosystem for different livelihood groups with time comparing with favorable scenario of case 3 (case 3_favorable). Figure 11(a) shows that in case 3A and case 3B bawalis give a very low pressure (0.07 to 0.08) on ecosystem than case 3_favorable (0.14) in most of the times and this value does not change significantly for case 3A and case 3B.From Figure 11(b), it is noticed that in case 3_favorable condition, mangrove fishermen creates pressure almost 0.23 where for case 3A and case 3B, this value remains about 0.2 in most of the times. Figure 11(c) represent that the pressure of household fishers on ecosystem has almost similar values for case 3_favorable and case 3B (0.42 and 0.4 respectively) where the value is comparatively lower in case 3A about 0.35) in most of the times. From figure 11(d), it can be realize that for case 3A farmers give the lowest pressure on ecosystem (about 0.55) and this value is significantly higher for case 3B (about 0.55) and case 3_favorable (about 0.6) in most of the times.

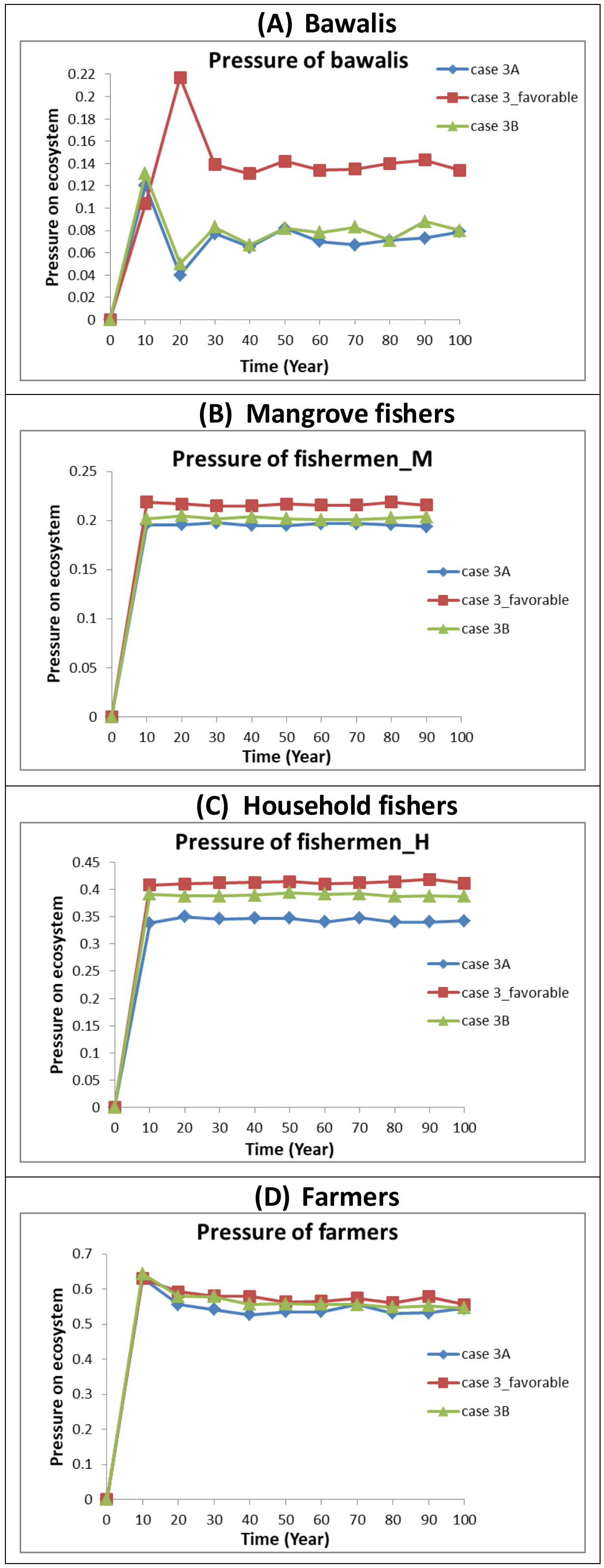


Figure 11: Pressure on the ecosystem in different conditions caused by: (A) Bawalis; (B) Mangrove fishers; (C) Household fishers; and (D) Farmers.

So, analyzing figure 10 and 11, it can be decided that in moderate condition of case 3 we need to keep conservation_growth_rate between 137.5 – 150 Metric ton, movement_cost of mangrove fishermen between 0.25 – 0.3125 Metric ton, production_cost_fish for household fisher between 0.5 – 0.25 Metric ton and fertilizer_cost of farmers between 0.625 – 0.75 Metric ton to maintain better livelihood security with ecosystem sustainability.

4.2 Livelihood and ecosystem sustainability

NetLogo simulation results indicate that the livelihood activities of the livelihood groups can be considerably influenced, both favorably and adversely, by the ecosystem characteristics and the institutional efficiencies. These influences vary in a range of cases and scenarios represented by the agents and global variables. Sustainability of the livelihood activities is also indicated by a change in the number of livelihood groups able to continue their activities in the long term. In general, the extraction or production capacities are relatively high in the favorable scenarios where the livelihood activities can sustain over a long period of time. However, this can lead to increased pressure on the ecosystem. In the critical scenario, low livelihood activity is associated with low pressure on the ecosystem, but reduced capacity, reflected in the increase in the number of people taking loans. Hence, this does not represent an optimal case, where livelihood is maximized and at the same time ecosystem is best preserved. The optimal balance may be found under the moderate scenario.

Ecosystem sustainability is, however, more sensitive to and dependent on the institutional policy for conservation of the ecosystem and preventing overexploitation. Providing financial security to the vulnerable livelihood groups encourages a lower level of resource exploitation thus indirectly contributing to ecosystem sustainability.

4.3 SES equilibrium and tipping points

Livelihoods of the main communities considered in this study - Farmers, Bawalis and Fishers - are closely related. They are part of the same SES and share resources, and often shift their livelihoods either to overcome a temporary financial crisis or on a more regular seasonal basis. This situation leads to a more dynamic complexity than what could be represented in this simplified model. However, it is evident that the SES reaches an equilibrium condition and averts a tipping point if institutional policies are formulated to support optimum levels of livelihood activities, and to ensure that the ecosystem resources do not deplete in the long term.

4.4 Role of institutional agents: sensitivity of policy change

As evident from the results, the institutional agents have significant influence on both the livelihood activities and ecosystem response. Efficient performance of the institutions is therefore essential to conserve the mangrove and secure the livelihoods. The ABM results indicate that protection and conservation of golpata in the Sundarbans is not only good for the livelihood groups but also it sustains the overall ecosystem. Similarly, fish conservation in the mangroves ensures continued ecosystem services as well as higher levels of fish catch.

We observe that comprehensive institutional policies to ensure mangrove SES sustainability and participatory management is missing in Bangladesh. All current policies are arbitrarily set either for a specific livelihood group, or within an administrative boundary of the local government, or only for forest management. The conservation rules and extraction licensing are based on approximate estimates rather than scientific observations such as fish catch and composition assessment or satellite data-based assessment.

5. Conclusion

ABM simulations and stakeholder interactions indicate that the vulnerable livelihood groups of the Sundarbans mangrove SES require policy support to sustain their livelihoods. Economic returns at the household level increase with an improved level of institutional decision-making based on scientific assessment. This, in turn, sustains the mangrove-dependent livelihoods, optimizes the availability of ecosystem resources, and ensures continued ecosystem services.

We conclude that a comprehensive policy is essential to ensure sustainability of the mangrove SES. Such policy should outline the roles of relevant institutions and stakeholders, the approach to science-based decision-making, the method to identify vulnerabilities of the livelihood groups and the ecosystem, and the priorities to provide support to the livelihood groups.

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