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Modelling the role of marine protected area in biodiversity conservation

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ABSTRACT

This study explored the anthropogenic stressors of a coral habitat and predicted the role of a proposed MPA around coral habitat on biodiversity conservation. The study was conducted in the Saint Martin's Island which is located in the south east coastal area of Bangladesh. Data on anthropogenic stressors were collected through intensive stakeholder survey and the role of MPA in biodiversity conservation was explored by utilizing Allometric Trophic Network model. This study identified about 16 anthropogenic stressors for the coral reef ecosystem. Increasing fishing pressure significantly reduced the species biomass while reduced fishing pressure increased the biomass of species. Biomass of the species in the system with no fishing area increased significantly (3–6%) while compared with the species biomass of an area without fishing restriction. Our simulations found that imposing fishing restriction in an exploited system significantly improve the species standing stock. Our model outputs suggest that declaration of MPA is beneficial for conservation of biodiversity. However, for sustainable implementation of conservation initiatives a proper management framework is necessary integrating diverse stakeholders.

1. Introduction

Marine ecosystems offer key habitats for a variety of species. These species varies from primary producers to tertiary consumers. Marine ecosystems also support a large number of vulnerable, endangered and critically endangered species. Regrettably, marine habitats worldwide face significant pressure from human activities. Consequently, marine resources and ecosystems are under severe threats (Botsford et al., 1997; Pauly et al., 1998). Thus, marine protected areas (MPAs) are globally used as an effective conservation tool for marine habitat and species diversity to ensure sustainable use of oceans (Davis et al., 2019).

Marine protected areas are known as the refugia or marine reserves which have been proposed for the mangeemnt of fisheries resources and the conservation of biodiversity (Allison et al., 1998; Salomon et al., 2002). Legal restrictions are imposed in MPAs to protect and maintainthe species diversity and associated cultural resources (Day et al., 2012). Currently MPAs are widely used management approch of marine ecosystems. For example MPAs are used to conserve the habitats of species and increase the biomass, density, and diversity of exploited fish species as well as on coral cover (McClanahan et al., 2012; McClure et al., 2020; Russ et al., 2017). Marine protected areas also play a key role to achieve sustanable development goal 14 (SDG 14) (Borges et al., 2020) and Aichi target 11. Therefore, the area of MPAs are increasing globally. For instance, as of 2020, the estimated coverage of Marine Protected Areas (MPAs) amounted to approximately 26,925,028 km^2, equivalent to 7.43% of the total area of the World Ocean (Sarker and Mahmudul, 2021). It is important to note that the current dedicated area for MPAs is more than 10 million square kilometers from 2000 (Gonçalves, 2023).

Bangladesh is a maritime country and considered as a major habitat for cetaceans. Bangladesh declared Swatch-of-No-Ground as the first MPA of the country which covers about 1738 km^2 area to conserve the cetaceans (i.e. dolphins, porpoises, whales and sharks). Bangladesh government declared second MPA (known as Nijuhm Dwip MPA) in 2019 which covers about 3188 km^2 area central coastal zone of the country. Both Swatch-of-No-Ground MPA and Nijuhm Dwip MPA cover about 2.8% of exclusive economic zone of Bangladesh. However, to achieve the Aichi target 11, Bangladesh needs to declare more MPAs. A recent study of Sarker et al. (2021) proposed a new MPA around the Saint Martin – Teknaf Peninsula based on socio-ecological criteria. The proposed MPA is located in the south-eastern coastal area of Bangladesh which covers about 2992.29 km^2 area. The study suggested three zoning scenarios for the proposed MPA i.e. no-entry, no-take zone (44.37 km^2); entry, no-take (710.92 km^2); partial reserve (1436 km^2) and general

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reserve zone (801 km^2). Nevertheless, there hasn't been an exploration of how the proposed Marine Protected Area (MPA) will specifically benefit the biodiversity conservation of this region. Consequently, it is crucial to gain a deeper understanding of the proposed MPA's role in safeguarding biodiversity within the area.

The offshore Saint Martin's Island (SMI) in the south western coastal area Bangladesh is the only coral bearing ecosystem of country. Shallow waters of this island with seagrass beds and rocky substratum is suitable for coral aggregations. The total annual economic value of the coral ecosystem of SMI was estimated as 33.6 million USD/year (Saha and Alam, 2018). The island generates its economic returns through various means, including fishing, tourism, shoreline protection, and the harvesting of seaweed and shellfish. Furthermore, it stands as one of the country's most sought-after tourist destinations, attracting several thousand visitors each year. The island is heavily influenced by frequent tropical cyclones and receives sediments from the discharge of the Ganges, Brahmaputra and Meghna rivers systems. The frequent cyclones and turbid water are making the coral ecosystem vulnerable. In addition, excess tourists and activities of local communities are also making the reef system fragile. Thus, in addition to evaluation of the role of MPA in conservation of biodiversity, it is also important to understand the anthropogenic stressors for this coral ecosystem. Hence, the primary objective of this study was to comprehend the anthropogenic stressors affecting SMI. Additionally, the research also delved into the impact of the Marine Protected Area (MPA) on the island's biodiversity. More specifically this study explored how different restrictions on fishing activities drive the species biodiversity of an offshore island ecosystem of Bangladesh which is an representation of tropical marine ecosystem. Finally, a framework to conserve the resources was proposed.

In this study a simulation study was performed to understand the role of MPA in biodiversity conservation. Simulations can provide predictive insights into how different management strategies and MPA designs may impact biodiversity conservation in the future. In many real-world examples, data may be limited, incomplete, or unavailable for certain critical variables. Simulations can fill in these data gaps. Policymakers often need to assess the potential impacts of different conservation policies and regulations before implementation. Simulation studies provide a tool for policymakers to evaluate the likely outcomes of MPA design and management strategies without risking ecological damage through trial and error. Since, Bangladesh has very limited data thus in this study aimed to perform simulations to understand the role of MPA in biodiversity conservation.

2. Materials and methods

2.1. Description of study area

This study was carried out in the SMI of Bangladesh (Fig. 1) which is the only coral bearing ecosystem of the country. The SMI is located in the south eastern coastal area of Bangladesh. The island is separated from the mainland of Teknaf by a 9 km wide channel (Chowdhury et al., 2011). The boundary of Myanmar lies 4.5 km away to the east. The area faces the Bay of Bengal to the western and southwestern sides (Hossain et al., 2007).

2.2. Social data collection

Stakeholder consultations were performed to collect the social data

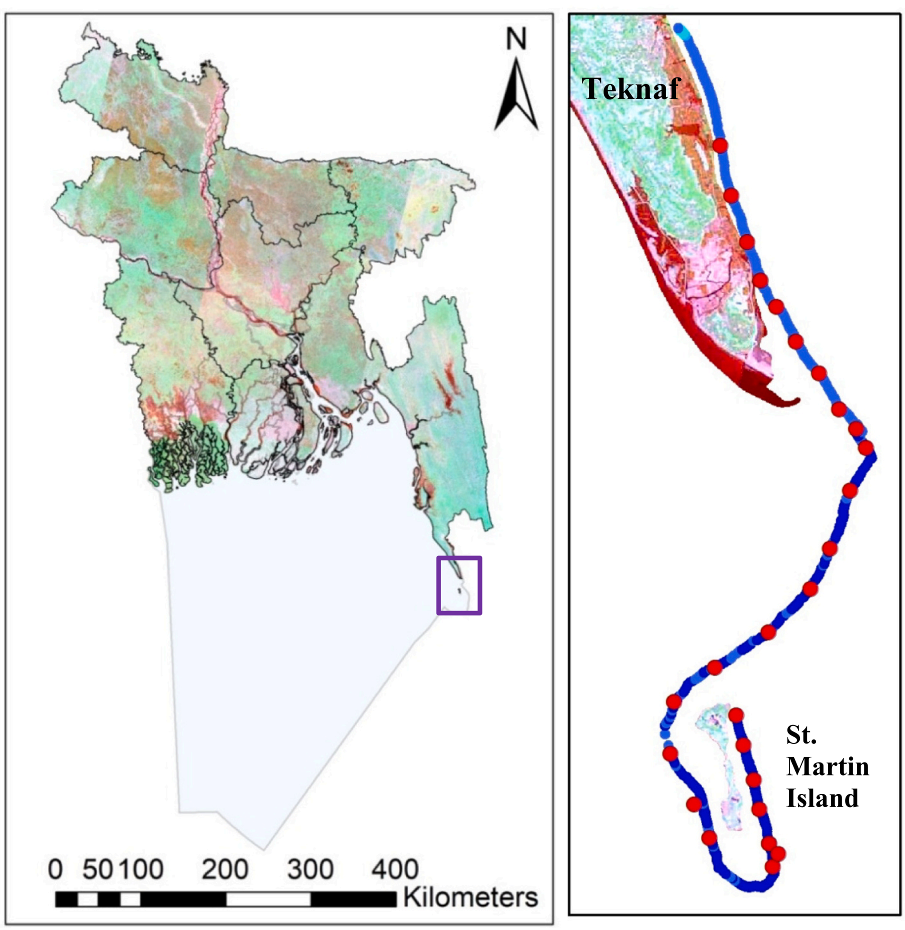

Fig. 1. Geographical location of Bangladesh (left panel) and the location of south east coastal zone of Bangladesh.

from the SMI to understand the anthropogenic stressors of biodiversity. A group of stakeholders with diverse interests for consultations were selected for this study. During stakeholder selection diverse issues (i.e. anthropogenic pressures to the biodiversity and ecosystem) were emphasized. In Bangladesh, quantitative data on anthropogenic threats to biodiversity are scarce. As a result, this study relied on the stakeholder consultations as the primary method for collecting data on these threats are not available. In addition, data from available literatures were also used in this study. This type of data collection is helpful for a data poor ecosystem (Sarker et al., 2019). Several meetings with stakeholders to understand their social and economic status were organized. For stakeholder consultation, meetings were organized with the researchers from universities and research institutes, officials from different government organizations (i.e. fisheries department, environmental department) and NGOs. Stakeholders were chosen based on various criteria, including their expertise and knowledge in specific areas or issues relevant to the project. The consultation meetings were conducted with stakeholders from January 2021 to November 2021. About 100 questionnaire surveys with fishers, 22 focus group discussions and 21 key informant interviews were conducted. In addition, some discussion sessions with academics, researchers and people involved with coastal zone management were performed during this study.

2.3. Modelling approach

The study used Allometric Trophic Network (ATN) model which is a set of ordinary differential equations (ODE) to simulate the trophic dynamics of species. Overall modelling approach is shown in Fig. 2. The model is later extended for n number of species by Williams and Martinez (2008). Specific functions for active metabolism, phytoplankton exudate, and detritus (dead particulate and dissolved organic carbon) are included by Boit et al. (2012) in the model. The governing equations for primary producers, consumers and detritus materials are defined with eq. 1, 2 and 3, respectively.

$$\frac{dB_i}{dt'} = r_i B_i G_i(B)(1 - S_i) - \sum_j \frac{x_j y_{ji} B_j F_{ji}(B)}{e_{ji}} \quad (1)$$

$$\frac{dB_i}{dt'} = -f_m x_i B_i + f_a x_i B_i \sum_j y_{ji} F_{ij}(B) - \sum_j \frac{x_j y_{ji} B_j F_{ji}(B)}{e_{ji}} - F_{max} S_{age} B_i \quad (2)$$

$$\frac{dD}{dt'} = \sum_i \left[\sum_j \frac{x_j y_{ji} B_j F_{ji}(B)}{e_{ji}} (1 - e_{ji}) \right] + \sum_i r_i B_i G_i(B) s_i - \sum_j \frac{x_j y_{ji} B_j F_{ji}(B)}{e_{ji}} \quad (3)$$

Where, B_i = biomass of guild i, r_i = intrinsic growth rate of species i, $G_i(B)$ = logistic growth function, S_i = fraction of exudation, x_j = mass specific metabolic rate of consumer i, y_{ji} = maximum consumption rate of guild i feeding on j, e_{ji} = assimilation efficiency describing the fraction of ingested biomass lost by egestion, f_m = fraction of assimilated carbon respired by maintenance of basic bodily functions, f_a = fraction of assimilated carbon used for production of consumers' biomass under activity $(1 - f_a)$ is respired.

The logistic growth function of eq. (1) is expressed as:

$$G_i(B) = 1 - \frac{\sum_{j=producers} c_{ij} B_j}{K_s} \quad (4)$$

This logistic growth function is dependent on competetion coefficient of producer c_{ij} and system wide carrying capacity K_s. In this study neutral competition effects for the basic models (c_{ij} = 1 for all algal guidls) were assumed. We set K_s to the maximum which is the product of average value of primary producer and the number of phytoplankton guilds.

$$F_{ij}(B) = \frac{w_{ij} B_i^{q_{ij}}}{BO_{ij}^{q_{ij}} + \sum_{k=consumers} d_{kj} P_{ik} B_k BO_{kj} + \sum_{l=resources} w_{il} B_l^{q_{il}}} \quad (5)$$

Where, w_{ij} = relative prey perference of consumer species i feeding on resource species j; q_{ij} = 1.2 which forms a relatively stable functional response intermediate between the Holling Type-II and Type-III functional responses (Williams and Martinez, 2008); BO_{ij} = half saturation constant of resource species j at which consumer species i achieves half its maximum feeding rate on species j; d_{kj} = coefficient of feeding interference of species k with i while feeding on species j; P_{ik} = the fraction of resource species shared between species i and k.

2.4. Model simulation design and analysis

Numerical simulations were performed in three steps. Biomass of different species (i.e. oyster, mussel, seaweed, echinoderms (seaurchine), sea cucumber, turtle, rayfish, crab, dolphin, harbivory fin fish and carnivory fin fish) were generated at different fishing restrictions in the first step. Six different types of fishing restrictions were generated (F = 0, 0.1, 0.2, 0.3, 0.4, 0.5). These restrictions were selected based on the

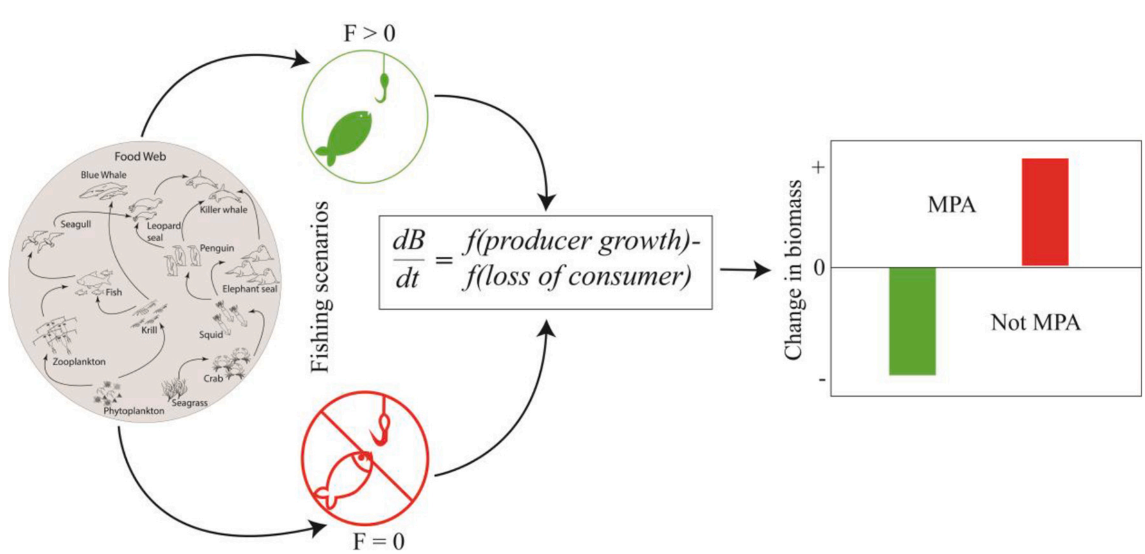

Fig. 2. Schematic diagram showing the modelling approach to examine the role of MPA on biodiversity.

available fisheries information of Bangladesh. F = 0 indicates no fishing restriction and F = 0.5 indicates strong fishing restriction (which reflects the scenario of MPA). A reference simulation was perfored considering the current fishing rate (F = 0.25). In order to assess the impact of varying fishing intensities, the change in biomass for each group with respect to each of the considered fishing scenarios (F) were conducted. In the second step to understand the impact of different F on species diversity, F was changed at different time interval. In the third step, to comprehend how changes in fishing intensity (F) affect the biomass of species over an extended period, F at various time intervals was modified.

In this study, simulations were conducted to model various scenarios related to different conservation levels. The data used in these simulations consisted of a combination of sources. Firstly, we incorporated numerical values derived from theoretical models and mathematical equations to construct our baseline scenarios. These numerical values were carefully selected to reflect the expected behaviors of the system under investigation. In addition to the numerical inputs, actual fisheries data was incorporated into our simulations to validate our models and assess their real-world applicability. These fisheries data were obtained from department of fisheries, government of republic Bangladesh. The incorporation of these empirical data allowed us to verify the accuracy and reliability of our simulations by comparing model outputs with observed trends and patterns in the fisheries industry. The combination of theoretical numerical values and empirical fisheries data provides a robust foundation for our simulations, ensuring that our results are both theoretically sound and empirically grounded. Parameters used in this sutdy are given in Table S1.

3. Results

3.1. Anthropogenic stressor of biodiversity

Stakeholder consultations identified about 16 types of anthropogenic stressors for the biodiversity of SMI (Fig. 3). About 85% respondents identified tourism is the main threats. Stakeholder also mentioned that coral collection (81%), over fishing (79%), use of destructive fishing gears (76%), by catch fishing (71%), aquatic resource collection (71%) and seaweage from hotels (57%) are the anthropogenic stressors for the aquatic biodiversity of SMI. In addition, plastic pollution (25%), oil spill (12%), wild seaweed harvesting (24%), heavy metal pollution (24%), sedimentation due to construction (45%), lack of awareness about biodiversity (46%), physical destruction of coral (43%), boat construction in the beach (29%) and boat anchoring (39%) were also found as the threats to the biodiversity.

3.2. Role of MPA in species diversity conservation

To understand the ecological effect of MPA, numerical simulations were performed in a system with no fishing (i.e., MPA) and with fising (Fig. 4a). Analysis of our simulated data found that controlled fishing area yield with higher species biomass (550 MT) than area with effective fishing (252 MT). This study found that magnitude of biomass change between different management policies (i.e., with and without fishing restriciton) was relatively higher for considered speices along the trophic levels (Fig. 4b). Biomass of the species in the system with no fishing area increased significantly (3–6%) while compared with the species biomass of a area without fishing restriciton. Our model outputs suggest that declaration of MPA is benificial for organisms with low movement rates (i.e., biomass increased by 5–6.5% for oyster, mussel, seaweed, echinoderms, sea cucumber). However, our findings also indicate that MPA is also benificial for dispersing ogranisms (i.e., biomass increased by 3–4% for turtle, rayfish, crabs, dolphins, herbivory and carnivory fish species).

To compare the ecological impacts of different levels of fishing restrictions on species biomass, we conducted simulations involving six distinct fishing pressure scenarios. Subsequently, we compared the species biomass observed in the current fishing pressure scenario with that in scenarios involving reduced and increased fishing pressure (Fig. 5). This stud found that increasing fishing pressure significantly reduced the species biomass while reduced fishing pressere increased the biomass of species. Maximum biomass of species were found when F = 0 was considered in the model. This suggests that declaration of MPA will enhance the natural stock of species.

The fishing pressure scenarios were changed in the ecosystem over the time to understand the role of MPA in maintaining a sustainable species stock (Fig. 6). We have observed that implementing fishing restrictions in a heavily exploited ecosystem leads to a substantial increase

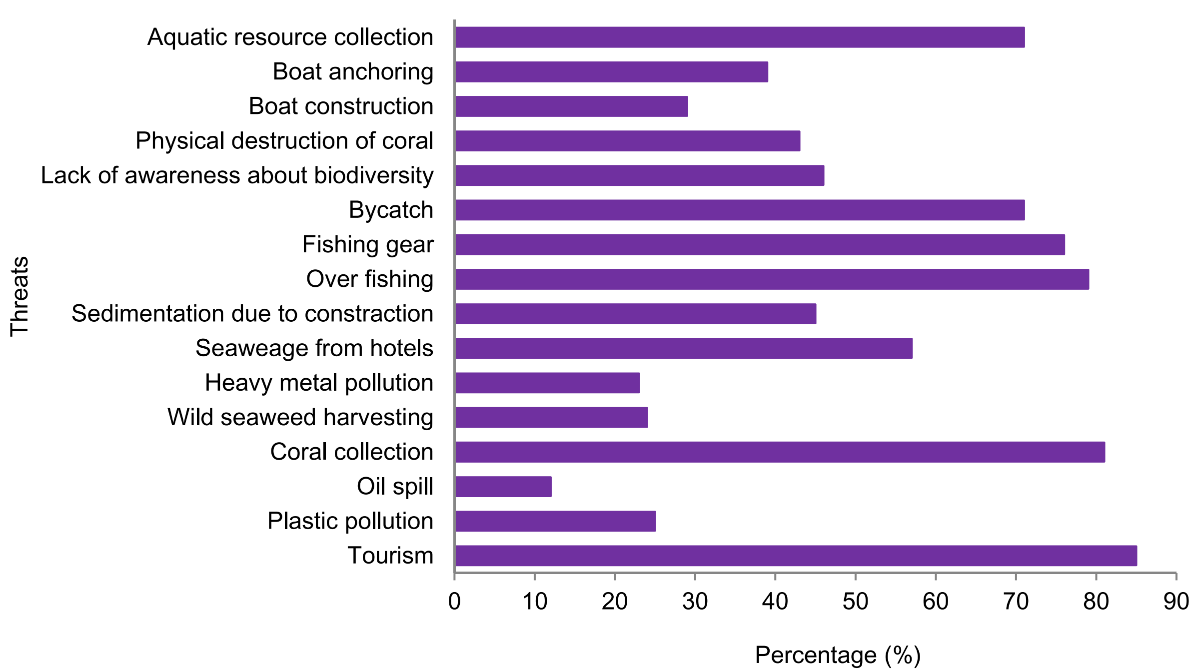

Fig. 3. Stakeholder responses to the anthropogenic stressors of the aquatic ecosystem of SMI.

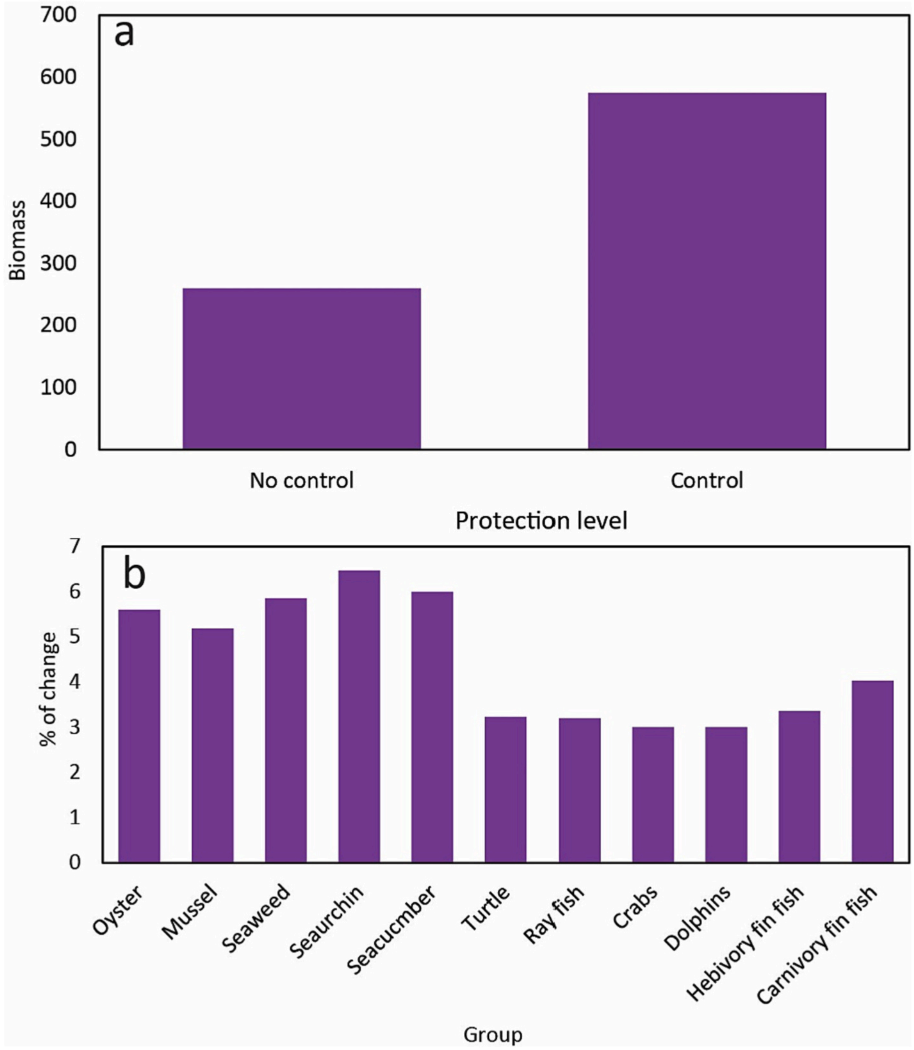

Fig. 4. Effects of MPA on biodiversity. (a) variation of species biomass at different protection levels and (b) changes in species biomass (%) in controlled fishing environment to uncontrolled fishing environemnt.

in the standing stock of species. Conversely, when the fishing ban is eased in such a system, there is a notable adverse effect on species biomass, resulting in a reduction.

To investigate whether MPAs can enhance species diversity, a system with no fishing pressure was created initially, allowing two species to coexist over an extended period ($t = 1000$ months). Subsequently, we introduced additional species at different time intervals (Fig. 7). Our findings indicate that the third and fourth species were able to coexist with the first and second species when introduced into the system at $t = 250$ months. Additionally, the fifth and sixth species were sustained. These results suggest that reducing fishing pressure can potentially increase the number of species within the ecosystem. Consequently, it is conceivable that MPAs could create an opportunity to enhance species diversity. In order to check our model implications, we analyzed field-based data from the northern Bay of Bengal. Our model found significant negative relationship between species biomass and fishing pressure ($R^2 = 0.93$; Fig. 8a). This suggest that reduced fishing pressure can enhance species biomass. Similar negative relationship ($R^2 = 0.91$; Fig. 8b) was also observed while we analyzed fishing mortality and species biomass data from the northern Bay of Bengal. In addition, from the long-term data of fish biomass from a fish sanctuary from the northern Bay of Bengal we found that after imposing restriction on fishing biomass of species increased significantly (Fig. 8c).

4. Discussion

This study delved into the anthropogenic stressors affecting biodiversity within the aquatic ecosystem of SMI. Furthermore, it utilized numerical model simulations to investigate the role of MPAs in biodiversity conservation. The research identified approximately 16 anthropogenic stressors that impact biodiversity and made predictions suggesting that MPAs have the potential to enhance species diversity within the ecosystem. Saint Martin's Island is a popular tourist destination in Bangladesh, drawing in more than 600,000 visitors annually (Sarker et al., 2021). This huge number of tourists is exceeding of carrying capacity of the island. Thus, tourism is considered as one of the major anthropogenic stressors to the ecosystem of SMI. Pollution from tourism industries, local communities as well as fishing boats, unplanned tourism and economic development are posing major threats to the coral ecosystem of SMI (Hossen and Sultana, 2023). Furthermore, the island is facing environmental challenges, as sewage and chemical pollution stemming from fertilizer runoff are causing significant damage to its coral reefs. Currently, a majority of sewage from hotels is directly discharged into the sea. Additionally, local communities are utilizing coral boulders to extract calcium, further impacting the fragile coral ecosystem. Turtle eggs, sea urchins, star fishes and shells are collected by local community for selling purpose (Rani et al., 2020). In addition, excessive exploitation of fisheries together with destructive fishing

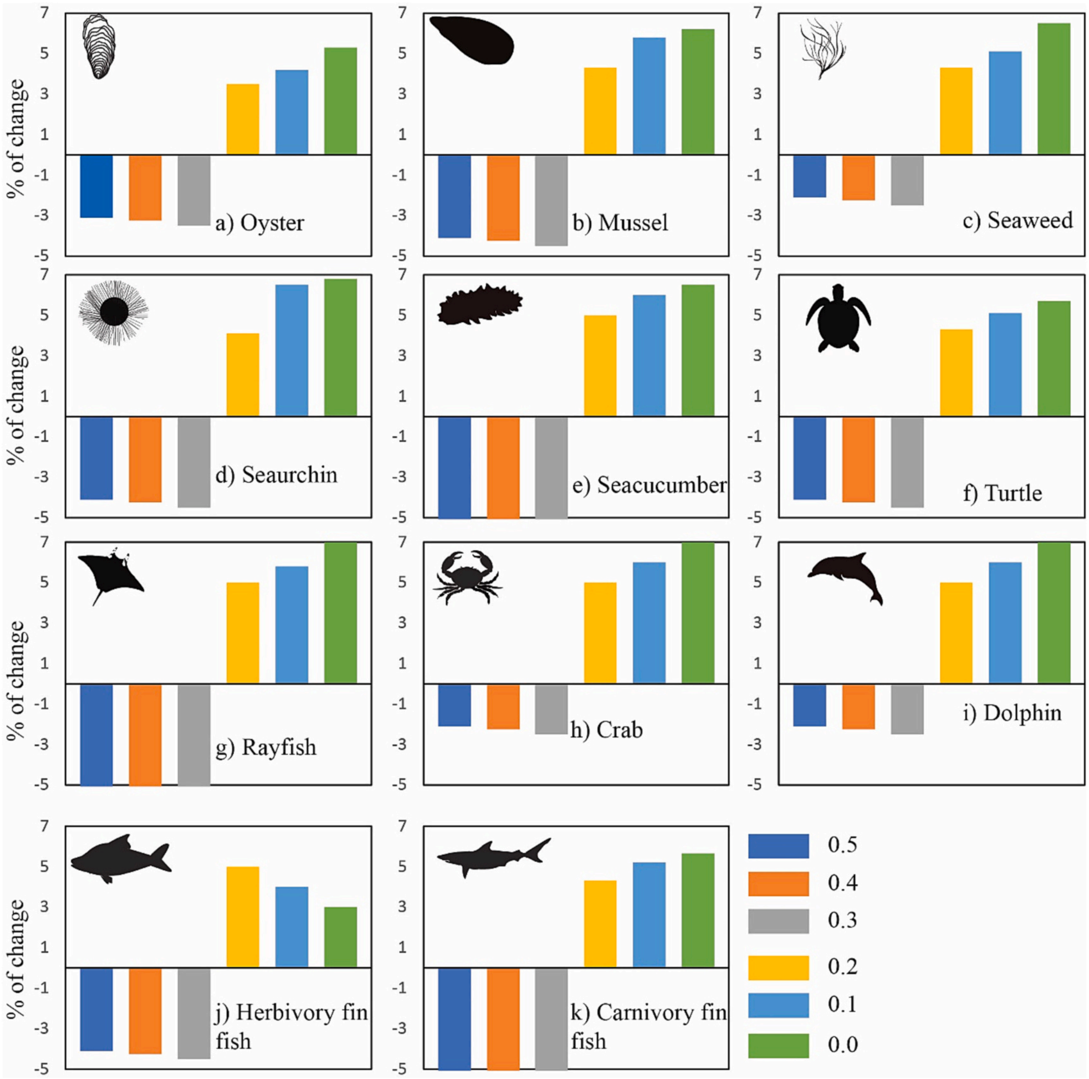

Fig. 5. Effects of MPA on the biomass of different species.

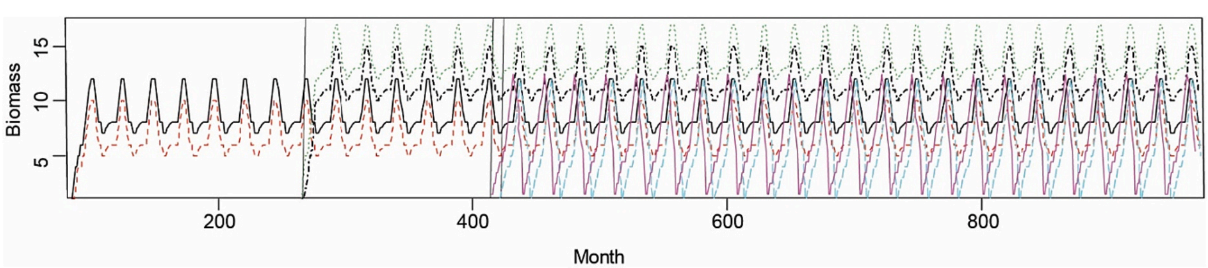

Fig. 6. Role of MPA in maintaining a sustainable species stock. Different number of species were injected at different time interval (i.e. 250, 410 and 420 months). Time intervals were selected randomly.

practices imposes a threat to the ecosystem. This study found that MPA yield with high species biomass compared to a area with fishing pressure. Well designed MPA can be benificial for fisheries (Holland and Brazee, 1996) and it is evident that an overfished area with a strategically designed MPA can increase yield of fisheries (Cabral et al., 2020). For example, Salomon et al. (2002) modelled the impact of MPA on the trophic level and found that MPA enhances the species biomass. Colléter et al. (2012) compared the species biomass of a area before and after MPA declaration and found that after imposing fishing ban total biomass in the system increased by a 2.5 factor in the west coast of Senegal. Overfishing is threatening the food security, livelihoods, human health and conservation goals in the developing nationals of the tropical areas (Costello et al., 2016). Implementing protection measures in an overfished area has the potential to yield significant fisheries benefits, primarily through the phenomenon of spillover, which encompasses both the dispersal of species' larvae and the movement of adult individuals (Buxton et al., 2014; Quinn et al., 1993). MPA reduce the harvesting mortality and lead to a higher abundacne, assemalage and richness of species (Coetzee et al., 2014). In addition, fishing ban create the oppurtunity to add common speices and thus increase the species

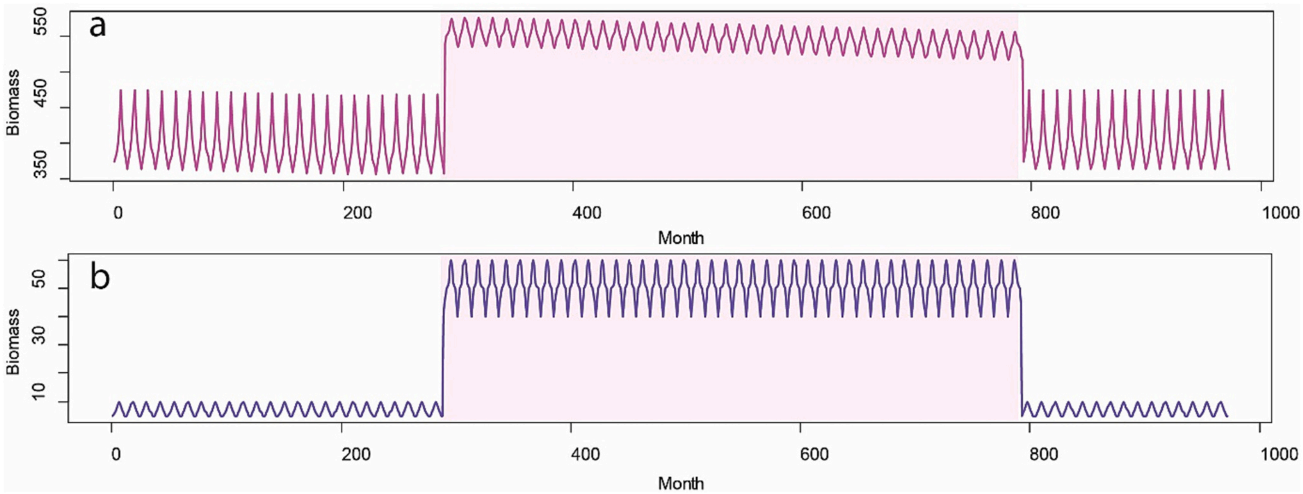

Fig. 7. Role of MPA in conservation of a over exploited marine ecosystem.

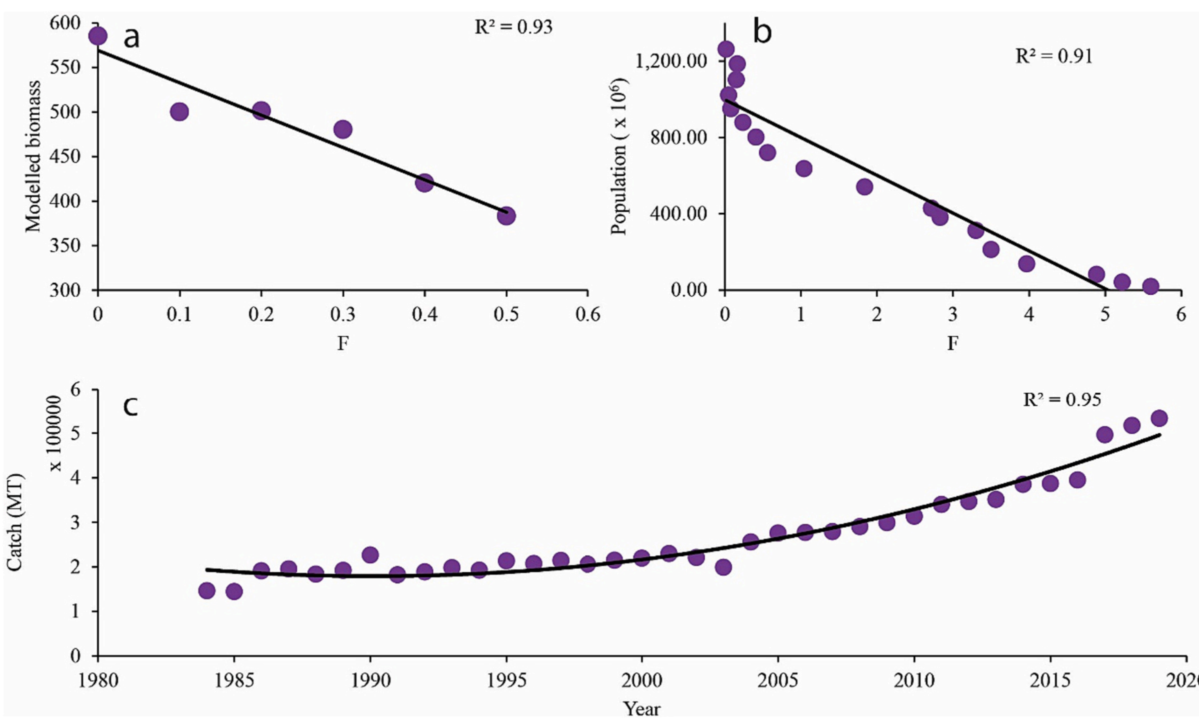

Fig. 8. Comparions of in-situ data on fish biomass and long term hilsha catch data (Data source: BBS, 2021) to validate the model outputs.

evenness (Blowes et al., 2020). The increase in species biomass (species covered in this study) may also related to entrance of new species which is driven by a refuge effect from outside fisheries (Afonso et al., 2008). This can be also related to a foraging arena effect (Jolles et al., 2020). In many cases such types of behavior in the ecosystem represent about 50% of the increase in the biomass and rest 50% is driven by the fishing mortalities (Colléter et al., 2012).

We found that more species can coexist when fishing pressure is nill and thus, MPA can enhance the species diversity in the ecosystem. Our findings are inline with the findings of existing studies. For example, species compositions is rich within the MPA than outside of MPA (Branch and Odendaal, 2003). Lasiak (2006) found that limpet species is absent outside the MPA while high density and biomass of species was observed inside the MPA. Kido and Murray (2003) also observed the similar scenario for the abundance and biomass of limpet after and before declaration of MPA. Davies et al. (2017) estimated MPAs can increase the diversity of species by morethan 40% in 2100. Large increases in density and biomass of species is observed inside the protected areas compared to non-protected areas (Lester et al., 2009).

So, what is the role of MPAs to enhance species diversity?

The major causes of biodiversity loss encompass several factors, including loss of habitats, environmental pollution resulting from anthropogenic activities, resource exploitation, and environmental changes. Legal restrictions (i.e. spatio-temporal control; quotas and license for fishing and restriction on fishing gears) are generally imposed within MPAs to regulate the natural system (Das et al., 2022). These legal measures help to protect the habitats of exploited species, breeding and nursery ground of vulnerable and endangered species (Sarker and Mahmudul, 2021). In the context of MPA zonal management, which includes designations such as no-use zones, no-take zones, buffer zones, and multi-use zones, these strategies are employed to control the intensity of human activities within the MPA. By doing so, they contribute to the conservation of species diversity. Additionally, temporal control measures can be implemented to restrict the exploitation of resources within the MPA during specific time periods, further aiding in conservation efforts. Target species can be protected through restriction of certain fishing gears and methods (Campbell et al., 2020). Quota system in fish catch can effectively enhance the stock and maintain a high yield (Stefansson and Rosenberg, 2005).

Model outputs suggest that MPA increase the biomass of sessile organisms much compared to dispersing organisms. Salomon et al. (2002) also found that buffer zones are beneficial for organisms with low movement rates because they dissipate the intensity of fishing pressure around the periphery of a MPA and therefore reduce edge effects. After settlement sessile organisms cannot move, and thus environmental conditions and disturbance significantly impact their distributions (Kanki et al., 2021). Reducing human interference within the MPA results in a decrease in exploitation pressure and disturbances. Consequently, this reduction leads to an increase in both biomass and biodiversity within the MPA.

When comparing various model outputs with field-based data, it was observed that both sources of information yielded similar findings. Specifically, these findings indicated that conservation initiatives support higher species biomass. In this study to analyze the signal long-term hilsha (*Tenulosa ilisha*) catch data was used. The government of Bangladesh has imposed a number of restrictions to control the exploitationand enhance the conservation of its fisheries sector (Begum et al., 2020). Until 2000–2001, annual hilsa catch increased significantly (Shampa et al., 2023). This is related to grown number of fishers and improved technologies. However from 2001 to 2002, the catch biomass dropped sharply which negatively impacted the livelihoods of the fishing communities (Islam et al., 2017). Therefore, interventions to increase the hilsa stock was an urgent requirement. Overfishing is the prime reason of reduced catch biomass of hilsha. Taking this into account, the government initiated several conservation measures to enhance the hilsha stock from 2003 to onwards (Mozumder et al., 2018). Therefore, the Hilsa Fisheries Management Action Plan (HFMAP) was implemented in 2003 with special focus to protect juvenile hilsha. It is now established that the jatka protection programme had a positive effect (Islam et al., 2016). All these suggest that MPA can enhance species biomass in the ecosystem.

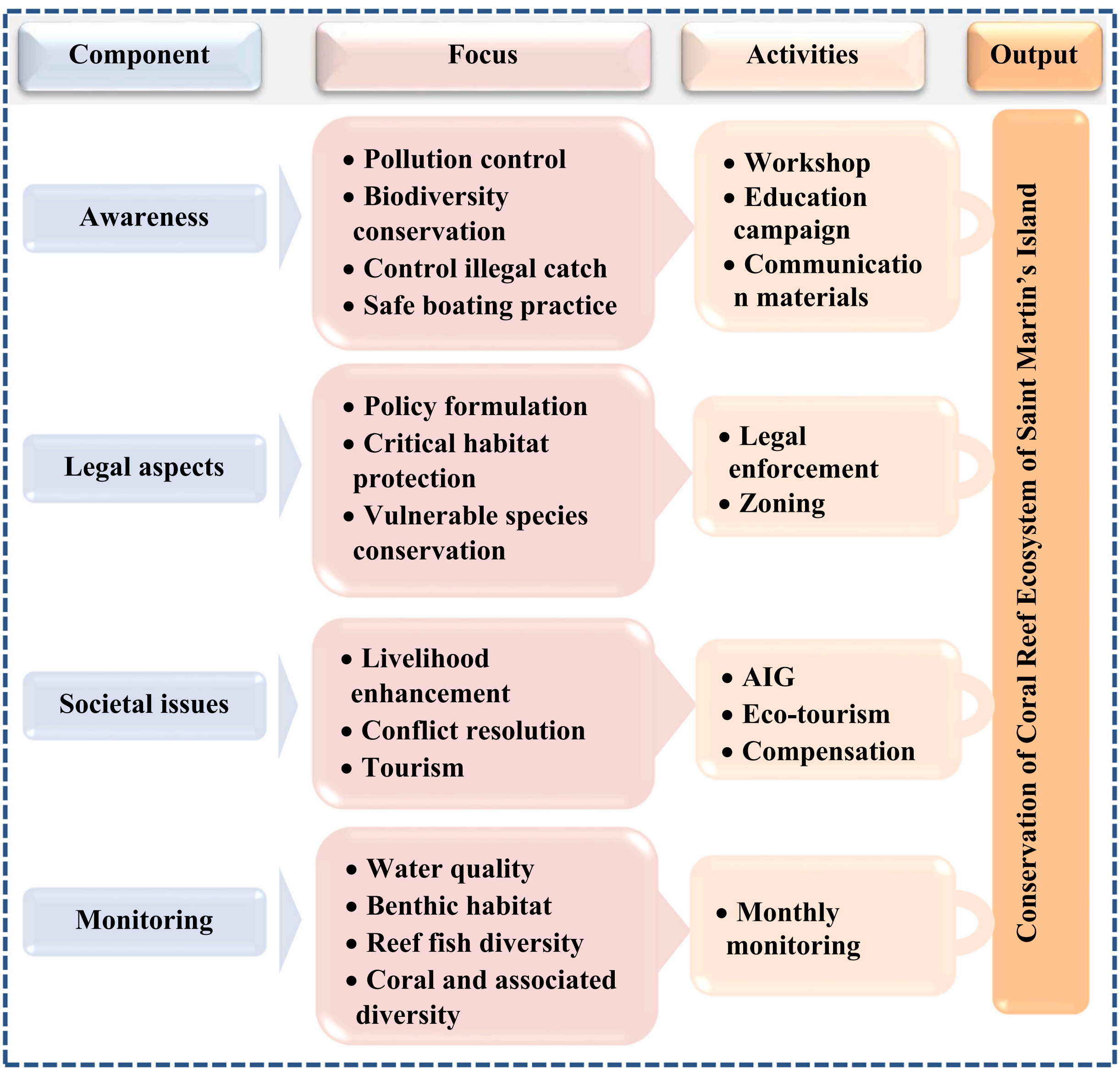

Fig. 9. Proposed management framework for coral reef ecosystem of Saint martin's Island.

5. Management framework

Straightening the management strategy for a vulnerable ecosystem like coral habitat is a long-term approach (Mora et al., 2016). However, through proper implementation of the adopted strategies can achieve the management goals. A framework (Fig. 9) for the coral ecosystem of SMI is developed which may serve as a tool for long-term conservation of vulnerable coral system. Our framework consists of four components i.e. awareness, legal aspects, monitoring and social issues.

5.1. Component 1: awareness

The coral ecosystem is indeed among the vulnerable marine systems, and it is alarming that approximately half of the world's corals have already disappeared. Urgent action is imperative, and raising awareness represents the crucial first step in addressing this critical issue. Though a number of initiatives have been taken to conserve the coral reef around the globe, however most of the programs failed to show significant results. This is due to the lack of awareness about the coral reef ecosystem among the local communities and the tourists. Therefore, management strategies should incorporate awareness-building programs as an integral component to support their goals. A supportive community attitude is essential for achieving successful conservation of the ecosystem, making it imperative to engage and educate the community through such programs. To conserve the coral reef ecosystem of Saint Martin's Island awareness building programs are required to control pollution, biodiversity protection and safe boating practice (Mora et al., 2016). Awareness programs can be organized through educational programs, making leaflets, school visits, community meeting, involving local leaders. Through educational initiatives within the local schools, hospitality industries and businesses around the island, awareness will breed more observant behavior to the coral ecosystem (Mozumder et al., 2018). In addition, education programs are fundamental platform for changing community outlooks to ecosystem services. Education also assists in environmentally-based enterprises to achieve management goals. Raising awareness by enhancing education plays a pivotal role in fostering a sense of responsibility within local communities. This heightened sense of responsibility is invaluable for effective conservation efforts (Trialfhianty and Suadi, 2017). Awareness among the islanders will build their understanding that conservation of coral reef ecosystem is required for their own benefits (Hughes et al., 2017). Therefore, an awareness-building program will motivate ecosystem users to behave responsibly and sustainably towards the ecosystem.

5.2. Component 2: legal aspects

Though a number of legal initiatives exist to conserve and protect the biodiversity in Bangladesh, a straight forward legal bindings are still missing to conserve the coral reef ecosystem (Sarker and Mahmudul, 2021). The rapid disappearance of corals on Saint Martin's Island underscores the urgent need for proper protection measures. To ensure the long-term viability of the coral ecosystem, the implementation of straightforward legal bindings is imperative. These legal aspects should prioritize policy formulation, with a strong emphasis on critical habitat protection and the conservation of endangered species. Proper implementation of legal issues can be achieved through law enforcement (Begum et al., 2020). Law enforcement should include zoning, temporal ban on tourism, penalty for pollution and removal of corals (Sarker et al., 2021). Zoning is an emerging practice for the sustainable management of ocean. In addition, zoning play a key role as a part of the adaptive management system of coral reef ecosystem (Day et al., 2012).

By identifying and designating habitats for endangered species through zoning, it becomes possible to limit human interference in specific areas of the island. This proactive measure can effectively halt the degradation of the ecosystem caused by human activities, contributing to the preservation of the island's natural environment. Being the only coral island of Bangladesh, Saint Martin's Island is a tourism hotspot. During 2019–2020, 9 passenger ships were operational to carry the tourists to the island (Sarker et al., 2018). These ships were operational for 139 days during 2019–2020 and carried about 6193,80 visitors (Rani et al., 2020). Huge number of tourists in a year is causing a serious threat to the coral reef ecosystem. Thus, it is an urgent need to impose ban on tourist visit for a certain time of the year. In addition, it is also important to fix the number of tourists can visit the island based on the carrying capacity. Since pollution and removal of coral are considered as major threats to the ecosystem, thus penalty should be imposed on such activities (Hughes et al., 2011).

5.3. Component 3: societal issues

For successful implementation of a conservatory management framework it is important to take into consideration the social safety, education and property rights (Weijerman et al., 2018). Therefore, as the third component of the management framework, we must take into account societal issues. These societal concerns should center on addressing the livelihoods of local communities, implementing conflict resolution mechanisms, and managing tourism in a sustainable and responsible manner. Societal issues can be achieved through offering alternative income generation options and developing ecotourism (Harvey et al., 2018). The livelihood option of Saint Martin's Island is highly influenced by tourism. Since a large number of tourists visit the island every year an extra charge can be imposed to tourists (McClanahan et al., 2012). The funds generated can be allocated towards the development of livelihoods for the islanders. However, the imposition of a temporary ban on tourism and restrictions on the maximum number of visitors may have an adverse impact on the local communities who depend on tourism. Therefore, it is crucial to provide affected local communities with suitable compensation schemes and opportunities for alternative gainful occupations to mitigate the negative economic consequences they may face.

5.4. Component 4: monitoring

With increasing stressors to coral reefs, defining tools that enhance resilience and support conservation is important. In this context, monitoring that focus on biological, physical and chemical aspects of the ecosystem is required. Monitoring focuses the gathering of data related to coral reef ecosystem which should be repeated on a regular basis (i.e. at least monthly) for an extended time period (McClanahan et al., 2012).

Given the diverse information required for the effective management of the coral reef ecosystem, it is essential to design a monitoring system that can adequately address these information needs. Monitoring efforts should encompass both ecological and physicochemical variables to provide a comprehensive understanding of the ecosystem. Ecological variables include factors such as coral species diversity, the size structure of coral communities, coral coverage percentages, the presence of newly settled corals and juveniles, species composition of reef fisheries, diversity of sea urchins, sea cucumbers, sea turtles, and seaweed. Additionally, monitoring should encompass the extent of coral coverage, occurrences of bleaching events, and the presence of diseases within the coral ecosystem.

Physicochemical variables are also crucial and should encompass water quality parameters, with a focus on assessing metal, plastic, and oil pollution levels. Other physicochemical variables to monitor include temperature, salinity, water current patterns, sedimentation rates, and water visibility.

Establishing a comprehensive monitoring program for the coral ecosystem of Saint Martin's Island can be achieved by setting up monitoring stations through collaborative efforts involving academic and research institutions. This collaborative approach will help generate the necessary background knowledge essential for supporting broad-scale sustainable management initiatives for the coral reefs in the region.

6. Conclusion

In conclusion, our study reveals several important insights about Saint Martin's Island in Bangladesh and its vulnerability to anthropogenic stressors, many of which are associated with the tourism industry. This model based study revealed that the declaration of a MPA in this region has the potential to enhance species diversity. In summary, our study underscores the importance of implementing MPAs with varying levels of restrictions while promoting eco-tourism activities as a means to ensure sustainable biodiversity conservation in Saint Martin's Island. However, it is important to mention that the results of this modelling study may vary as conditions changes and generalizations or applicability of results may be limited in other locations.

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Declaration of Competing Interest

The authors have no conflict of interest.

Data availability

Data will be made available on request.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.seares.2023.102457.

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