Economic perspective of marine reserves in fisheries: A bioeconomic model

Kunal Chakraborty a, *, T.K. Kar b

a Information Services and Ocean Sciences Group, Indian National Centre for Ocean Information Services, Hyderabad, "Ocean Valley", Pragathi Nagar (BO), Nizampet (SO), Hyderabad 500090, India
b Department of Mathematics, Bengal Engineering and Science University, Shibpur, Howrah 711103, India

1. Introduction

There is broad recognition that the oceans and their living resources are under stress. Increasing use by humans, especially in the coastal zone but increasingly offshore as well, have damaged marine habitats and led to overfishing of many marine fish stocks. Significant numbers of marine organisms, including mammals, birds, and turtles, as well as some commercially harvested fish and shellfish, are now threatened or endangered. Clearly, new management approaches or options must be considered to stem the damage and ensure that marine ecosystems and their unique features are protected and restored. In this regard, marine reserves are more often proposed as major tools to relieve stress on marine resources and ecosystems. Therefore, it is indispensable to analyze the use of protected areas as a tool for wild harvest fisheries management. Focus should be placed on the economic and biological conditions where fishery rent could be improved through the use of protected areas.

The use of marine protected areas (or marine reserves or no take zones) has been extensively studied using mathematical models by several researchers. Ami et al. [1] have investigated the impacts of MPAs creation on both economic and biological perspectives. Their attention has been focused on the obtained the-
total standing biomass increases with increasing MPA size but only up to a point. Sumalia [10] also provided an overview of marine protected areas and the role of economic analysis and modeling in designing, implementing and evaluating such MPAs. Lubchenco et al. [11] focused on the multiple benefits of MPAs which include protection of habitats, conservation of biodiversity, protection or enhancement of ecosystem services, recovery of depleted stocks, export of individuals to fished areas, insurance against environmental or management uncertainty and sites for scientific investigation, baseline information, education, recreation and inspiration.

Kar and Matsuda [12] examined the impact of the creation of marine protected areas (MPAs), from both economic and biological perspectives. In particular, they examined the effects of protected patches and harvesting on resource populations. They discussed the impacts of MPAs on resource populations and provided important conclusions towards the use of marine protected areas. Boncoeur et al. [13] investigated some economic consequences of creating a marine reserve on both fishing and ecotourism, through considering a range of controlled fishing effort and the impact of the reserve on the ecosystem. They presented a simulated model to develop further insights into the economics of marine reserves, from a multi-species perspective and taking into account non-extractive uses of marine ecosystems. Kar and Chakraborty [14] considered a prey–predator fishery model with prey dispersal in a two-patch environment, one of which is a free fishing zone and other is protected zone. They described different consequences of reserve using numerical simulations. Their simulation results clearly indicated that prey–predator interactions do matter when the implementation of a reserve is considered. They concluded that reserves will be most effective when coupled with fishing effort controls in adjacent fisheries. The dynamics of a fishery resource system in an adequate environment which consists of two zones, such as a free fishing zone and a reserve zone where fishing is strictly prohibited, was studied by Kar [15] using a non-linear mathematical model.

Hannesson [16] analyzed the effects of marine reserves using a logistic model for a population with a patchy distribution. He formulated the model depending on the assumption that the marine reserve is established for the territory of one of two sub-populations which interact through migration. He concluded that the total population increases while the total catch declines for the most part and a high rate of migration would, however, dilute the conservation effect. Moreover, he introduced a stochastic variant of the model to show that the variability (sum of squared deviations) of catches may decrease as a result of protecting one of the sub-populations and reached to a conclusion that even if all rents disappear by assumption, it is possible to identify this as an economic benefit, particularly when the average catch increases. Flaaten and Mjølhus [17] considered a pre-reserve population to follow logistic law of growth and formulated two models for post-reserve population to theoretically investigate to what extent a nature reserve may protect a uniformly distributed population of fish or wildlife against negative effects of harvesting. In this regard, they concluded that when the migration rate is less than the growth rate both models imply that the reserve can be chosen so that extinction cannot occur. On the other hand, when migration is large compared to natural growth, a marine reserve alone cannot assure survival of the population. It is globally accepted that the prey–predator dynamics plays an important role towards implementing a sustainable ecosystem. We make an attempt to analyze the effects of marine reserve on predator–prey dynamics. It may also be noted that it is necessary to illustrate the effects that predators and other parameters can play regarding economic perspective of the system. Hannesson [18] examined the economic consequences of establishing marine reserves and investigated what would happen to fishing outside the marine reserve and to the stock size in the entire area as a result of establishing a marine reserve. Finally, he compared three regimes (1) open access to the entire area; (2) open access to the area outside the marine reserve and (3) optimum fishing in the entire area.

The primary goals of marine reserves include protecting biodiversity and ecosystem structure. Therefore, a multispecies approach to designing and monitoring reserve networks is necessary. To gain insight into how the interactions between species in marine communities may affect reserve design, Basket et al. [19] synthesized marine reserve community models and community models with habitat destruction and fragmentation, and developed new extensions of existing models. This synthesis highlights the potential for species interactions to alter reserve design criteria; in particular, accounting for species interactions often leads to an increase in reserve size necessary to protect populations. Kar and Chakraborty [20] considered a dynamic reaction model of a prey–predator type fishery with a partial closure of prey species to analyze the dynamical behavior of the model system. They concluded, in the optimally managed fishery, a marine reserve may or may not increase fisheries rent.

In this paper, a bioeconomic model of a prey–predator fishery is used to test the performance of protected areas as a management tool in a two patch, two species fishery with homogeneous environments. One of these patches is considered to be a marine reserve and the remaining adjacent patch is used for harvesting of the resource. This assumption is familiar to the literature dealing with marine reserves or MPAs. The difference lies in the realistic dynamic model constructed to represent the direct and indirect impacts of resource across the patches. We first outline the basic theoretical model describing the biological dynamics of two homogeneous stocks and the importance of the dynamics in the reserves and fishing zones, and then we add exploitation to the system. We compute some numerical simulations to determine the optimal conditions under which the biological steady state can be attained and to draw some important conclusions regarding reserve designs. The results obtained in presence of predator population are compared with the results obtained in absence of predator population. We also consider the optimal area of the reserve and exploitation rate in the fishery.

2. Model description and assumptions

In this section we describe a deterministic model of the interaction between the fish stock in a fishing ground and that of an adjacent marine reserve. The model is used to evaluate the impact of marine protection on the optimal fish biomass, predation, catch and economic rent of the fishery. The basic nature of a fishery associated with the reserve and fishing ground is described by the net transfer or migration of fish from the reserve to the fishing grounds. Let us assume that the growth of the population under pre-reserve conditions follows the logistic model. Now to model the possible interaction between the fish stocks in the reserve area and the fishing grounds, let us assume $x$ & $y$ are respectively the stock into patch1, reserve area and patch 2, the fishing grounds at time $t$. The marine reserve is fully protected from fishing and if the fish are not in the protected region they are exploitable. Again, we consider the catch of fish by fisherman which is the only possible interaction between the fish stocks in the reserve area and the fishing grounds, let us assume $x$ & $y$ are respectively the stock into patch1, reserve area and patch 2, the fishing grounds at time $t$. The marine reserve is fully protected from fishing and if the fish are not in the protected region they are exploitable. Again, we consider the catch of fish by fisherman which is the only possible interaction between the fish stocks in the reserve area and the fishing grounds, let us assume $x$ & $y$ are respectively the stock into patch1, reserve area and patch 2, the fishing grounds at time $t$. The marine reserve is fully protected from fishing and if the fish are not in the protected region they are exploitable.
environmental carrying capacity is uniformly distributed in the entire area. Let us assume $z$ is the density of predator species at time $t$. The predator population consumes the prey population in both the areas at Holling type-II (Holling, [21]) functional response which are respectively \( mzx/(a + x) \) and \( nyz/(b + y) \) where $m$ and $n$ are respectively the maximal predator per capita consumption rate, i.e. the maximum rate at which the prey population from the reserve and open areas can be eaten by a predator per unit time and $a$, $b$ are the half capturing saturation constant, i.e. the number of prey from reserve and open area necessary to achieve one-half of the maximum rates (Arditi and Ginzburg [22]).

Further, the predator grows as per the logistic law with intrinsic growth rate $s$ and carrying capacity proportional to the total population size of prey. $y$ is the amount of prey required to support one predator at equilibrium. For more details regarding the predator Eq. (1c) see the references of Kar and Chakraborty [14] and Boncour et al. [13].

Hence the basic dynamics of the marine reserve and fishing ground are described by the following model in the presence of the net migration function $M$ and harvest function $H$:

\[
\begin{align*}
\frac{dx}{dt} &= r x \left( 1 - \frac{x}{Kz} \right) - M - \frac{mzx}{a + x}, \\
\frac{dy}{dt} &= y \left( 1 - \frac{y}{K(1 - x)} \right) + M - \frac{myz}{b + y} - H(t), \\
\frac{dz}{dt} &= sz \left( 1 - \frac{y}{x + y} \right).
\end{align*}
\]

where $s$ is the intrinsic growth rate of predator species.

In order to simulate the model let us first specify an appropriate functional form of the migration function.

The migration rate of the resource depends mainly on the size of the reserve, the mobility coefficient and the comparative densities of the stocks in the reserve zone and fishing ground. It is assumed that the population migrates from the area with higher density to the area with lower density and, if the densities are equal, then the migration is considered to be zero. The net transfer from the protected area to the unprotected area is assumed to be equal, then the migration is considered to be zero. The net transfer density to the area with lower density and, if the densities are

The problem of maximizing \( V(x) \) in (5), subject to population equations (3a)–(3c) and the control constraint \( 0 < H < \max \) can be solved by applying Pontryagin’s maximum principle. The convexity of the objective function with respect to $H$, the linearity of the differential equations in the control and the compactness of the range values of the state variables can be combined to give the existence of the optimal control.
Suppose $H^*$ is an optimal control with corresponding states $x^*$, $y^*$ and $z^*$. We are seeking to derive optimal control $H^*$ such that the Hamiltonian $L$ must be maximized for $H \in [0, H_{\text{max}}]$ where the current-value Hamiltonian for this control problem is

$$L = (p - \nu H) H - \frac{c}{qY} H + \lambda_1 \left[ rX - \frac{a}{a + c} - \left( \frac{x}{K} - \frac{y}{(1 - \alpha)K} \right) - \frac{mX}{a + X} \right] + \lambda_2 \left[ rY - \frac{b}{b + c} - \left( \frac{x}{K} - \frac{y}{(1 - \alpha)K} \right) \right] + \lambda_3 \left[ sz - \frac{z^2}{X + Y} \right].$$

(6)

where $\lambda_1$, $\lambda_2$ and $\lambda_3$ are adjoint variables.

For optimal control we have $\frac{\partial L}{\partial \lambda_i} = 0$, $i = 1, 2, 3$.

Therefore, $\mu(t) = p - \frac{c}{qY} - \lambda_2 - 2H \nu = 0$.

(7)

We intend to derive here an optimal equilibrium solution of the problem. Since we are considering an equilibrium solution, $x$, $y$ and $z$ are to be treated as constants in the subsequent steps.

Now the adjoint equations are:

$$\frac{d\lambda_1}{dt} = \delta \lambda_1 - \frac{\partial L}{\partial x} = \delta \lambda_1 - \left[ \left( \frac{2x\lambda_1}{Kx} - \frac{am\lambda_1}{(a + c)} \right) \right] + \frac{sz\lambda_3}{(x + y)^2} - \frac{\lambda_1 \sigma}{Kx} + \frac{\lambda_3 \sigma}{Kx}.$$

$$\frac{d\lambda_2}{dt} = \delta \lambda_2 - \frac{\partial L}{\partial y} = \delta \lambda_2 - \left[ \left( \frac{ch}{q^2} - \frac{mb\lambda_2}{(b + y)} \right) + \left( \frac{2y\lambda_2}{K(1 - \alpha)} \right) \right] + \frac{sz\lambda_3}{(x + y)^2} - \frac{\lambda_2 \sigma}{K(1 - \alpha)}.$$

$$\frac{d\lambda_3}{dt} = \delta \lambda_3 - \frac{\partial L}{\partial z} = \delta \lambda_3 - \left[ \left( \frac{2s\lambda_3}{X + Y} \right) \right].$$

Hence, there exists an optimal control $H^*$ and corresponding solution $x^*$, $y^*$ and $z^*$ that maximizes $V(x)$ over $[0, H_{\text{max}}]$. Furthermore, there exist adjoint functions $\lambda_1$, $\lambda_2$ and $\lambda_3$ satisfying the above adjoint equations. Moreover, the optimal control is given by

$$H^* = \frac{1}{2\nu} \left( p - \frac{c}{qY} - \lambda_2 \right).$$

Thus, we have established the existence of an optimal equilibrium solution that satisfies the necessary conditions of the maximum principle.

Marine Protected Areas (MPA) have already emerged as an essential tool for managing marine resources. Many of the benefits associated with MPAs have been widely investigated and the field is an active area of research in theoretical ecology (Flaat and Mjelhus [24], Sanchirico [25], Boncoeur et al. [13] and Sandal and Steinshamn [26]). However, scientists and researchers consider the increasing scope of closed areas for the conservation of marine biodiversity (Bohnert [27], Anderson [28], Sobel [29]). The use of MPAs is directed towards ecosystem functioning where ecosystems are easily disrupted by fishing efforts, so reserves may be a more appropriate option. MPAs also have the potential to provide a margin of safety and perhaps enhance the productivity of some fisheries. The objective of this study is to investigate the consequences of marine reserves towards conservation of marine resources and the economic optimality of implementing an MPA.

The reduced management costs are relatively an unexplored issue in fisheries economics, which can also be included among the benefits of the use of MPAs. The essential question in this context is whether or not the management costs in fisheries are likely to vary with different management regimes, and whether this should be a factor in determining optimal management costs. In order to achieve the conditions of optimal management strategies, we intend to define premium (Kvamsdal and Sandal [30]) of marine protected areas. It may be noted from the observations reported in the literature (Neubert [31]) that marine protected areas result in ecological improvements within the no-take area. Moreover, it is also clear that the fish population densities in reserves are, on average, much higher than that of populations in unprotected reference sites. Therefore, it is obvious that if there is no reserve initially the rent earned from the fishery should be greater than the rent earned from the fishery in presence of certain reserve size. Therefore, the expression of premium, can be considered as a function of the reserve area, is formulated as follows:

$$P(X, Y, Z, x) = V_0 - V(X, Y, Z, x),$$

where $P$ denote the premium of the marine protected area and $V_0$ is the net economic revenue earned from the fishery when there is no reserve.

4. Results based on numerical simulations

Although the numeric analysis deprives us the possibility of drawing conclusions on a general level, the analysis clearly indicates that multi-species interactions do matter when the implementation of a reserve is considered. Numeric analysis is used due to the complexity of the analytical solutions, where obtainable. Using numeric analysis instead of real world data, which of course would be of great interest, has the advantage that it is easy to isolate the effects of the multi-species interactions. With real world data the prices, costs and technological factors are likely to vary from fishery to fishery, and it would be harder to assign the causes for different results. It may also be noted that the simulations presented in this paper should be considered from a qualitative, rather than a quantitative point of view. However, numerous scenarios covering the breadth of the biological feasible parameter space were conducted and the results display the gamut of dynamical results collected from all the scenarios tested.

The numerical values of the parameters are assigned as follows:

$$r = 0.5, \quad K = 100, \quad q = 1.5, \quad \sigma = 0.25, \quad \gamma = 3.01, \quad s = 0.199, \quad m = 0.4, \quad n = 0.4, \quad a = 20, \quad b = 30, \quad p = 15, \quad c = 2, \quad \omega = 0.5, \quad \delta = 0.01.$$
It is to be noted that all the simulation results obtained in presence of predator population are compared with the results obtained in absence predator population. Fig. 1 depicts the impact of the relative size of the reserve on the premium of the marine protected area. Here the premium of the marine protected area is considered to be a function of the relative size of the reserve. It is clearly observed from the figure that the premium of the marine protected area increases with the relative increasing size of the reserve. Again, it is to be noted that the value of the premium is always less than the value of the reserve in the absence of the predator population. Therefore, if we want to protect the resource through creation of a reserve then the standardized net economic revenue of the fishery remains always lower than the value of the reserve. It is to be further noted that, in presence of the predator population, the value of the premium is kept approximately similar to the value of the reserve. Thus, it is evident from the figure that predation has great influence on the premium of the marine protected area. It is clear that, in the presence of predator population, the value of the premium of the marine protected area is kept always higher compare to the numerical value of the premium of the marine protected in the absence of the predator population with the increasing size of the reserve. It may be explained due to the fact that in the presence of predation and harvesting from the unprotected area the density of the resource decreases compare with the density of the resource in protected area. As a result, migration comes into the picture to tend to shift the resource density towards the same level in both patches, and consequently, the resource remains available in the unprotected area. Moreover, the rate of migration towards the density of the resource directly incorporate several effects on the stock of the resource but indirectly responsible for the effects on the market economics of the fishery.

The economic parameters namely, price per unit biomass of catch, fishing cost per unit effort and discount rate together determine the stock level, in turn maximizing the present value of the flow of resource rent over time. Therefore, characterization of the system for those parameters should be analyzed to determine the efficiency of the fishery in economic sense. Fig. 2 shows the effect of the relative size of the reserve on the premium of an MPA for different discount rates. The following three important results can be observed in this figure: (a) the premium is always positive and increasing with the relative size of the reserve; (b) increasing the discount rate reduces the premium and (c) the premium in the presence of predator population is kept approximately similar to the value of the reserve.

Fig. 1. Variation of the premium of the marine protected area with the increasing size of the reserve.

Fig. 2. Variation of the premium of the marine protected area with the increasing size of the reserve. The four components of the figure correspond to four different discount rates as: 1%, 10%, 20% and 50%.
absence of the predator is always less than the premium in the presence of predator. The first observation may be explained due to the fact that we optimize our returns in the unprotected area and it decreases as the relative size of the reserve increases. The second observation is a consequence of the fact that a higher rate of discount gives a higher profit. The driving force behind the last observation is the change in density levels of prey population due to the presence or absence of the predator population. Therefore, the changes in density of prey population influence the profit directly through the stock of the resource. Thus prey–predator
interactions do matter when the implementation of a reserve is considered.

Fig. 3 illustrates the impact of the relative size of the reserve area on the optimal equilibrium level of prey biomass, catch and value function of the fishery. It is observed that, as the reserve area increases, optimal prey biomass increases in the protected area but it decreases in the fishing area. This is the consequence of the fact that as the reserve size increases, harvesting decreases in the unprotected area. Therefore, the prey population may get some protection with the increasing size of the reserve. The same result is followed for the value function of the fishery, due to the fact that the optimal resource rent earned from the fishery is directly proportional to the harvesting. It is to be noted that, in the absence of the predator, the prey population reaches its peak level when the relative size of the reserve is unity. It is also to be noted that, in the absence of predation, the prey population, catch and the value function remains higher compared to the quantities in the presence of predation, which simply implies the strong effect of predation on the dynamics of the system.

The fundamental objective of the fishery management is to ensure conservation of fishery resources for our future generation and to provide a sustainable flow of economic benefits to the human society. In order to control the stock and harvesting intensity, it is necessary to derive some useful managerial tool that can be applied on fishery, which can avoid overexploitation. In case of fisheries management, the focus is mainly based on the nature of the fish production function, and how the fishing effort and capital interacts with the fish stock, but it is also necessary to understand the dynamics of the system. It is possible to identify the concept of maximum sustainable yield (MSY), when the rate of growth of the resource reaches its maximum. This concept is interesting because if we have an amount of growth equal to MSY, the stock of the resource will remain constant and will be able to reproduce the same amount of resource for the next period. So, levels of production or harvest equal to MSY allow users to take the maximum amount of resources from the stock without decreasing its capacity of reproduction over time. However, it is well known to us that the biological overfishing occurs when the stock biomass reaches the level of negative marginal growth (a point beyond MSY). To overcome this situation, we introduce a new concept, known as ‘effect on relative growth’ (ERG) (see Kvamsdal and Sandal [30]) to reach the potential production in both the patches. It is possible to measure the ERG as the ratio of the density dependent growth of the population to the growth of the population when the production or harvest is equal to MSY. Thus, the ERG of the protected area can be expressed as:

\[ \text{ERG}(x) = \frac{rx}{K} \left(1 - \frac{x}{K}\right) / \left(\frac{rK}{4}\right). \]

Here MSY = rK/4 for the logistic growth model.

In Fig. 4, we compare the effect on relative growth for both the patches with the increasing size of the reserve. It is clearly observed that the ERG of the protected area decreases with the increasing size of the reserve. This supports the theoretic perception, that with the increase in size of the reserve, production or harvest function decreases in the unprotected area. Consequently, the rate of migration increases from the protected area to unprotected area, and as a result the relative growth of the population in the protected area decreases. Similarly, increase of the relative growth of the population in the unprotected area can be explained as being due to heavy migration rate of the population with the increase in size of the reserve. The effects of predation on ERG of prey population for both the patches are also clearly observed in the figure and it is interesting to observe that the ERG changes considerably due to the prey–predator interactions.

Fig. 5 shows the variation of absolute migration of prey population from the reserve area to the open area with the increasing size.
of the reserve. The expression of the absolute migration has been described in Eq. (2). It is obvious that the rate of migration increases with the increase in size of the reserve. However, density of the stock inside reserve area decreases due to the movement of the population from the protected area to the non-protected area, which ultimately controls the harvesting efficiency and stock of the resource. It is evident that, in the presence of the predator population, the rate of migration is higher than the rate of migration in absence of predator population. Migration, in this context can be perceived as a part of the production system, changes due to changing densities and may eliminate the chance of extinction of the total stock.

Now, we are going to study two more biological measures. The first one is the relative increase in standing stock (ISS) from establishing an MPA. Hannesson [18] pointed out that the increase in stock is an increase in biological gain. When there is no upper limit on harvesting capacity, an increase in stock represents an increase in value of the fishery for any relevant stock level. The ERG is such a biological measure that can be considered to overcome the extinction of the population. It is obvious that the density of the population is entirely dependent on the size of the reserve and therefore, the relative increase in standing stock can be expressed as:

\[
\text{ISS}(x) = \frac{x(x) + y(x) - y(x = 0)}{y_0}.
\]

It is clearly observed from the Fig. 6 that the relative ISS is positive and increases with the increasing size of the reserve size. The positive slope indicates that for a certain value of reserve the sum of the standing stock in both the patches is more than the stock when there is no reserve. Therefore, it is evident that the standing stock of the fishery can be controlled using the creation of a suitable size of the reserve.

The variation of relative increase in standing stock compared to the premium of the marine protected area with the increasing size of the reserve is depicted in Fig. 7. The figure also depicts the influence of the predator population on the relative increase of the standing stock compared to the premium of the MPA. The figure shows that, in the presence of the predator population, initially relative ISS dominates the premium of the MPA but if we create about 60–70% of marine reserve then relative ISS is almost coincides with the premium of the MPA. However, with the further increase in reserve size, the premium of the MPA dominates the relative increase in standing stock. Moreover, in the absence of predator population, it is clearly observed that ISS always dominates the premium of the MPA. Therefore, it may be concluded that the prey– predator interactions do matter when the implementation of a reserve is considered to achieve the economic optimality of the fishery. It may also be pointed out that a marine reserve will be most effective if it is coupled with the conventional fishery management tools.

While the ISS measures how much the MPA strategy increases the standing stock, protected standing stock (PSS) (another biological measure) provides the share of the standing stock which is protected. Following Kvamsdal and Sandal [30], the PSS is expressed as follows:

\[
PSS(x) = \frac{x(x)}{x(x) + y(x)} - x.
\]

Fig. 8 illustrates that the protected standing stock (PSS) is positive and increases with the increasing size of the reserve. It is further noted that after a 40–50% size of the reserve area, the PSS decreases. This is due to the fact that the effects of marine reserve and its optimal size on PSS are varied with the level of fishing effort being exerted on the resource. It may be concluded that in fisheries where extremely high fishing effort levels being employed, marine reserves can protect the stock from extinction.

Fig. 9 shows the impact of the predator–prey interaction on biomass and catch with respect to the size of the reserve for a given fishing effort. By taking into account the prey– predator interaction,
it is evident from the figure that a loss in terms of harvesting of resource is incurred by the fishermen. It may further be noted that total exploitation (predation together with the catch by fishermen) decreases as the size of the reserve increases. It is clearly observed that the total predation term increases with the increasing size of the reserve. This is due to the availability of sufficient food to the
protected areas can shift the balance of stocks towards more optimal proportions, improving rent and also having distributional effects on the surrounding fisheries. To analyze the economic perspective of the fishery, we have designed the premium of the marine protected area as a function of the relative size of the reserve. Therefore, the outcomes of the paper will definitely assist the policy makers and interested parties to achieve the economic optimality through creation of a suitable reserve. Moreover, the biological measures can improve the discounted value of the fishery through optimal exploitation. It is therefore expected that the outcomes in the form of improved management tool will enhance the livelihood prospects and socioeconomic aspects of the fishery. In this regard, it may be concluded that the creation of reserve incorporate several positive effects on the stock of the resource as well as on the market economics of the fishery. Hence, marine protected areas can be used as an effective management tool to improve resource rent under a number of circumstances.

5. Conclusions

The present study deals with a prey–predator type fishery model with a reserve zone for prey species. Several consequences of reserve are analyzed and biological measures of the system are discussed through numerical simulations. The obtained results are not only important for the resource conservation but also very useful towards the economic perspective of the fishery. Our analysis clearly indicates that multispecies interactions do matter when the implementation of a reserve is considered. The premium is always less than the value of the reserve in absence of the predator population. It is also found that if we want to protect the resource through the creation of a reserve, then the standardized net economic value of the fishery always remains lower than the value of the reserve. However, in presence of the predator population, the value of the premium is kept approximately similar to the value of the reserve. The comparison of all the economic measures studied here strongly support that a reserve is a suitable method to protect a stock from overexploitation as well as when multispecies interactions are considered.

The basic aim of fishery management is to address the existing problems of overexploited and unregulated fisheries in order to preserve stocks and to increase the value generated from fish resources. Our simulations results indicate that marine protected areas can substantially reduce the risk of fisheries collapse. It is clearly observed that prey–predator interactions do matter when the implementation of a reserve is considered. It is also established that the biological measures such as increase in standing stock (ISS) and protected standing stock (PSS) are two essential tools towards effective fishery management. These biological measures incorporate the migration of the resource, from protected area to open area and vice versa, as an important factor towards the standing stock assessment in both the areas which ultimately control the harvesting efficiency and enhance the fishing stock to reach its extinct limit. It is found that the fraction of stock inside the reserve zone may save the stock from extinction. It is also shown that protected areas can shift the balance of stocks towards more optimal levels.

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