Commun Nonlinear Sci Numer Simulat 54 (2018) 34–49

Contents lists available at ScienceDirect

Commun Nonlinear Sci Numer Simulat

journal homepage: www.elsevier.com/locate/cnsns

Research paper

Impact of marine reserve on maximum sustainable yield in a traditional prey-predator system

Prosenjit Paul[a,*], T.K. Kar[a], Abhijit Ghorai[b]

[a] Department of Mathematics, Indian Institute of Engineering Science and Technology, Shibpur, Howrah 711103, West Bengal, India
[b] Department of Mathematics, Shibpur Sikshalaya, Howrah 711102, India

A R T I C L E I N F O

Article history:
Received 3 October 2016
Revised 25 April 2017
Accepted 18 May 2017
Available online 19 May 2017

Keywords:
Prey-predator
Exploitation
Maximum sustainable yield
Marine reserve area
Extinction

A B S T R A C T

Multispecies fisheries management requires managers to consider the impact of fishing activities on several species as fishing impacts both targeted and non-targeted species directly or indirectly in several ways. The intended goal of traditional fisheries management is to achieve maximum sustainable yield (MSY) from the targeted species, which on many occasions affect the targeted species as well as the entire ecosystem. Marine reserves are often acclaimed as the marine ecosystem management tool. Few attempts have been made to generalize the ecological effects of marine reserve on MSY policy. We examine here how MSY and population level in a prey-predator system are affected by the low, medium and high reserve size under different possible scenarios. Our simulation works shows that low reserve area, the value of MSY for prey exploitation is maximum when both prey and predator species have fast movement rate. For medium reserve size, our analysis revealed that the maximum value of MSY for prey exploitation is obtained when prey population has fast movement rate and predator population has slow movement rate. For high reserve area, the maximum value of MSY for prey's exploitation is very low compared to the maximum value of MSY for prey's exploitation in case of low and medium reserve. On the other hand, for low and medium reserve area, MSY for predator exploitation is maximum when both the species have fast movement rate.

1. Introduction

Nowadays, overexploitation has depleted many fish populations and invertebrate stocks, and many fish populations are in risk of extinction. Many researchers and fishery managers have recommended the establishment of marine reserves or marine protected areas (MPAs) to protect biodiversity and recover stocks. The techniques of fishery management have been proposed that marine protected areas to harvesting increases yield as well as conservation [1,2]. Due to considerable uncertainty, the use of management based on point estimates and optimal sustainable yields are general failures of many fisheries management practices, which have been widely discussed [3,4]. Therefore, a different and more protective approach is needed, which is suggested by earlier works. Hence, marine protected areas to fishing has been broadly proposed as a strategy to be caution against uncertainty and overexploitation [5].

To reach the goal of sustainable harvesting, a balance is needed between over and under exploitation of ecosystems. So, biologists have proposed a concept called maximum sustainable yield (MSY) which can be defined as the maximum

* Corresponding author.
E-mail addresses: prosenjit.paul58@gmail.com, Prosenjit.paul58@gmail.com (P. Paul), tkar1117@gmail.com (T.K. Kar), ssgabhijit@gmail.com (A. Ghorai).

http://dx.doi.org/10.1016/j.cnsns.2017.05.013
1007-5704/

catch from a fish stock [6,7]. Traditionally, maximum sustainable yield policy and marine protected areas have been used on models that have a single-species point of view [8]. Although these analysis of models are very useful in the perspective of sustainable use of fish populations, they are sometimes ineffective because they ignore other factors, such as spatial structure or species interactions [9]. In marine ecosystems, fishing can drastically change the trophic structure by direct removal of biomass and introduction of a strong bias in the exploiting species impacted [10].

Hastings and Botsford [5] examined that for reserves designed to enhance or conserve fisheries, one baseline level of yield is that achieved by conventional management approaches based on control of effort or catch. After that Botsford et al. [11] have shown that the effects of exploitation up to MSY level are also partly dependent on the migratory capacity of the species. Hence, an understanding of the effects of MPAs on target species requires models that consider multiple species and spatial structures also. Therefore, the effect of MPAs on MSY policy has been evaluated using models that differ in the models of competition, age structure, and larval dispersal. We focused on a general characterization of the impact of marine reserve areas design on MSY policy flexibility. Specifically, we check how stock mobility, proportion of areas closed, influence yield.

The classical theory of MSY for single species has been criticized heavily by Larkin [12] and Clark [3] for neglecting ecological interactions, age classes and economic factors in fishing. Despite such shortcomings, by the Johannesburg Implementation Plan [13], MSY has been legally adopted for world fisheries with intent to enable fisherman to catch a maximum that is sustainable and to preserve over fished stocks [14]. Legovic et al. [15] demonstrated that harvesting the prey species at MSY level will cause the extinction of predator species in traditional prey-predator system. After that Ghosh et al. [18] show that predator species may not go to extinction in the case of prey harvesting at the MSY level if predator possesses strong intraspecific competition in one prey-two predators system. Recently, Paul et al. [7] have studied a traditional prey-predator system, in which the prey species is targeted for commercial fishing while the predator species is not subject to fishing but is potential basis to implement the eco-tourism. They claimed that prey exploitation at MSY level may be sustainable policy under certain conditions.

There are important issues that remain to be addressed about the role of marine reserve areas in generating dynamic patterns of exploitation at MSY level and their impacts on abundance of species. The focal point of the analysis presented in this paper is not to calculate exact quantities corresponding to alterations in maximum sustainable yield either from prey or predator from the implementation of closed areas, but rather to know, in a universal sense.

In this paper we explore the potential effects of introducing marine reserve on MSY policy and species abundance in a prey-predator system. We study a prey-predator system in two different patches, one is allowed to fisherman for exploitation (on either species) and the other is reserved area. By using a deterministic model, we ignore any role of uncertainty or variability. The paper is organized as follows: In Section 2, we introduce the model. Section 3 exposes the dynamic of MSY policy from prey exploitation in the non-reserve areas. In Section 4, we illustrate and compare MSY from exploitation of predator under different strategies of species migration. Section 5 concludes.

2. Exploitation in traditional prey-predator model with marine reserve

We first consider a simple traditional prey-predator system incorporating independent harvesting effort on both the species as follows:

$$\frac{dx}{dt} = rx\left(1 - \frac{x}{K}\right) - \alpha xP - q_1 e_1 x \tag{1a}$$

$$\frac{dP}{dt} = \beta\alpha xP - mP - q_2 e_2 P. \tag{1b}$$

Here x and P are the population sizes of the prey and predator respectively. r is the per capita reproductive rate and K is the carrying capacity of prey species. For simplicity, we consider the type I functional response: the predator captures the prey at a rate proportional to prey abundance with rate coefficient α and β is the conversion coefficient due to predation. The last terms on the right hand side of Eqs. (1a) and (1b) represent the loss due to fishing. Here, the harvest is assumed to be proportional to the abundance of the target stocks (x or P), as commonly assumed in fishing resource management models. q_i and e_i represent the catchability coefficient and harvesting effort, respectively ($i = 1$ for prey and $i = 2$ for predator species) [16]. We consider the conversion coefficient $\beta < 1$. Introducing proportional harvesting to either of the species or both the species with independent harvesting efforts, we have the following results proposed by Ghosh and Kar [17] and Ghosh et al. [18]:

- In traditional prey-predator system (1a and 1b), fishing to reach the MSY of the prey population only will cause extinction of the predator population(see more explanations in Appendix A).
- In traditional prey-predator system (1a and 1b), fishing to reach the MSY of the predator population only is unlikely to cause extinction of lower trophic level species.

To model the effect of establishing marine reserve, we consider two areas: an open area where fishing is allowed and a closed area where fishing is not allowed [19,20]. These two areas are connected by the migration of the two species. We take the fractions of these areas as $1 - s$ and s, respectively, where $0 \le s \le 1$. If $s = 0$, there is no reserve, which relates to