Ecological Modelling 340 (2016) 106–115

Contents lists available at ScienceDirect

Ecological Modelling

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

Impacts of invasive species on the sustainable use of native exploited species

Prosenjit Paul *, T.K. Kar

Department of Mathematics, Indian Institute of Engineering Science and Technology, Shibpur, Howrah 711103, West Bengal, India

ARTICLE INFO

Article history:
Received 15 June 2016
Received in revised form 1 September 2016
Accepted 2 September 2016

Keywords:
Prey–predator
Harvesting
Cleaning effort
Maximum sustainable yield
Extinction

ABSTRACT

In recent years, the important challenging issues are biological invasions to biodiversity, overexploitation and extinction of several species. Invasive species often alter the workings of ecosystems around the globe. In the present research, our aim is to study the possible impacts of invasive species on the sustainable use of native exploited species. To address this issue, cleaning operation is introduced to protect biodiversity and recover stocks. It is found that presence of invasive species reduces the maximum sustainable yield (MSY) of native species. In case of prey–predator system, prey harvesting at MSY level causes the extinction of predator species, but extinction effort increases with the cleaning effort. It is also observed that when independent efforts are applied on both the prey and predator species, global maximum sustainable total yield (MSTY) exists and it increases as the cleaning effort increases. In all the cases it is found that appropriate cleaning effort may reduce the impacts of biological invasions on the sustainable use of resources.

1. Introduction

Invasions of ecosystems by alien species have been the focus of a growing field of research in applied biology and ecology. There is a evidence that invasive alien species have affected ecological systems around the world (MeGeoch et al., 2010). Globally, biological invaders drive habitat loss by displacing native species and negatively affect the quality of remaining habitat through competition, predation, herbivory, alteration of nutrient cycling, etc. The biological invasions management, which encompasses both prevention and control, is measured as a public good (Perrings, 2002) and thus may require public policies. Ongoing management of these invasive species, even in permanently protected ecosystems, is essential if native biodiversity is to be sustained. Thus, although species diversity may generally improve the stability and resilience of a marine ecological system, it may result in a lower equilibrium catch of targeted species. There are two major motives that drive the intrinsic value of biodiversity conservation. First, when a species goes to extinction, the social value associated with its possible future use is lost (Solow et al., 1993). Second, natural ecosystems are complex and species are interdependent, and so the loss of any one species could affect the entire ecosystem, and a small perturbation may lead to far-reaching changes with unexpected repercussions (Bezabih, 2007). It is therefore important that fishery scientists take an ecosystem-based approach to fishery management to meet the long-term management goals (Sanchirico et al., 2007).

Maximum sustainable yield (MSY) policy (Clark, 1990), maximum economic yield (MEY) policy (Flaaten, 2010), optimal taxation policy (Kar and Chaudhuri, 2003), creating marine reserve (Ghosh and Kar, 2013a; Bensenane et al., 2013) and in recent day ecosystem based fishery management policy (Matsuda and Abrams, 2013) are some fundamental tools to protect biological resources. In the Johannesburg Implementation Plan (IP, 2002), MSY policy 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 (FMA, 2008; ISEU, 2006). May et al. (1979) completed a remarkable work for global maximum sustainable yield with the application of independent efforts in krill and baleen whales system and concluded that global maximum sustainable total yield (MSTY) from both species will cause the extinction of the whales. Walters et al. (2005) show that the widespread application of MSY policy would in general cause severe deterioration in ecosystem structure, in particular the loss of top predator species. Smith et al. (2011) concluded that harvesting the small pelagic (i.e., prey) species at conventional maximum sustainable yield (MSY) level can have large impacts on other parts of the ecosystem. They suggested to half the exploitation rates to reduce higher impacts on marine

---

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

http://dx.doi.org/10.1016/j.ecolmodel.2016.09.002
0304-3800/

ecosystems and to achieve 80% of MSY. Legovic et al. (2010) established that harvesting the prey species at MSY level will cause the extinction of the predator species in traditional prey–predator system. Kar and Ghosh (2013b) show that predator species may not go to extinction in the case of prey harvesting at the MSY level if predator possesses strong intra-specific competition in traditional prey–predator system. Matsuda and Abrams (2013) showed that predator species will go to extinction if prey is harvested in a prey–predator model with weak intra-specific competition among the predator species and they suggested that the system could be managed by means of feedback control. Paul et al. (2016) proposed a model to study sustainable use of predator species through ecotourism. They have showed that predator species may not go to extinction at MSY level harvesting of prey species.

In the present research we find some potential disadvantages of introducing invasive species in the ecosystem and sustainable use of resources. We consider several features common to any ecosystem-based fishery management such as MSY, species extinction, biodiversity, fishing and non-fishing effort. We extend the work of Paul et al. (2015) by incorporating the carrying capacity of the prey (native) stock proportional to the unharmed areas of the ecosystem. Thus, we account for prey species (native) diversity in our models to determine the maximum sustainable yield at equilibrium and effects of invaded areas on it. Moreover, following recent developments in the literature (Kar and Ghosh, 2013b; Legovic et al., 2010), we relax the assumption of constant carrying capacity and assume that it depends indirectly on invaded areas of bay.

The paper is organized as follows. In Section 2 we consider the dynamics of a native species and invaded area and study the effects of invasive species on the maximum sustainable use of native species. Section 3 presents the dynamics of a prey–predator system where carrying capacity of prey population is directly proportional to the unharmed area. In Section 4 we study the effects of invasive species on the maximum sustainable yield from the prey species and possible impacts on predator species. In Section 5, we consider the dynamics of an exploited prey–predator system with independent harvesting efforts. Subsequently, we examine and compare the impact of invasive species on the maximum sustainable total yield (MSTY) with different cleaning strategies. Finally, in Section 6, we summarise our findings and discuss their implications for management.

2. Single species model with invaded area

One of the most basic harvest models is the Schaefer model (Schaefer, 1954), which can be described as:

$$\frac{dx}{dt} = rx\left(1 - \frac{x}{k}\right) - qex, \tag{1}$$

where
x is population abundance, r is the per capita growth rate, k is the carrying capacity of the environment and e is the harvesting effort. For this model, MSY is obtained as $rk/4$ and, when MSY is reached, population abundance is equal to $k/2$ at the effort level $e_{MSY} = r/2q$.

But our model corresponding to native stock differ fundamentally from Schaefer model in the carrying capacity. In marine ecosystem, invasive species come from harvesting of native species and anthropogenic dispersal and influence the carrying capacity of native species (Fresard and Ropars-Collet, 2014). The native stock is negatively affected by the spread of an invasive alien species. The invasion is the only environmental disturbance in the fishery. The invasion has been released by invasive species as a measure of diversity. To account for biodiversity, the dynamic equations of the native stock and invaded area are as follows:

$$\begin{aligned} \frac{dx}{dt} &= rx\left(1 - \frac{x}{(1-s)k}\right) - qex, \\ \frac{ds}{dt} &= (A + ge)s(1 - s) - QFs. \end{aligned} \tag{2}$$

Here we use two state variables: the native stock biomass x and the invaded share of the whole area of the bay s. All these variables are subject to a non-negativity constraint and $0 \le s < 1$. In the model of native species underlying our analysis, the carrying capacity of native species experience loss at a rate sk.

We avoid the value of invaded areas as unit area ($s = 1$) which implies the carrying capacity $(1 - s)k$ reduces to 0. Here r is the biotic potential and k is the carrying capacity of the native population in the absence of invaded area. Harvest is proportional to the product of the amount of effort e and the native population biomass x with a constant of proportionality q. The natural and anthropogenic dispersal coefficients are taken as A and g, respectively. Q represents the productivity of cleaning operations which means the ratio between the number of square units area cleaned per unit of effort F and the whole invaded areas. The only equilibrium point in which both native population level and invaded area may be positive is $P(x^*, s^*)$ where

$$x^* = k\frac{FQ}{A + eg}\left(1 - \frac{qe}{r}\right), \quad s^* = 1 - \frac{FQ}{A + eg}.$$

The conditions for the existence of the equilibrium point $P(x^*, s^*)$ with $x^* > 0$ and $s^* > 0$ are $e < \frac{r}{q}$ and $F < \frac{Aq+rg}{qQ}$. It is found that the equilibrium is stable if it exists. Details are given in Appendix A. The corresponding yield at equilibrium $Y(e)$ is given by: $Y(e) = qex^* = qek\frac{FQ}{A+eg}\left(1 - \frac{qe}{r}\right)$. Now $\frac{dY(e)}{de} = 0$ gives $e = \frac{\sqrt{A^2q^2+Agqr}-Aq}{gq}$ and for this value of e, $\frac{d^2Y}{de^2} < 0$. Therefore, $e_{MSY} = \frac{\sqrt{(A^2q^2+Agqr)}-Aq}{gq}$ and $MSY = Y(e_{MSY}) = \frac{FkqQ\left(\sqrt{Aq(Aq+gr)}-Aq\right)\left(Aq+gr-\sqrt{Aq(Aq+gr)}\right)}{g^2r\sqrt{Aq(Aq+gr)}}$. It is observed that MSY increases with the cleaning effort F of the invaded area and its maximum value is obtained for $F = \frac{A+e_{MSY}g}{Q}$ at which $s^* = 0$. At this level of F, MSY is same as we obtained from the single species.

One of the possible objectives of fisheries management is maximizing sustainable yield in order to secure enough protein for people. Yield function at equilibrium of the exploited system (2) is given by $Y(e) = k(1 - s^*)qe(1 - \frac{qe}{r})$, and it is a decreasing function of steady state invaded area s^*. At interior equilibrium from (2) the invaded space is given by $s^* = \frac{A+eg-FQ}{A+eg}$, which is minimized i.e., $s^* = 0$ at $F_{\min} = \frac{A+eg}{Q}$. Therefore, we have $e_{MSY} \to \frac{r}{2q}$ and $MSY \to \frac{rk}{4}$. We now illustrate our results numerically. For the purpose of simulations we take the ecological parameters as $r = 1$, $k = 50$, $q = 0.1$, $A = 0.2, g = 0.01, Q = 0.2$ in appropriate units. It is observed that native stock $x_* = 22.47F$, $s_* = 1 - 0.82F$ and $MSY = 10.10F$ at $e_{MSY} = 4.5$.

Therefore, both x_* and MSY are increasing functions of cleaning effort F but invaded area s_* is a decreasing function(Figs. 1 and 2a). However, when the value of cleaning effort F approaches 1.22, the interior equilibrium point (x_*, s_*) is shifted to boundary equilibrium point (27.53, 0). At this situation the $MSY = 10.10F$ has maximum value 12.37. From Fig. 3 we see that the invaded area increases with fishing efforts but invaded area remains low, medium and high if cleaning efforts F have high (1.0), medium (0.5), low (0.1) value, respectively.

For a fixed cleaning effort, the invaded area increases with harvesting effort. Figure also shows that invaded area gradually decreases as cleaning effort F increases.