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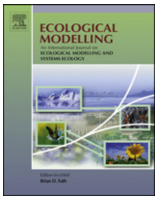

Impacts of maximum sustainable yield policy to prey–predator systems

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ABSTRACT

This article investigates the effects of reaching the maximum sustainable yield (*MSY*) in prey–predator systems where the prey population follows logistic law of growth. Two different models are proposed: (i) first model involves linear prey–predator interaction and intraspecific competition among predator populations, and (ii) the second one is a ratio-dependent prey–predator system. In the first model, our results suggest that the introduction of intraspecific competition among predator population has important consequences for the fishing to reach MSY from prey species and maximum sustainable total yield (MSTY) for combined harvesting of both prey and predator species. On the otherhand, in the second model, our results suggest that though the harvesting of prey species at MSY level shall be guaranteed the coexistence of both the species, but the combined harvesting of both the species at MSTY level may cause extinction of the predator species. However, for both the models, predator harvesting at MSY level may be a sustainable fishing policy. Therefore, based on our results we can conclude that MSY (or MSTY) policy in prey–predator systems in nature are not likely to fit requirements of Conservation of Biological Diversity (CBD, 1992) in all cases.

1. Introduction

The exploitation of biological resources and harvesting of population are commonly practiced in fisheries, forestry, and wildlife management. In particular, the management of a fishery is a decision with multiple objectives. Some of the desirable objectives are the provision of the good bio-mass yield, the conservation of fish population, the provision of good economic returns and the provision of recreation. The formulation of good harvesting policies which take into account these objectives is a complex and difficult task. Maximum sustainable yield (MSY) is a simple way to manage resources taking into consideration that over-exploited resources lead to a loss in productivity. But, we have seen that the traditional MSY approach to fishery management relies on single species model of population dynamics and ignores species interactions with other member of the communities. Single species assessments and management controls may produce misleading prediction and pathological changes in the ecosystems. Even simple food-chain models predict stronger compensatory responses for any species when interactions with the rest of the system are accounted for, owing to the negative impact of harvesting on its predators, and the positive impacts on its food organisms.

We have come through a long way from targeting MSY using equilibrium population level. Schaefer (1954) was first to introduce *MSY* policy for a single species fishery having logistic law of growth and subject to proportional harvesting. Clark (1990) also discussed the importance of the concept of MSY policy for fishery management. Recently, Kar and Matsuda (2007) investigated the MSY policy for single species fishery with strong Allee effect. Legovic (2008) mentioned the effects of harvesting of MSY policy in a single species fishery. Walters et al. (2005) show that the widespread application of single species model MSY policy would in general cause severe deterioration in ecosystem structure, in particular the loss of top predator species. All the above results suggest that MSY exists for a single isolated population living in nature but there are significant dangers of adopting single-species management approaches that may be myopic. Therefore, can we really get away with considering exploitation of one species at a time, and ignoring interactions among species? This is the subject of our study in this paper.

Individual species do not live in isolation, which means that the population dynamics of different species are inevitably linked. Therefore, it is not at all obvious whether we should expect higher or lower yields from an entire ecosystem than would be predicted from application of single species harvest control policy. Recently, Matsuda and Abrams (2006) examined various food web models, such as two-prey one predator system, three species with three trophic levels, six species systems with multiple trophic levels and asserted that independent harvest of species within the web can cause extinction, but that this is less likely to happen. In their work

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(2010b), Legovic and Gecek investigated a community of independent and logistically growing populations under a common harvesting effort which leads to the maximum sustainable total yield (MSTY). Their results suggest that in the case of two independent populations with approximately equal carrying capacities, both the populations persist at its *MSTY* level. Their results also suggest that the MSTY with a common harvesting effort implies suboptimal fishing of some population, overfishing of others and extinction of the rest of the populations. Legovic et al. (2010a) show that approaching MSY in ecosystem means that most likely fish species will be driven to extinction in every fishery that includes exploitation of at least one trophic level which is directly or indirectly used as food for a higher trophic level. In addition, Legovic and Gecek (2012) studied the impact of *MSY* policy in mutualistic communities and interestingly noticed that harvesting of all species to the *MSTY* level will induce extinction of the species with lower biotic potentials and carrying capacities.

In this paper, we have studied the impacts of MSY policy on two different prey–predator systems under different harvesting scenarios. Section 2 provides the general understanding about *MSY* policy and revision of the outcomes due to Legovic et al. (2010a). In Section 3, we introduce an intraspecific competition term to the predator equation and study the impacts of MSY policy when either prey or predator species is harvested or MSTY policy when the combined harvesting effort of both prey and predator species are taken into account. In Section 4, we study the impacts of MSY (and MSTY) policy in a ratio dependent prey–predator system. Section 5 provides some concluding remarks of our investigated models.

2. Effect of *MSY* policy in a simple prey–predator system

We first consider a single species population model followed by proportional harvesting as follows:

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

where x is the population size at any time t, r is the intrinsic growth rate, k is the environmental carrying capacity of the population and e is the harvesting effort. A basic assumption of most of the models is to determine a catch level rate for which a stock can be sustained indefinitely based upon the average productivity of the stock. Therefore, largest average catch that can be employed on a sustainable basis from a stock under existing environmental conditions has become the main goal to manage exploited populations. The maximum sustainable yield (MSY) is based on equilibrium biomass of the species and yield. For a single species model as given in Eq. (1), $MSY = rk/4$ and it is occurred at effort level $e = r/2$. In fact, even for this single species fishery, fishing at the MSY level does not ensure constant catches in the future, because of the substantial variability in reproductive success and recruitment. In good years, fishers may prosper with MSY based catches, but in years when the environment is less favorable and recruitment and productivity decline, the stock will diminish and MSY may quickly lead overfishing.

Most management measures are directed at individual stock of a single species and these do not take into account species interactions, such as predator-prey relationship. To study the consequences of MSY policy in multispecies system, Legovic et al. (2010a) considered the following prey–predator system:

$$\begin{aligned} \frac{dx}{dt} &= rx\left(1-\frac{x}{k}\right) - axy \\ \frac{dy}{dt} &= axy - my, \end{aligned} \tag{2}$$

where x and y are respectively the prey and predator biomass at any time t. r is a constant intrinsic growth rate (biotic potential) and k is the environmental carrying capacity of prey population, a is the predation rate, m is the natural mortality rate of the predator. The prey–predator model (2) is simple in the sense that predator consumes prey population according to *Holling type I* functional response and the intraspecific competition of the predator is not taken into account. Introducing proportional harvesting to either prey or predator or both the populations with *combined fishing effort* we have the following results proposed by Legovic et al. (2010a) as:

In any prey–predator system, fishing to reach MSY of the prey population only will cause extinction of the predator population.

In any prey–predator system, fishing to reach MSY of the predator population only, is unlikely to causes extinction of either prey or predator species.

In any prey–predator system subject to equal fishing effort on both prey and predator populations, the ultimate MSTY will be the MSTY of a single species population composed of prey only, which means that the predator population has gone to extinction.

3. Impacts of *MSY* policy under intraspecific competition

Legovic et al. (2010a) extends our knowledge on effects of MSY policy in prey–predator models, however, they have considered predation as the only interaction in their prey–predator systems. But there are various other factors that may be taken into account when modeling of such a system. One such key and somewhat novel feature is the intraspecific competition in the predator growth dynamics (Kuang et al., 2003; Ruan et al., 2007). This intraspecific competition is assumed to induce additional instantaneous deaths to the predator population and the increased death rate is proportional to the square of the predator density. To completely eliminate density-independent mortality is as biologically unrealistic as eliminating density-dependent mortality (Caswell and Neubert, 1998). Recently, Hixon and Jones (2005) also found this density-dependent mortality in demersal marine fishes, which is often caused by the interplay of predation and competition. As this intraspecific competition enhances the mortality rate of the species, it is expected that the MSY policy will be significantly differ from the MSY policy in a traditional prey–predator system, and hence, in this section, we proceed to study the MSY policy in a prey–predator system having intraspecific competition in the predator growth dynamics when either prey or predator or both the prey and predator populations are subject to harvest.

Therefore, our modified model becomes

$$\begin{aligned} \frac{dx}{dt} &= rx\left(1-\frac{x}{k}\right) - axy \\ \frac{dy}{dt} &= axy - my - \gamma y^2, \end{aligned} \tag{3}$$

where γ is the coefficient of intraspecific competition.

Coexistence equilibrium of the system (3) is $P(x^*, y^*)$, where

$$x^* = k\left(\frac{am+\gamma r}{a^2k+\gamma r}\right)$$

and

$$y^* = \left(\frac{r(ak-m)}{a^2k+\gamma r}\right),$$

provided $ak > m$. Since the environment cannot support a population size above its carrying capacity, therefore $x^* < k$ would be ecologically meaningful prey abundance.

We now examine whether *MSY* or *MSTY* policy can be implemented in our prey–predator system for a possible sustainable fishing activity. Various scenarios associated with *MSY* and *MSTY* are observed successively.