

Managed extinctions in fisheries

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Abstract

Common focus of interest in fisheries management is the target species. However, most species belong to an ecological community, and the management of one species is very likely to affect also the other species in the community. In this study, we focus on community level responses to fisheries management.

Loss of a single species from the community may be followed by extinction of other community members. It may also result in cascading extinctions. Such cascades not only occur following extinction events, but also as the result of significant reductions in population size. Thus, the number of species in a community can be reduced when one species is subject to harvesting.

We used a Ricker-type population model with Lotka-Volterra competitive interactions to create viable competitive communities, and harvested a selected target species. Furthermore, instead of harvesting, we enhanced the population size of the least abundant species by stocking.

After altering the population size of the target species, we observed single species extinctions and harvesting and stocking cascades. In addition, we studied the effect of space: harvesting or stocking was done either in all patches or in one of the patches in the environment. These results have implications for population management both in terms of harvesting and conservation biology.

Introduction

The total yield of biomass in marine fisheries is around 90 million tonnes per year, more than 80% of global fish production [1]. Witnessing the current worldwide decline of marine resources [2, 3] fisheries management is concerned with controlling the unwanted effects of harvesting – collapse of the resources, economic inefficiency, increasing unemployment, habitat loss or decrease in the abundance of rare species.

Stocking, the artificial enhancement of population size of a target species, is also a common management practice, especially in freshwaters. Stocking was first considered in fresh waters in the middle of the 19th century with marine species coming into focus somewhat later [4]. Nowadays most countries and >300 species are involved with such practices [5]. As such, the management of a target species is often successful, but not always. For example, the salmon populations in the Baltic, as well as the related fishing activity, have long been maintained by stocking [6].

Individual species do not live in isolation. They may feed on each other or compete for resources such as food and space. Thus, population dynamics of different species may often be linked. A community approach is often applied when studying biodiversity [7, 8]. Biodiversity is largely determined by the number of species in the community, the variability and stability of the population dynamics of each species and the overall biomass in the community as well as by the extinction and invasion dynamics.

It is often argued that if one or more of the species in a community become rare or extinct then other more or less similar species may take over the ecological niche of the extinct species. When viewing this problem in a community setting it soon becomes clear, that in a community the system becomes unexpectedly complicated due to the indirect interaction between the species [9, 10]. Removal of a species from a community may not only allow similar species more space for existence, but also may take other similar and even very different species along to extinction. The stability of a community may not only depend on the pair wise competitive relations between species but also on more complicated indirect interactions.

It is known that removing a species from the community can result in loss of other community members [11, 12, 13]. In particular, Lundberg et al. [13] analysed a problem that they referred to as community closure. Here, a stable community was composed, and then one of the species was removed from the community. Lundberg et al. [13] were able to show that extinction cascades often followed the removal of a single species, that is, more species became extinct than just the one removed. Furthermore, after such an extinction cascade, it may often be impossible for the removed species to invade back into the community. Lundberg et al. [13] did not consider the effects of harvesting or stocking.

In this study, we analyse the community consequences of harvesting and stocking. We concentrate on possible extinction cascades only. We studied communities of different sizes subject to local or global management actions. After subjecting one species to harvesting or stocking in a single patch or in all patches, we followed the fate of the community and recorded the volume of the single species extinctions and extinction cascades.

Material and methods

We simulate the dynamics of spatially distributed competitive communities with a Ricker-type growth equation [14]. The competition between the species is

described as Lotka-Volterra interactions of k species on p patches. The community dynamics become

$$\tilde{N}_{t,i,p} = N_{t,i,p} \exp\left(r\left(1 - \sum_{j=1}^k \alpha_{i,j} N_{t,j,p}\right)\right), \quad (1)$$

where $N_{t,i,p}, \tilde{N}_{t,i,p}$ are the population sizes of species i in patch p at time t prior to and following reproduction. Parameter r is the intrinsic growth rate of the species. A fixed fraction m of the population leaves the natal patch. After dispersal the population sizes are given as

$$N_{t+1,i,p} = (1-m)\tilde{N}_{t,i,p} + \sum_{q=1, q \neq p}^s M_{p,q,t} \quad (2)$$

The number of migrants, leaving patch q and ending up in patch p , follows the equation defined by the exponential dispersal kernel

$$M_{p,q,t} = m\tilde{N}_{t,i,q} \frac{\exp(-cd_{p,q})}{\sum_{j,j \neq q} \exp(-cd_{q,j})} \quad (3)$$

The constant m describes the proportion of emigrants leaving each patch and c is a parameter describing the characteristic distance emigrated. The parameter $d_{p,q}$ denotes the distance between patches p and q . The number of patches, five, remained constant throughout the analyses. Community size was taken to be four, six, or eight species.

In our model, the only factor in which the species in the communities differed was their competitive ability. Competition occurs for a common, implicit resource, and the strength of intraspecific competition always exceeds the interspecific competition, that is, the competition between conspecifics is stronger than the competition between different species. The interaction strengths, α -values, were produced by randomly assigning values with limits $[0,1]$ from a uniform random distribution for each between-species interaction. The random assignment of interaction terms also means that interactions were asymmetric, so that a certain species pair did not necessarily have a similar impact on each other. Positive interaction parameters rule out mutualistic interactions.

After assigning the random values for interaction strengths, the community was left to stabilise for 1000 generations. If all the species remained present after this initial transient phase, we commenced either harvesting or stocking. If the desired community size was not fulfilled, the assembly process was until a stable community had formed.

In both harvesting and stocking we used two strategies: either harvesting / stocking on one patch (local) or over all five patches (global). Thus, in the presence of harvesting or stocking, equation (2) will be replaced by

$$N_{t+1,i,p} = \left[(1-m)\tilde{N}_{t,i,p} + \sum_{q=1, q \neq p}^s M_{p,q,t} \right] (1 \pm h_{t,i,p}), \quad (4)$$

where the harvest or stocking is defined as a fraction of the harvestable stock size, given in the brackets. In harvesting, the target was set as the most abundant species, whereas in stocking the population size of the least abundant species was enhanced. When a species was harvested or stocked in all patches the implementation of the action was equal everywhere. When a species was harvested or stocked only in one patch, this patch was selected randomly.

When harvesting we used a fluctuating, positively autocorrelated time series where 5-15% (mean 10%) of individuals were removed every generation (mimicking 'natural' harvesting time series, [15]). In stocking, we used a similar procedure: stocking time series was also fluctuating, positively autocorrelated with 0-5% (mean 2.5%) enhancement in population size every generation. The management period for both harvesting and stocking lasted 1000 generations.

The variable $h_{t,i,p}$ is assumed to be positively autocorrelated and is derived using the following iterative first-order autoregressive process [16, 17]

$$h_{t,i,p} = \kappa h_{t-1,i,p} + w \varepsilon_t \quad (5)$$

where $h_{t,i,p}$ is the stochastic management action, κ is autocorrelation coefficient and ε is normally distributed white noise. If $\kappa > 0$ the series is positively autocorrelated. Here we assume that $\kappa = 0.8$. Parameter $w = s\sqrt{1 - \kappa^2}$ determines the amplitude of the process in such a way that its variance is independent of the values of κ .

In both harvesting and stocking we repeated the above procedure for 100 times in order to calculate frequencies for the number of replicates where extinctions occurred and also the number of species that went extinct. In this study we are interested in global extinctions only.

Results

In all communities of different sizes extinctions occurred as a result of management actions (Fig. 1). Harvesting caused extinctions more often than stocking, and communities including more species experienced extinction events more often than the communities with fewer species did. Interestingly enough, management actions implemented locally (in only one of the five patches) also caused global extinctions (Fig. 1). However, the occurrence of extinctions was less common when the management actions were limited to only a single patch.

As described above, extinction cascades are extinctions that result from extinction(s) of other species in a community [13]. In our study, the number of extinction cascades (Table 1) followed the same lines as the overall number of extinctions (Fig. 1). Both harvesting and stocking caused extinction cascades, but harvesting more often than stocking. In addition, management actions in all patches show clearly a stronger impact on the process of extinction cascades compared to management actions limited to a single patch. Note that the extinction numbers shown in Table 1 do not contain the number of single species extinctions, which often might take place especially when the population is harvested.

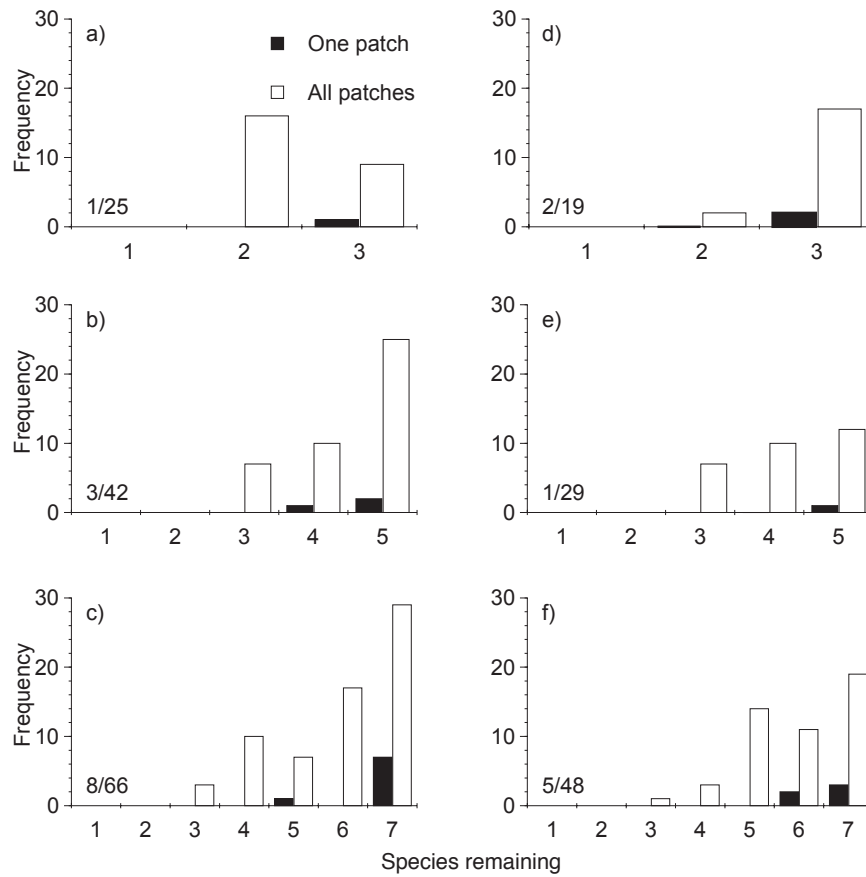


Figure 1: Remaining community size after management induced extinction events in 100 replicate runs. In subplots a-c extinctions caused by harvesting, d-e extinctions caused by stocking. Numbers indicate the frequency of extinction events when management procedures were carried out in one patch / all the patches, respectively. Note that only replicates where extinctions occurred are included.

Table 1. Percentage of extinction cascades in different management scenarios and differently sized communities.

Initial Community size	Harvesting		Stocking	
	One patch	All patches	One patch	All patches
4	0	16	0	2
6	1	17	0	17
8	1	37	2	29

Discussion

In this study, we analysed the effect of harvesting or stocking of a single species on community structure. We found that both harvesting and stocking may change the competitive interactions in the community such that an initially stable composition becomes unstable, followed by the extinction of a single species or several of them. We also observed that the risk of extinction of a single species and cascading extinctions increases with increasing community size, e.g. increasing number of interacting species. This is likely to be due to more severe competition, but the ultimate mechanisms of this phenomenon are not fully understood.

When analysing the problem of community closure, Lundberg et al. [13] showed that removing a single species may or may not cause a series of extinctions of other species. In the present study, when the management action was restricted to one patch only, the corresponding probability of a cascade is considerably lower. However, when the management actions are extended to apply across all patches then the probability of cascading extinctions increases considerably (Table 1). An important conclusion from the comparison of the present results to those of Lundberg et al. [13] is that cascading extinctions may also be brought about by subtle changes in population levels, instead of completely removing single species from the community.

The fact that only altering the population size of a single species in a community can lead to extinctions of other species provides new challenges and perspectives to fisheries management and conservation. In some cases, the community approach may be needed to understand the dynamics of a resource stock when subject to harvesting or stocking. Our study also underscores the importance of considering the spatial structure of species in a community and the spatial aspects when implementing management actions.

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