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SCIENCE DIRECT
Marine Policy 29 (2005) 471–479
MARINE POLICY
www.elsevier.com/locate/marpol

Uncertainty and the active adaptive management of marine reserves

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Received 15 April 2004; received in revised form 16 July 2004; accepted 31 July 2004

Abstract

Unpredictable environmental fluctuations are a major problem in fisheries. To mitigate these uncertainties, reserves are advocated to help ensure population persistence, reduce population and harvest variance, provide a 'hedge' against management failures and increase resilience. Using recent insights from the modelling of marine reserves, we propose a six-step process for establishing and adaptively managing reserves for fishery purposes.

Keywords: Marine reserves; Uncertainty; Adaptive management

> Most principles of decision-making under uncertainty are common-sense … consider a variety of possible strategies; favor actions that are robust to uncertainties; hedge; favor actions that are informative; probe and experiment; monitor results; update assessments and modify policy accordingly; and favor actions that are reversible [1].

1. Introduction

Uncertainty conveys our limited ability to both model and predict the state of nature. In fisheries, arguably the greatest uncertainty is in the form of temporal variations in populations, sub-populations and cohorts of species. Uncertainty also includes spatial variations in fisheries and the effects of interactions across trophic levels [2] such that shocks in one location, or on one species, can have consequences for entire ecosystems and can cascade across many different places and populations.

In the past decade, scientists and managers have argued for the greater use of marine reserves to help address uncertainty and ensure the sustainability of fisheries (e.g. [3,4]). By creating 'no-take' areas, populations of exploited species can increase due to reduced fishing mortality and then act as a source to harvesting areas. Empirical evidence shows that reserves, within their boundaries, can increase the spawning biomass and mean size of exploited populations [5], population abundance [6] and population density, biomass, fish size, and diversity [7]. Increased abundance within reserves may also lead to positive spillovers in harvested areas as fish migrate from reserves to adjacent locations [8,9]. Reserves may also result in a more desirable population structure (characterised by age, gender or individual size) that may improve breeding success and raise mean recruitment into the harvested population [10,11].

Despite the potential benefits of reserves, the establishment of no-take areas does not guarantee a positive payoff to fishers. Moreover, despite many empirical studies on reserves only a few of these investigations

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doi:10.1016/j.marpol.2004.07.006

include before and after data and spatial variation [12]. Well-designed empirical studies are necessary to separate the 'reserve effect' from the 'habitat effect' [13] and to determine the efficacy, or otherwise, of marine reserves. Equally as important, uncertainties in terms of the 'connectivity' between reserves and no-take areas at the larval, juvenile and adult stages [14], and also critical habitat size [15], renders the problem of determining the size and location of reserves a very difficult task [16]. Moreover, fishing spillovers from reserves very much depend on their design and must consider advection, as well as diffusion processes, and an appreciation of both dispersal distance and the number of population sources [17,18].

In this paper, we focus on the potential benefits of marine reserves in mitigating environmental uncertainty and the policy implications for the design and establishment of reserves. First, we present key results from the modelling literature on marine reserves with uncertainty that suggest appropriately designed reserves can potentially generate a 'win-win' in terms of both ecological and economic benefits. Second, we propose a six-step decision and active adaptive management process to help manage the uncertainties in determining the size, location, number, and duration of reserves. Third, we use recent modelling results to provide fishery management insights about the establishment of marine reserves. Our conclusions emphasise the importance of stakeholder participation and adaptive processes in the design of marine reserves for fishery purposes.

2. Marine reserves with uncertainty

Models of marine reserves may be divided into deterministic approaches that assume no external or environmentally induced variation, and those that include environmental uncertainty and stochastic processes. Deterministic models have shown that reserves can generate benefits if stocks over overexploited and harvesting is suboptimal, but find that if harvest or fishing effort can be set optimally, reserves provide no, and may even reduce, the economic payoff to fishers [19–21]. Even in the case of 'nonlinear' ecosystems, but with no environmental uncertainty, reserves can increase yields but nevertheless represent a second-best strategy to optimal effort controls [22].

The finding that reserves are superfluous if harvest or fishing effort is optimal, however, is not necessarily true in models that include environmental uncertainty such that stocks are subject to negative and stochastic shocks. For instance, the larger is a population and the less negative shocks are propagated over spatially heterogeneous sub populations, the less likely is a given population to become extinct from environmental or demographic fluctuations [23]. [24,25] were the first to model these ideas in relation to marine reserves. Their work shows that the less control managers have over setting a desired harvest rate, or the greater the level of ignorance about the actual exploitation rate, the more valuable is a reserve in its ability to ensure population persistence. This is important in terms of marine reserves because total and complete control through traditional forms of fisheries regulations, such as input and output regulations, is impossible [26]. Moreover, fishery managers often find it difficult to keep to desired exploitation rates because of lack of information on stocks sizes [27] or because of political pressure against large reductions in catches [28].

Doyen and Béné [29] specifically address the issue of uncertainty in setting output controls and examine the relationship between uncertainty, defined as the difference between the actual and targeted harvest rate, and marine reserves. They show that reserves can simultaneously increase population persistence and raise the 'guaranteed' harvest with uncertainty. In particular, they derive a critical minimum threshold level of uncertainty above which a reserve is necessary to ensure the fishery remains above its minimum viable level. They also find that the higher the target harvest rate, the lower is the uncertainty threshold. Their result supports an earlier derivation by Mangel [30] of a 'no-take invariant' with an uncertain harvest rate, where the higher is the maximum harvest level, the larger the reserve size required to ensure a sustained harvest.

Another important result from the modelling of marine reserves is their ability to reduce the variance of the population and the harvest if they are subject to negative shocks. Conrad [31] finds that harvesting increases the variance of exploited populations relative to the populations in reserves, and also shows that the smaller a reserve, the less its ability to reduce the population variance. Similar conclusions have been derived by others using different models. For instance, Sladek-Nowlis and Roberts [32], and also Mangel [33], find that reserves can reduce the variance in the harvest while Hannesson [34] obtains this result where random environmental effects are modelled by a Wiener process in the population growth equation. The implication is that if fishers are concerned about the variance of their net returns and the state of the environment is uncertain, then the use of reserves can reduce income variation—a desirable feature not shared by effort or output controls for the same average level of harvest.

One of the most recent papers [35] on reserves provides another important modelling insight as to the extra payoff of a reserve to fishers, even if harvesting is optimal. In their model, they incorporate two forms of uncertainty: *environmental stochasticity* through a Wiener process that can be both positive and negative, and *negative shocks* through a Poisson process with a given probability. In a spatially implicit model, they use a