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Addressing ecosystem effects of fishing using marine protected areas

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This article is a synthesis of the current literature on the potential of marine protected areas (MPAs) a useful management tool for limiting the ecosystem effects of fishing, including biological and socio-economic aspects. There is sufficient evidence that fishing may negatively affect ecosystems. Modelling and case studies show that the establishment of MPAs, especially for overexploited populations, can mitigate ecosystem effects of fishing. Although quantitative ecosystem modelling techniques incorporating MPAs are in their infancy, their role in exploring scenarios is considered crucial. Success in implementing MPAs will depend on how well the biological concerns and the socio-economic needs of the fishing community can be reconciled.

Cet article fait la synthèse de la littérature sur la possibilité d'utiliser les zones marines protégées (MPAs) comme outils de gestion afin de limiter les effets de la pêche sur les écosystèmes, en incluant les aspects biologiques et socio-économiques. La littérature fournit suffisamment d'évidences à l'effet que la pêche peut avoir un effet négatif. Les MPAs établies dans divers habitats à travers le monde ainsi que les modélisations montrent que MPAs offrent une certaine protection contre ces effets négatifs. Les techniques quantitatives de modélisation des écosystèmes, bien que cruciales pour l'exploration de scénarios de gestion, n'en sont encore qu'à leurs débuts et mériteraient encore plus d'attention. Finalement, le succès des MPAs dépendra de la manière dont on réussira à allier les aspects biologiques et les intérêts socio-économiques.

Key words: ecosystem effects of fishing, marine reserves, marine protected areas, community involvement, socio-economic.

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Introduction

Traditional living resource management includes the setting aside of areas from exploitation in both terrestrial and marine systems. These areas ensure the continuity of stocks for future generations and these practices are still being employed in developing countries throughout the world. The notion of setting aside protected natural areas solely for their scenic, natural, or scientific values, however, is a relatively recent trend (MacEwen and MacEwen, 1982). The first recorded attempts to establish marine protected areas (MPAs) were early in the 20th century, in the Great Barrier Reef (Morning Post, 1906). Fishers rejected the proposal then, and it was not until 1935 that the first MPA was declared at Fort Jefferson National Monument, Florida (Randall, 1968). The legislation used to protect this area of the Dry Tortugas, however, was primarily designed for terrestrial systems. In the post-war era, more parks with significant marine areas were established (Bjorklund, 1974), but many areas were also based on terrestrial legislation. Even today, few MPAs are declared using specific legislation (Alder, 1996).

Although there are signs of overexploitation in most of the world's fisheries (Ludwig, 1993; Safina, 1995), we still have to formally address the effects of fishing on entire ecosystems. The dependence on accurate estimates of single-species stocks, as well as on efficient control

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of effort and catch, raises serious concerns about the efficacy of current fisheries management strategies in ensuring sustainable fisheries. In addition, reducing effective fishing effort is almost impossible to achieve in the face of gear efficiency through technological improvements (Pitcher, in press). Focusing on only one stock at a time, we fail to realize the significance of serial depletion of individual stocks and fishing grounds, as illustrated by fisheries in all parts of the world (Pauly, 1988; Dugan and Davis, 1993; Orensanz *et al*., 1998). In fact, many world fisheries, once targeting long-lived, high-trophic-level piscivorous fish, are now catching more invertebrates and short-lived pelagic planktivores (Caddy and Rodhouse, 1998; Pauly *et al*., 1998).

In addition, fishing may have an impact on fish community structure by altering predator–prey relationships (e.g. Mehl, 1991). Several studies suggested the impact of declining forage-fish populations (often due to overfishing) on the survival of marine mammals (Hansen, 1997) and on the breeding success of seabirds (e.g. Anker-Nilssen, 1997). The impact is not merely restricted to the total abundance of prey but may also extend to its spatial distribution and the encounter rate between prey and predators (Furness, 1982). Fishing may even eliminate trophic groups or keystone species and result in a complete change to the overall community structure (Botsford, 1997; Hall, 1999). Finally, trawls and dredges may modify or destroy habitat, reduce seabed complexity and remove those macrobenthic organisms that provide shelter (Sainsbury, 1993; Auster *et al*., 1996). Poiner *et al*. (1998) found that each consecutive trawl removes 9–13% of the sessile and mobile benthic invertebrates, and fish communities.

Fishing down an ecosystem exposes us unnecessarily to the vagaries of uncertainty, and deprives us of any insurance policy against fishery collapse (Lauck, 1996; Sumaila, 1998c). Marine reserves, areas closed to exploitation, are seen as an additional management tool that could control fishing mortality and thus hedge against the risk of fisheries collapse (Bohnsack, 1996; Guénette *et al*., 1998; Sumaila, 1998c). In tropical fisheries, where the existence of numerous species prevents managers from applying single-species stock assessment techniques, closed areas may be the only available tool (Roberts and Polunin, 1993; Williams and Russ, 1995). MPAs, as an ecosystem management strategy, should aim at contributing to the maintenance of biodiversity, ecological processes, and sustainable resource usage.

An MPA refers to a management area in which usage is regulated by zoning for different activities. It includes marine reserves, which are strictly no-take areas. It is beyond our scope to extensively review and cite the literature on the subject. Rather, we first discuss the role of MPAs as a possible mitigating tool against ecosystem effects of fishing, through a synthesis of the current literature. The section thereafter briefly presents a number of promising quantitative modelling methods for the assessment of marine reserves as ecosystem/fisheries management tools. Issues pertaining to socio-economic effects of fishing practices and how these might change as MPAs are implemented are incorporated throughout. We finish with suggestions on how to move forward.

MPAs as a management tool

Ecological factors

From the single-species point of view, a marine reserve is expected to help control fishing mortality and, by so doing, restore, at least partially, pre-industrial exploitation patterns, when less efficient fishing techniques and lower boat power prevented the exploitation of portions of the fishing grounds. Increases in mean body size, density, and biomass of various species and especially those targeted by the fishery have been reported in several reserves (reviewed in Guénette *et al*., 1998). As a result, reproduction potential would increase within and perhaps outside the reserve. The presence of even limited exploitation within the protected area diminishes expected benefits (Jennings, 1996; Attwood *et al*., 1997; Wantiez, 1997). Also, benefits decrease rapidly after exploitation resumes in previously unfished reserves (Alcala and Russ, 1990).

Although marine reserves have not been shown to swell the fish population in the unprotected parts of the habitat, in some cases they sustain yield by adult migration into the neighbouring fishing grounds (Bennett and Attwood, 1991; Ramos-Espla and McNeill, 1994; Bohnsack, 1996; Russ and Alcala, 1996). Closed areas used as part of fishery management regimes (for single species) produced positive results for several species (Davis and Dodrill, 1989). Owing to the presence of numerous confounding factors, other case studies were much less positive regarding the benefits of MPAs (Pastoors *et al*., in press; Frank *et al*., in press). In other cases, poor results have been shown when the protected area is located in unfavourable habitats (Tegner, 1993) or is not protecting a sufficient portion of critical habitats (Armstrong *et al*., 1993). Reserves may also be a suitable tool to reduce by-catch, when critical habitats of the species or age group at risk are protected. Such reserves would be more efficient than size limits, as well as easier to regulate and enforce than single-species oriented regulations.

The observed effects of fishing on benthic-community structure underline the importance of creating permanent reserves. By eliminating fishing by mobile gears, the bottom complexity as well as the benthos and fish species composition are likely to change from disturbed to mature ecosystems (Watling and Norse, 1998). Long-lived species and those requiring highly structured

habitat would be expected to thrive. Evidence that closed areas may result in community structure modification has been found in several reserves (McClanahan and Obura, 1995). However, because some epibenthic species are slow growing and long lived (up to 100 years; Watling and Norse, 1998), rebuilding the habitat structure may be a long process.

Both larval dispersal and adult migration patterns are important to determine the location, size, and number of reserves necessary to protect a particular species (Allison *et al*., 1998). A fast rate of adult migration outside the reserve is likely to decrease the efficiency of the reserve since a large proportion of individuals would still be vulnerable to exploitation (Guénette *et al*., 1998). In consequence, the need for knowledge of home range and migration patterns becomes crucial (Bennett and Attwood, 1993; Zeller, 1997). The patterns of larval dispersal, the location of their settlement, and the presence and contribution of neighbouring populations are central to the efficacy of the reserve and its ability to sustain a population (Allison *et al*., 1998). A few cases convincingly point out the importance of accounting for larval dispersal in sustaining or rebuilding fished patches (Tegner, 1993). However, complete knowledge of sources and sinks may never be available in a timely manner. A good option would be to create a network of marine reserves close to one another (Roberts, 1998), in a way that would allow us to learn about the processes. Compared with one single reserve, a network would lend a greater protection against environmental variation and local catastrophes (Ballantine, 1997).

The effectiveness of any MPA depends on its size and location in relation to life-history characteristics and habitat requirement of the species to be protected. Designing a program to evaluate whether MPAs are meeting their objective is extremely complicated (Pastoors *et al*., in press; Frank *et al*., in press). Even the design of a closed area for studying impact of fishing is by no means straightforward (ICES, 1994a). Thus, although an MPA is unlikely to have adverse effects, its generic potential to solve fisheries management problems should not be overestimated.

Socio-economic factors

Social scientists have argued that fishing communities ought to be considered as part of the ecosystem (Coward *et al*., in press). Apart from resource conservation and food supply, ecosystem management goals include generation of employment and economic wealth and the maintenance of viable fishing communities (Behnken, 1993). A journalist once asked the Minister of Fisheries in Namibia how he planned to handle the trade-offs between the need to conserve fishery resources and that of maintaining high levels of employment in the fishing sector. The Minister countered (we believe rightly) that the question missed the point. The issue, according to the Minister, was not "conservation vs employment", but rather "employment today vs employment tomorrow" (*Namibia Brief*, 1994). Given the collapses of various fish stocks around the world and the scientific evidence gathered so far (Safina, 1995), it is almost certain that, at current global fishing levels, we are unnecessarily sacrificing tomorrow's employment for today's.

The long-term effects of fishing on the economic and social well-being of fishing communities may be positive if the interaction between the community and the fish is such that the ecological base of the resources remains intact through time. A failure to achieve this constitutes a negative interaction, as illustrated by the huge economic and social pain that followed the collapse of the cod fishery off Newfoundland, Canada (Ommer, 1994).

Economic factors are generally not taken into account in the planning of MPAs (Tisdell, 1986), probably because MPAs are usually created either in anticipation of biological and ecological benefits, or in response to public pressure, in particular from conservation groups. Arguments have been put forward for the inclusion of both social and economic variables in the decision to establish marine reserves (Sumaila, 1998c). Economic justification for establishing marine reserves usually takes two broad forms. First, it is argued that economic benefits may follow the establishment in the form of creating employment through non-consumptive activities such as tourism and recreation. Second, it is expected that MPAs may protect future jobs by increasing the chances of managing stocks sustainably.

Most economic analyses are of the cost-benefit type or the bioeconomic type. Cost-benefit analysis seeks to determine the net economic benefits that can be expected, considering the possibility that non-consumptive activities may increase. Methods such as contingent valuation, hedonic pricing, and travel cost are commonly used to evaluate the benefits of marine reserves (Dixon, 1993). On the other hand, bioeconomic analysis seeks to isolate the usefulness of marine reserves as tools to support and enhance sustainable management (Holland and Brazee, 1996; Sumaila, 1998b).

In a review of net benefit evaluation for marine reserves, Hoagland *et al*. (1995) compared 62 economic studies published between 1980 and 1995. Their results show that only about 18% of these provided dollar estimates of benefits and costs based on empirical analysis. Only two studies included both market and non-market values of marine reserves in the estimate of costs and benefits. Despite problems in getting complete information on species composition, or on effects of pollution for example, Dixon and Sherman (1990) demonstrated that in many cases market benefits alone may justify the creation of a MPA.

Quantitative modelling for assessing MPAs

Single species

Single-species modelling has been useful in showing how marine reserves could help rebuild overexploited populations by increasing population abundance, survival, and the numbers of older individuals, thus serving as a hedge against stochastic recruitment failure (Guénette *et al*., 1998). Equilibrium models are useful for exploring the influence of population dynamics and basic mechanisms behind marine reserves, such as the impact on fishing mortality, yield, body size, mean age, and the implications of high exchange rate between protected and unprotected areas. The addition of stock–recruitment relationship and reproductive potential lead us to consider resilience to exploitation induced by the increase in the number of large spawners in closed areas (Guénette and Pitcher, 1999; Sladek Nowlis and Roberts, in press). The balance between stock rebuilding and yield improvement depends on the exchange rate of biomass between protected and unprotected areas. Larval dispersal may be another possible mechanism for rebuilding the stock (Quinn *et al*., 1993).

A few single species bioeconomic models of marine reserves have been published so far. Holland and Brazee (1996), assuming fixed effort, concluded that reserves would sustain or increase discounted economic benefits in heavily fished inshore fisheries. Other models assume that fishing effort is variable from year to year to ensure optimum economic benefits to the fleet. For instance, Sumaila (1998b) uses data on the Northeast Arctic cod to determine the bioeconomically optimum size of marine reserves for the Barents Sea fishery. This model considers uncertainty in the form of a shock to the system through recruitment failure in the fished area of the habitat. According to this study, the establishment of a marine reserve is bioeconomically beneficial when net exchange rates for cod are reasonably high and reserve size is large. Large reserves provide good protection for the stock in the face of the shock, while high transfer rates make the protected fish available for harvesting after the shock has occurred. Hannesson (1998), using a single-age model, found that reserves alone would not lead to any economic or biological gain.

In need of a conservation objective to start with, scientists have tried to devise a minimum proportion of the habitat that should be protected. Based on the minimum spawning biomass that should be preserved in exploited stocks, the Plan Development Team (1990) suggested that 20% of the total habitat be protected. The appropriate proportion, although unknown, is likely to be larger. Modelling based on species with different life histories suggests that a large proportion of the total habitat (up to 50%) should be included in reserves to efficiently protect both the habitat and the animals contained therein from the negative impacts of exploiting the resources (for review Guénette *et al*., 1998). Based on observed dispersion rates for commercial North Sea fish stocks, Daan (1993) showed that if a contiguous area of 25% was closed, the reduction in mortality would only be in the order of 12%.

Spatial modelling

Because the marine environment is not homogeneous, spatial structure of the species' habitat should be included in modelling to help understand the influence of larval dispersal, adult migration, and age-specific habitat needs. To date, only a few spatial studies have incorporated marine reserves. For instance, Attwood and Bennett (1995) used a simple single-species spatial structure to compare three species with different life histories (longevity, reproduction, migration). They showed how migration influences the size of the reserve necessary to rebuild the population.

Spatial dynamics of fish distribution and fishing effort should also be included if the goal is to limit fishing mortality and compare benefits emerging from different management strategies. Rijnsdorp and Pastoors (1995) used a spatially-explicit model that takes into account the distribution of plaice (by age group) and of fishing effort and quantity of discards, both by season and area in the North Sea. Assuming that fishing effort would redistribute around the boundaries of closed areas, the authors concluded that a closed area located to protect undersized fish would be beneficial for plaice populations. However, in practice the "plaice box" closure has been inconclusive regarding its benefits on recruitment of plaice (Pastoors *et al*., in press). Guénette *et al*. (in press) used an age- and spatially-structured model that included explicit seasonal migration of northern cod, and contraction of geographic distribution when abundance decreases. The results suggest that marine reserves by themselves may not be sufficient to control fishing mortality of a migrating species subjected to extreme fishing effort. In this context, a reserve should be accompanied by output control (e.g. quota system) and/or effort control. A similar conclusion had also been drawn by Daan (1993).

Using spatially based bioeconomic models of marine reserves, Sanchirico and Wilen (1999) found that in many cases the industry might benefit from closing areas that are less profitable rather than areas that are biologically unique. Holland (1998) added fishers' choice of fishing grounds based on interviews to a spatially structured, multi-area and multispecies bioeconomic model. The model showed that (i) it is unlikely that area closures will increase fishery profits significantly when effort is already very high, but they may allow for the maintenance of higher levels of spawning biomass; and

(ii) area closures may affect various groups of fishers differently (i.e., there may be losers and gainers).

Ecosystem modelling

The recognition that exploited stocks are parts of ecosystems and that species usually interact (e.g. predator–prey relationships) has compelled fisheries scientists to conclude that models that aim to contribute to the sustainable management of marine resources must take the ecosystem approach. Hence, several generic approaches to multispecies and ecosystem analysis have been developed in recent times. At least four different approaches to ecosystem management can be identified (Walters *et al*., 1997): (i) multispecies virtual population analysis, (ii) differential equation models for biomass dynamics, (iii) bioenergetic models, and (iv) the ecosystem model known as ECOPATH (Christensen and Pauly, 1995)

All four approaches appear to have the potential of being extended to allow for the analysis of the effect of establishing MPAs. An example of such an extension is provided by Watson and Walters (1998), who developed a simple model based on ECOPATH, with quasi-spatial relations between biomass and fishing mortality, to examine the potential impacts of MPAs. Sumaila (1998a) built on this approach to evaluate the economic benefits that are achievable for different sizes of marine reserves. A further extension is a spatially explicit model, which includes movement rates to compute exchanges between grid cells and habitat preferences for each functional group (Walters *et al*., 1998).

For comparison and validation purposes, it would be useful to apply other ecosystem models as well. For example, the multispecies virtual population model published by Tjelmeland and Bogstad (1998) for the Barents Sea could be extended to assess the possible impact of marine reserves. The model is spatially structured and includes sea temperature, growth, migrations, and trophic interactions between cod, capelin, herring, harp seal, and minke whale.

Clearly, modelling ecosystems is rendered difficult by poor data for several trophic levels and by a lack of adequate knowledge of the interactions between different species and their habitats. It is also difficult to capture sudden changes in ecosystem state. Despite these and other limitations, ecosystem modelling could be useful both for generating hypotheses about ecosystem function and for evaluating policy choices.

The way forward

Difficulties in establishing MPAs are common, irrespective of country. The establishment of the Florida Keys Marine Sanctuary (USA) was delayed for several years while issues between state and federal authorities were negotiated. This delay intensified the conflicts between fishers, managers, and conservationists (National Research Council, 1997). Generally, conflicting interests, such as those between conservation and exploitation, represent a major issue in resource-allocation exercises. Therefore, resource-use analysis is needed for zoning and management planning (Rigney, 1990).

Fishers are willing to embrace the MPA concept if it is at least economically neutral, and when the potential to increase their economic gains is not unduly constrained. The development of Australia's Oceans Policy, which is based on an ecosystem approach and includes a representative system of MPAs, has been controversial because many stakeholders are concerned with their future access rights. It is helpful to consider the benefits of MPAs in terms of trade-offs between long-term protection of rich ecological resources and their more immediate use for economic gain. These trade-offs are not easy to administer, as they involve uncertainties associated with the ecological benefits, non-monetary values that people put on resources, intra- and intergenerational equity considerations, and socio-cultural preferences of local communities. As stated by Dixon (1993), in some instances it may be more important to consider a balanced use of natural resources for both economic and ecological functions than to strictly preserve the resources in the area.

Keys to success

Establishing MPAs is like any other public policy decision. It is a political process where scientific knowledge may inform the debate and influence the outcome, but the decisions are taken elsewhere (Sobel, 1996). According to Ludwig *et al*. (1993), policy-makers should not wait for scientific consensus before creating marine reserves as a common-sense precautionary measure.

It has been widely recognized that public participation and local community involvement is an essential factor contributing to the success of MPAs (Kaza, 1988; Rigney, 1990; Fiske, 1992; Wolfenden, 1994). In the absence of strong community support, the integrity of MPAs relies more heavily on efficient enforcement, which is costly and not easily achieved. The local community can also initiate the process. Bonavista Bay, a small coastal community in Newfoundland (Canada), is formulating its own local management measures using no-take marine reserves to maintain lobster stocks (Lien, 1998). This 'bottom-up' initiative is from stakeholders who have recognized the need to pro-actively manage their own resources. Involving the public also means taking into account the social, cultural, and political concerns of the communities. The marine sanctuary in Fagatele Bay (American Samoa) is a good example which shows that successful implementation depends

largely on acknowledging these issues (Fiske, 1992). However, co-management and community involvement require a great deal of commitment and energy from all parties. Despite its potential benefits, community involvement is not without difficulties and pitfalls (McCay, 1988). A better understanding of fishing patterns and fishers' reactions to marine reserves is needed. Fishers must be involved early in the decision-making process to ensure support and ultimately to reap the expected benefits (Alder *et al.*, 1994; Neis, 1995), because they possess detailed knowledge of their fishing grounds (Neis, 1995), which is essential for the design of acceptable and efficient reserves. In addition, fishers' reactions to temporal or spatial area closures should also be taken into account. The 'plaice box' in the North Sea demonstrates this. Although fishing effort had decreased following the exclusion of big trawlers, small boats increased their total effort within the box (ICES, 1994b). At the same time, the trawling activity started to concentrate along the borders of the closed area. Because involving fishers implies that fisheries management is partially controlled at the local level, scientists and policy-makers need to improve their communication with fishers to eliminate mutual distrust and to truly share responsibilities.

New directions

Acknowledging our limitations in understanding the ecosystem fully, one might try to use a precautionary approach in creating a network of marine reserves. At this point, we should not aim at sustaining the present state of ecosystem health (or misery?) but to rebuild ecosystems (Pitcher and Pauly, 1998). MPAs can be used, in combination with other management measures, as part of an adaptive management scheme in that respect. Rather than solely controlling fishing mortality for targeted species, reserves should be designed to allow permanent and/or temporal closures to cover critical habitats such as nurseries, spawning and feeding grounds or to protect the stocks during crucial life-history events such as migrations and spawning aggregations. MPAs should be seen as tools for learning and experimentation with target and non-target species recovery, ecosystem management, and co-management.

Research should be directed towards the evaluation of existing marine reserves to determine their success and potential benefits. Well-designed long-term monitoring programmes will be necessary to gather data about the pathways of population and ecosystem rebuilding, to assess benefits, to increase knowledge of both fishers and scientists, and to improve the level of protection. Keeping track of fishers' behaviour and fishing power will also be essential to maintain the protection conferred. Future bioeconomic models will have to incorporate the fact that, in most cases, habitat loss or disturbance results in decline of species of commercial value with time. In our view, protecting the marine habitat is bound to lead to higher productivity in the future, which at the next level will benefit catches and economic gains. Capturing these types of benefits of marine reserves in the next generation of bioeconomic models will be crucial. Another important contribution that can come from economic modelling is the design of incentive regimes that will ease the regulation and control functions, and reduce poaching.

In addition, an objective-based assessment model might be used to evaluate the success of marine reserves. For example, a scoring system called COMPARE (Criteria and Objectives for Marine Protected Area Evaluation) has been developed by Hockey and Branch (1997) to measure the effectiveness of MPAs, in terms of their scientific, socio-economic, and legal performance. Another suggestion for evaluation is to use an index that provides relative measures of the importance of biophysical changes, such as the damage schedule approach presented in Chuenpagdee (1998).

Finally, it is important to recognize that threats and damage to MPAs may come also from the adjacent land (siltation, sewage, coastal pollution, river run-off, etc.). MPAs alone may not guarantee the long-term persistence of the targeted species. Catastrophic events such as pollution and climatic changes may impact the habitat and its biota in an uncontrollable manner (Allison *et al.*, 1998). Therefore, management and objectives of MPAs must be closely linked with the overall planning for the coastal zone.

In conclusion, if properly established, MPAs offer a viable additional management tool to help stem the decline of fisheries at risk, rehabilitate those that have collapsed, and contribute to the sustainability of future fisheries. Not only can MPAs help to address the ecological problems of poorly managed fisheries, but they can also assist in improving the long-term socio-economic welfare of coastal communities that often rely on the very resource they are depleting. Achieving these changes requires more than just drawing lines on a map and declaring the area closed. A range of approaches, from basic ecological assessments to ecological and economic modelling and resource use analysis, is required to fully realize the potential of MPAs.

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