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The Bioeconomics of Marine Reserves: A Selected Review with Policy Implications

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Abstract

The paper ‘bridges the divide’ between the biological and economic literature on marine reserves. It provides a selected review of the traditional use of reserves, the early reserve literature, the potential benefits of reserves, spillovers from reserves to harvested areas and bioeconomic models of marine reserves. The bioeconomics literature is examined from the perspectives of deterministic models, spatial economic models and models that include uncertainty and stochasticity. Insights from the review are used to provide management implications in terms reserve design, stakeholder cooperation and process, reserve-fishery transfers, traditional management controls, and ecosystem approaches to managing fisheries.

Key words: reserve spillovers, deterministic, stochasticity, spatial models, fisheries management

JEL Classification: Q2

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Introduction

A marine reserve may be defined as a spatial area where some, or all, species receive long-term protection from harvesting. Reserves may exist in certain locations because of natural or physical features, but are also imposed as part of the management of marine resources. In both cases, zero harvesting of all species within a reserve is rare. Reserves or ‘no take’ areas often form a part of larger marine protected areas (MPAs) that have less protection and may include areas that allow for some consumptive use. For example, in the US a variety of activities, but not oil or gas extraction, are allowed within some areas of ‘marine sanctuaries’. In one of the world’s largest MPAs, the Great Barrier Reef Marine Park, only about one third of its total area is now either within no entry or ‘no-take’ zones while the rest is divided into zones where some form of access and harvesting are permitted.

In recent years marine reserves have received increased attention by both policy makers and researchers. In part, this has been driven by concerns over the need to preserve both representative marine habitat and biodiversity, and because of fears that fisheries management has, in general, failed to adequately conserve marine resources (Ludwig et al. 1993, Pauly et al. 2002). These issues have led some governments to include MPAs as key components within their management of fisheries and led many others to agree to the implementation of networks of MPAs within the coming decade (United Nations 2002).

Despite a burgeoning interest in marine reserves, especially in the biological literature, the bioeconomic — the integration of biological and economic — study of reserves is relatively limited. A cause for the lack of bioeconomic models is that many specialists within biology and economics are relatively uninformed about each other’s disciplines. We take a step in ‘bridging

the divides' by providing a selected review of the literature that incorporates both biological and economic features of marine reserves. Given that the bioeconomics of marine reserves depends greatly upon the positive spillovers from reserves to fished areas, the paper also provides a selective review of the biological aspects of the potential benefits of, and spillovers from, marine reserves. The review will prove useful to decision makers, many of whom are not fully aware of the implications of the marine reserve literature for fisheries management.

The paper divides the marine reserve literature into several distinct, but related parts. First, the paper provides a brief review of the early marine reserve literature. Second, it examines a selection of the theoretical and empirical studies on the potential benefits of reserves. Third, the possible spillovers from reserves to fished areas are reviewed. Fourth, the bioeconomics literature on reserves separated into deterministic approaches, spatially explicit models of fisher behaviour, and stochastic models are discussed in detail. The paper concludes with insights for fisheries management to make reserves a more effective fisheries management tool.

Early Literature and Traditional Use of Marine Reserves

Marine reserves have existed in one form or another for thousands of years. In Oceania, permanent reserves were traditionally designated 'tapu' or sacred sites (Johannes, 1978) and existed for many generations before the arrival of Europeans. Such reserves were frequently located in areas identified as key population 'sources' for existing fisheries, such as breeding or nursery areas. In addition to permanent reserves, fish have also been protected for particular periods of the year in almost every fishing culture, and temporary closures still remain an important component of fisheries management in many countries.

By contrast to the long-standing and traditional use of marine reserves, the scientific interest and study of the benefits of reserves is relatively recent. In their classic book, *On the Dynamics of Exploited Fish Populations*, Beverton & Holt (1957, pp. 147-148) develop a model where in part of the habitat there is no prey or fishing and predict the effects on fishing yields from reserves, or what they call ‘refuges’. They also evaluate the effectiveness of reserves within fisheries regulation and observe that if the rate of transfer of fish from a reserve to a harvested area is too low then a reserve will reduce fish yields, while if the transfer is too high a reserve would provide very few harvesting benefits (Beverton & Holt 1957, p. 393). They conclude that for a reserve to increase yields an intermediate case of fish transfer is required, and emphasise the difficulties of using reserves to manage fisheries because of the complexity in calculating the transfer of fish.

Two contributions from 1990 in terms of theory (Polachek 1990) and empirical measures of reserve benefits (Alcala & Russ 1990) became the starting point for what has now become a huge literature. Indeed, the literature has expanded to such an extent that already there are several comprehensive reviews of marine reserves including Guénette et al. (1998), National Research Council (2001), Ward et al. (2001), Gell & Roberts (2002), among others, as well as several special issues on the subject in scholarly journals.

Polacheck (1990) lists at least three potential benefits of reserves, if effectively enforced. First, by eliminating fishing mortality, ‘no take’ areas can increase the spawning biomass — especially with overexploited stocks — and may even increase yield per recruit and help prevent recruitment overfishing. Second, a reserve can provide an increased assurance with harvesting that a given proportion of the population will persist into the future. Third, the costs of

establishing and enforcing reserves are likely to be less than traditional methods of regulation making them an attractive tool for fisheries management. The first two benefits, however, depend crucially on the rate of transfer or spillovers between the reserve and the fishery.

The issue of spillovers to fished areas is addressed by Alcala & Russ (1990) in one of the first ‘natural experiments’ of the effects of a marine reserve. In particular, they measure the impacts of the removal of a decade-long protection of an island reef in the Philippines. They find that both abundance and yields decline after reserve protection ceased. Their work provided a stimulus to others to empirically test and measure within and beyond reserve effects in other locations. A problem with some of these studies, with several exceptions that include Bennett & Attwood (1991), Davidson (2001), McClanahan & Kaunda-Arara (1995) and Edgar & Barrett (1999), among others, is that without before and after studies where reserve locations are matched to control locations, differences attributable to reserves may be caused by other factors (Guidetti 2002).

Potential Benefits of Reserves

Reserves can generate a range of potential benefits, some of which may generate spillovers in harvested areas. These benefits arise from reduced mortality and/or decreased habitat or environmental damage due to the establishment of no-take areas. The habitat benefit can be important in fisheries (Roberts & Sargent 2002) where, for example, evidence exists that bottom trawls used to catch demersal species and dredging for shellfish can damage marine habitats, increase mortality of fish not caught in trawls, and reduce the rate of recruitment of some species (Turner et al. 1999).

Bohnsack (1998) extends earlier work of others from the US National Marine Fisheries Service to list 41 potential non-fishing benefits from reserves. He summarises these benefits under three headings: one, protect ecosystem structure, function and integrity, two, increase knowledge and understanding of marine systems and three, improve non-consumptive opportunities. In terms of non-consumptive benefits, reserves can increase aesthetic and recreational values because of higher population densities and/or larger individuals both within no-take areas and adjoining areas (Bhat, 2003). In addition to Bohnsack's three categories, reserves may also reduce the probability of extinction or extirpation by helping to ensure a minimum viable population (Levins 1970, Shaffer 1981).

In terms of ecosystem integrity, a reserve can generate two principal payoffs. First, a more desirable population structure (characterised by age, gender or individual size) within a reserve can increase breeding success and mean recruitment into the harvested population (Bohnsack 1998, Gell and Roberts 2002, Jennings 2001, Trippel 1995). Second, reserves can result in a greater number (and possibly a greater level of abundance) of species, especially populations harvested outside of the reserve (Côté, Mosquera & Reynolds 2001, Halpern 2003), and also generate positive harvesting spillovers for adjacent areas (Roberts et al. 2001).

The potential benefits of reserves, however, are highly dependent on their design. For instance, establishing reserves of an inappropriate size (too large or too small) and number, especially without proper consideration of larval and adult dispersal patterns (Gaines et al, 2003), will reduce their effectiveness and may even reduce the overall returns from fishing. For example, reserves of a small size may impose selective pressure for shorter dispersal distance (Botsford et al. 2001) that would, in general, not be beneficial in terms of generating spillovers to

adjacent exploited areas. In the extreme, reserves located in population ‘sinks’ may even reduce harvests while providing few, if any, future spillovers.

Christie et al. (2002) also point to the limitations of single, isolated marine reserves that can favour the intensive redistribution of effort along the reserve boundaries. Instead, they suggest that a network of areas (nested within broader management regimes to restrict the overall amount of effort) is more beneficial to the maintenance of abundance in areas adjacent to marine reserves. Kramer and Chapman (1999) also predict that population densities and modal sizes of fish will directly depend on the size of the reserves, their area to edge ratios, the number of habitat types, natural barriers, and the difference in habitat quality between reserve and non-reserve areas.

A large number of empirical studies show reserves can increase abundance, and some indicate that reserves generate spillovers to adjacent fisheries. The National Research Council (2001) and Ward et al. (2001), among others, provide a summary of this literature. Table 5-3 of the National Research Council (2001) lists the effects of reserves in terms of biomass, abundance, size of fish, density, biodiversity and effects on adjacent fisheries. Appendix 1 of Ward et al. (2001) lists their impacts in terms of abundance, age and size, and fecundity. In a recent survey of 112 independent measures of marine reserves, Halpern (2003) finds, relative to reference sites, that reserves on average appear to double population density, nearly triple biomass and raise size and diversity by 20-30%. Where reserves generate benefits, these appear to occur in a relatively short period of time of one to three years (Halpern & Warner 2002), although some of this increase is likely due to redistribution of fish rather than exclusively natural growth within reserves (Jennings 2001).

Empirical evidence of the benefits of reserves is also supported in various case studies synthesised by Gell and Roberts (2002), and in a meta-analysis of 19 marine reserves where abundance of targeted fish species was 28% higher within reserves (Côté, Mosquiera & Reynolds 2001). Such benefits, at least for some reserves, have spilled over to neighbouring exploited areas as evidenced by increased catches per unit of effort and increased population size in adjacent areas (Gell & Roberts 2003, Roberts et al. 2001), as well as harvests of larger and often more higher valued individuals (Bhat 2003).

The empirical studies suggest that the benefits of reserves will tend to be greater the more overexploited are fish populations. Given density dependent growth, however, it is conceivable that long-established reserves that are successful at generating high densities may eventually reduce growth rates and, thus, spillovers to adjacent fishing areas. For example, Béné & Tewfik (2003), in a study of a fishery reserve off the Turks and Caicos Islands in the Caribbean, show the potential for density-induced *lower* growth rates where a much higher density in the reserve has led to significantly smaller conches. This suggests that if yield or spillover benefits of paramount importance, it may be worthwhile in some fisheries to periodically harvest target species within reserves so as to raise yields and spillovers to harvested areas (Neubert 2003).

Fishing Spillovers

A key factor in modelling the bioeconomics of reserves is the net spillovers, or the net rate of transfer of larvae, juveniles and adult fish from reserves to harvested areas. Transfers represent a trade-off in the sense that the more mobile are fish between reserves and harvested area, the less protection provided by a no-take area and, thus, the lower is the spawning biomass in a reserve

(DeMartini 1993, Guénette & Pitcher 1999 and Apostolaki et al. 2002). In other words, the greater the net transfer out, the larger is the size of the reserve required to maintain the same level of protection from harvesting. For ‘super mobile’ species such as large pelagic fish like tuna and billfish that migrate over thousands of kilometres, the size of the reserve required to reduce fishing mortality could be very large and would also need to account for the migration routes of the fish and where the fish are targeted for harvesting (Hyrenbach et al. 2000). Conversely, although a low transfer rate provides increased protection from fishing, for a given reserve size, it also reduces the benefits to fishers as less fish spillover to harvested areas.

Gell and Roberts (2003) provide an informative review of the studies of spillovers from reserves to adjacent areas. Despite the difficulties of measuring changes directly attributable to reserves, spillover studies provide substantial evidence of the potential payoffs from reserves. These benefits come in two main forms: net larval export that can increase recruitment into the fishery in the future and net export of adults that are immediately vulnerable to harvesting (Rowley 1994). Spillovers, however, are highly dependent on reserve design especially if fish migrate on a seasonal basis and aggregate at different places and times throughout the year (Holland 2000). Moreover, transfers from reserves to fished areas cannot be assumed to be a simple diffusion process without reference to currents or other physical factors (Gaines et al. 2003), but requires an understanding of both dispersal distance and the number of population sources (Allison et al. 1998). Indeed, some suggest that the dispersal pattern of larvae is the critical issue when designing marine reserves (Lockwood et al. 2002).

Not surprisingly, an understanding of source-sink dynamics (Pulliam 1988) also provides a key to understanding the benefits of marine reserves. Building on earlier work by Roughgarden

& Iwasa (1986), Tuck & Possingham (1994) examine the problem of optimal harvesting strategies of a metapopulation with positive harvesting costs. They find that local populations that are sources should incur less harvesting than if all local populations were managed as a single population. Brown & Roughgarden (1997) also show the value of preserving some local populations as sources while harvesting in only one location. Bulte & van Kooten (1999) find that changes in the harvest of two distinct sub-populations alter the rate of in and out flow, as can shocks, especially if a positive shock in one population corresponds to a negative shock in the other. This source-sink literature emphasises the importance of modelling transfers between protected and exploited populations in the presence of shocks, that reserves should be placed in source habitats rather than sink ones (Tuck & Possingham 2000), and that the spatial location of reserves is critical to population enhancement when there are directional currents (Crowder et al. 2000).

Bioeconomics of Marine Reserves

Bioeconomic models of marine reserves need to consider a number of key processes: the transfer rate and flows between reserves and harvested areas, the effect of reserves on fisher behaviour and the influence of environmental stochasticity and shocks on both the reserve and fished populations.

Deterministic Models

One of the first economic models to examine the efficacy of reserves was developed by Holland and Brazeel (1996). Using a deterministic framework they show that the relative benefits of

reserves depends on their effect on harvesting in exploited areas and the discount rate — the greater the short-term harvest loss through reserve creation and the greater the discount rate, the smaller are the benefits of a reserve and the smaller its optimal size. In simulations, they also find that at higher fishing effort levels a correspondingly larger reserve size is required to generate greater discounted rents. Their work is also noteworthy for stressing the value of reserves as ‘insurance’ to management failure from an inability to control either fishing effort or harvests in exploited areas. However, they emphasise that if effort (and harvests) can be perfectly controlled reserves may be of little value.

In subsequent work, Holland (2000) observes that reserves can, in some cases, raise harvest and revenues if fishing effort was very high prior to their implementation, although this could also be accomplished with more direct controls on fishing effort or harvest. The conclusion that reserves are essentially redundant in a deterministic system if the total catch or harvesting effort can be directly and perfectly controlled, is supported by both Anderson (2002) and Hannesson (1998). In particular, Hannesson (1998) shows that reserves would need to be in the order of 70-80% of a fishing area to yield benefits associated with an optimally controlled fishery and, to the extent that reserves initially reduce harvests in exploited areas, will raise fishing costs and also exacerbate problems of overcapacity.

Pezzey et al. (2000) and Sanchirico & Wilen (2001) both prove that, with density-dependent growth, a reserve can increase the abundance of the population and, in some cases, may even raise the aggregate harvest in the exploited area if stocks are overexploited. In particular, Pezzey et al. (2000) show that the equilibrium catch can rise if the ratio of the population to its carrying capacity before the creation of the reserve (with open access) is less than half. This so-called

‘double payoff’ with sub-optimal harvesting can arise where the chosen area for the reserve is at a low population level such that the marginal benefits of closure (reduced mortality, but with spillovers) outweigh its costs (loss of harvest in previously exploited area). Sanchirico & Wilen (2002) also show in the case of overexploited stocks managed by input and license controls that reserves can raise both the total population and the lease price for fishing licences.

Spatial Economic Models

In an attempt to better link the biology and economics of reserves, Sanchirico & Wilen (1999 and 2001), Holland (2000) and Holland & Sutinen (2000) emphasise that establishing reserves will invariably change the level of fishing effort in exploited areas. Under reasonable assumptions about fisher behaviour it is unlikely that all the effort previously directed to a reserve would go elsewhere, as is commonly assumed. How effort redistributes with a reserve thus depends not only the biology, but also on the costs and returns of harvesting in different locations. Sanchirico & Wilen (1999) show that the effects of reserves on fishing are highly dependent on how fishers reallocate effort. In particular, fishers have a tendency to reallocate their effort to areas that generate higher relative rents. This effect generates spatial ‘economic gradients’ that may be quite different to ‘biological gradients’ generated by larval export and adult transfers. A key point of this work is that both economic and biological factors have an important effect as to whether a particular location becomes a population source or sink in equilibrium.

Applying spatial economic modelling to the California sea urchin fishery, Smith & Wilen (2003) find that discounted rents fall with the creation of a reserve in heavily fished area if the spatial behaviour of fishers is accounted for, but is predicted to rise if it is not. Their modelling

also has implications for other forms of fisheries management, such as minimum size limits (Wilén et al. 2002). In sum, spatial modelling indicates that the location of reserves requires both biological and economic understanding.

Uncertainty and Stochastic Models

Without incorporating the uncertainty inherent in wild populations (Cohen 1966), and the possible mitigating effects of reserves in the face of unexpected shocks and management failures, deterministic models will likely understate the value of no-take areas (Gerber et al. 2003). Moreover, models that do not explicitly consider shocks (positive and negative) in fisheries will be unable to determine an appropriate size and/or location for reserves.

In an uncertain environment, if a reserve reduces the mortality rate within its boundaries then it can also raise the likelihood that the reserve population (and also the entire population because of transfers out of the reserve) will not be extirpated due to a negative shock. This is because for many negative shocks, the smaller is the population the higher is the chance of its elimination (Shaffer 1981). Also, by separating a population into exploited areas and reserves the nature of the negative shocks may be different, and may even be mitigated in reserves, if the shocks are correlated with the level of harvesting.

Reserves can also act as a hedge against irreducible uncertainty, especially those associated with harvesting of exploited populations (Ludwig et al. 1993, Botsford et al. 1997) where harvest rates and population stocks are measured with error and harvests are less than fully controllable (Clark 1996, Lauck et al. 1998). Moreover, by acting as a ‘safety net’ to overexploitation,

reserves may even permit greater levels of exploitation that would otherwise be possible while ensuring the long-term sustainability of the resource (Lauck et al. 1998).

A key result by Lauck et al. (1998) is that reserve size should increase with the level of uncertainty so as to ensure population persistence. In simulations, Mangel (2000a) demonstrates that the longer the desired persistence of the population in the face of negative shocks, the larger should be the reserve. Sumaila (1998) and Mangel (1998) also show the existence of a negative relationship between reserve size and the degree of uncertainty. In particular, Mangel (1998) derives a ‘no-take invariant’ that implies that a higher maximum harvest level requires a larger reserve size to maintain the sustained harvest. This result is similar to that obtained by Guénette & Pitcher (1999) who show that marine reserves increase persistence by maintaining higher levels of the spawner biomass and by raising recruitment success with high rates of exploitation.

Using the concept of an invariance kernel, Doyen & Béné (2003) find that the greater the level of uncertainty (size and/or probability of a negative shock) the greater the share of the population required in a reserve to maintain a minimum viable population. Under certain conditions, they show that reserves can help maintain a minimum viable population and also raise the ‘guaranteed’ harvests in exploited areas. In addition to ‘persistence payoffs’ of reserves, Conrad (1999) finds that with a constant environment a reserve reduces the economic payoff from fishing if effort controls are optimal. By contrast, in a fluctuating environment Conrad (1999) shows that reserves can be beneficial by reducing the variation in the population — a result also obtained by Sladek Nowlis & Roberts (1998). In subsequent work, Mangel (2000b) and Hannesson (2002) also show that reserves can reduce the variation in the catch for a given size of the resource.

One of the most recent papers on reserves incorporates two forms of uncertainty: environmental stochasticity that can be both positive and negative, and negative shocks into a bioeconomic model (Grafton et al. 2004). They identify a ‘resilience effect’, defined as the speed it takes for a harvested population to return to its level before the shock (Pimm 1984), that monotonically increases in reserve size and occurs whenever the sensitivity of a negative shock in the fishery is equal to or greater than the sensitivity for the reserve population. Resilience occurs because a greater population density in the reserve allows for a transfer of fish to the harvested area. This is advantageous because it permits fishers to harvest at a higher rate immediately after a negative shock than without a reserve.

Under a wide range of parameter values, Grafton et al. (2004) show that a reserve size greater than zero, even of a small size, will generate a higher discounted net return from fishing than no reserve in the presence of unexpected negative shocks. Their result is important because, contrary to the deterministic literature, they show that reserves can generate positive economic payoffs even if the population is persistent, harvesting is optimal in the absence of information as to when negative shocks might occur, and the fishery is not overexploited. Moreover, these benefits cannot be obtained from either input or output controls.

Implications for Fisheries Management

To what extent reserves offer benefits over existing fisheries management (such as total harvest and effort controls) can only be judged relative to the goals of management, and by incorporating the economics of harvesting with the biological aspects of reserves. Policy makers must also be very clear as what goals reserves are intended to achieve and must incorporate these

objectives in the design of reserves (Agardy et al. 2003, Hastings & Botsford 2003, Halpern & Warner 2003). Thus reserves established for fisheries management purposes may need to be designed very differently than if they were established to maintain biodiversity and representative habitats. For instance, in the case of biodiversity it may be highly desirable to provide maximum protection from harvesting and so creating reserves of a large size may be desirable. By contrast, reserves designed to buffer negative shocks to the fishery must not be so large that there are no spillovers of larvae, juveniles or adults from reserves to harvested areas.

Some evidence exists that a network of marine reserves, as opposed to one single isolated closure, is more effective in yielding fisheries benefits. For example, Rakitin & Kramer (1996) observe a gradual decrease in trap catches with distance from the center of the reserve and McClanahan & Mangi (2000) point to the importance of the edge to area relationship of reserves. Stamps et al. (1987) also investigate edge permeability, but on a more intuitive level, and argue emigration should be expected to be greater from patches with high ratios of perimeter to area (i.e. elongated strips) than for blocks of habitat.

Whatever the expressed goal of reserves, their effective design, monitoring and enforcement require stakeholder participation and co-operation. In most fisheries, fishers have a wealth of information to provide that can help design marine reserves. In some cases, fishers may even be much better informed than scientists as to relative fish densities in differing locations. Apart from their ability to inform decision-making, the co-operation of fishers is also critical to ensure reserves are respected (Jones 1999, Helvey 2004). For example, even in a rich country such as Australia with a long history of marine reserves, no-take areas have been less than successful in reducing fishing mortality to zero (Russ 2002, p. 426). In developing countries, with

overexploited fisheries and little financial support for monitoring and enforcement, community and fisher acceptance of reserves is crucial to ensure reduced fishing mortality within reserve boundaries (Francis et al. 2002).

Key management issues when establishing reserves are the process and criteria to be used in their design, and clarity over what reserves can achieve (Allison et al. 1998). Inglis (1992) was one of the first to list a number of criteria that include diversity of species, rarity of species, ecological fragility, among others, when establishing marine reserves. More recent insights by Botsford et al. (2003), Gerber et al. (2003), Roberts et al. (2003) and Ward et al. (2001), among others, provide useful guides to policy makers in terms of reserve design. Roberts et al. (2003), in particular, use 12 design criteria that incorporate the conservation goals of biological and genetic diversity, restoration and maintenance of ecosystems and protection of key life cycles. In terms of implementing reserves, Ward et al. (2001, p 127) describe a four-step process for the establishment and management of reserves: selection (design, number, etc.), declaration (stakeholder participation), management planning (strategies for successful management), and performance assessment (whether goals have been realized, understanding of key processes).

Given the lack of knowledge in fisheries about net transfers across locations, performance assessment and on-going studies of the within and spillover effects of reserves are critical to ensure the long-term success (Holland 2002). Such assessments are also needed by stakeholders, who must be shown that reserves generate positive payoffs, and also by decision-makers to ensure active adaptive management (Walters & Hilborn 1978) of reserves and fisheries. By various means, such as tagging and acoustic surveys and experiments in terms of larval dispersal, and with adequate resources, managers should be able to develop a better understanding of the

key issue of marine reserve design — the net transfers of fish between reserves and harvested areas.

In terms of fisheries management, reserves are neither a panacea for current problems nor should they be treated as superfluous management tool in the presence of input or output controls. For example, with a fluctuating environment the result that a reserve and fixed exploitation rate are equivalent methods of control (Hastings & Botsford 1999) in terms of fishing yields is simply not true if fish populations face unexpected negative shocks. Instead, marine reserves should be understood as a complementary management tool to maintain or enhance yields rather than being used in isolation of effort and output controls (De Martini 1993, Hannesson 1998).

Reserves alone cannot address the ‘race to fish’ problem common in input-controlled fisheries and neither are they a substitute for effective management strategies in harvested areas, such as minimum size limits. The need to integrate reserves with other controls is also supported by evidence that effort tends to redistribute along the boundaries of reserves and, thus, potentially may outweigh some of the benefits promised by no-take areas (Christie et al. 2002, Smith & Wilen 2003). Given unexpected environmental shocks, reserves can also play a unique role by helping stocks to recover faster and to mitigate management error and failure (Guénette et al. 1998, Lauck et al. 1998). In other words, in an uncertain world reserves provide payoffs that cannot be realised by traditional management, even if such controls are implemented optimally, but without a full knowledge as to when shocks might occur (Grafton et al. 2004). It would seem therefore, that the more fluctuating is the environment and the greater the vulnerability of

fisheries to shocks (natural or fishing-induced), the more valuable are marine reserves as a management tool.

Increased attention by policy makers about the benefits of marine reserves is concomitant with a greater emphasis on ecosystem management within fisheries (Sumaila et al. 2000). This is no coincidence. It reflects concerns over the status of fish stocks and an appreciation that impacts in one location, or on one species, may cascade across many different places and populations. A few authors have combined the two approaches and have incorporated reserves within large-scale ecosystem models (Walters et al. 1999, Walters 2000, Beattie et al. 2003). Beattie et al. (2003), in particular, use a spatially explicit ecosystem model that incorporates both economic and ecological factors to evaluate four policy options for the North Sea. The value of ecosystem models is that they include key drivers of marine systems and can be used to examine a range of possible scenarios regarding the effects of marine reserves. Such an approach is required if policy makers are to comprehend the benefits of marine reserves within the broader context of fisheries management.

Concluding Remarks

The past few years has seen a literal explosion in interest, and also in the number of studies, on marine reserves. In part, this has been a result of dissatisfaction over management failures and overexploitation in some developed fisheries. Despite the increased attention and a commitment by many governments to establish a network of marine protected areas, many policy makers are struggling to decide where to establish reserves, of what size, and to reconcile short and long-term tradeoffs and differences among stakeholders, particularly between fisher and conservation

groups. One of the barriers to moving towards the better use of marine reserves, at least in a policy context, is the relatively small number of studies that combine both the biological and economic drivers of marine reserves. Moreover, a knowledge gap exists between fisheries economists, biologists and decision makers in their understanding of marine reserves. To bridge this divide, the paper provides a selected review of the key benefits and spillovers of marine reserves combined with a more detailed description of bioeconomic models of reserves.

The paper reveals that deterministic bioeconomic models provide important insights about reserves, but also understate the value of reserves to fishers in a fluctuating environment. Models that explicitly include the spatial behaviour of fishers are of particular importance to managers as they emphasise the importance of economic considerations when establishing reserves, and also the explicit modelling of fishing effort in a decision-making framework. Bioeconomic models that allow for negative shocks, management error or environmental stochasticity have been used to show that reserves can reduce the variation in harvested population and harvests, and increase population persistence. Stochastic models also demonstrate that reserves can raise the discounted net returns to fishers even when stocks are not overexploited and harvesting is optimal in the absence of shocks.

Insights from the literature provide broad policy implications in terms of the establishment of marine reserves, especially for the purposes of improving the economics of fishing. The key management insights include one, the importance of designing reserves to meet defined objectives and the difficulty of establishing reserves that meet multiple objectives, two, the need to include stakeholders as an integral part of the planning and monitoring process, three, the merits of actively and adaptively managing reserves given the lack of knowledge of key drivers

about reserves, especially spillovers, four, the increased payoffs from reserves in the face of uncertainty and, five the value of incorporating reserve management into broader ecosystem approaches to management. Further study, especially developments in the bioeconomics of marine reserves, should, in the fullness of time, improve the management of both reserves and fisheries.

References cited

- Agardy, Tundi, Peter Bridgewater, Michael P. Crosby, Jon Day, Paul K. Dayton, Richard Kenchington, Dan Laffoley, Patrick McConney, Peter A. Murray, John E. Parks & Lelei Peau. 2003. Dangerous targets? Unresolved issues and ideological clashes around marine protected areas. *Aquatic Conservation: Marine and Freshwater Ecosystems* 13: 353-367.
- Alcala, Angel C. & Garry R. Russ. 1990. A direct test of the effects of protective management on abundance and yield of tropical marine resources. *ICES Journal of Marine Science/J. Cons. Int. Explor. Mer* 46: 40-47.
- Allison, Gary W., Jane Lubchenco & Mark H. Carr. 1998. Marine reserves are necessary but not sufficient for marine conservation. *Ecological Applications* 8(1), supplement: S79-S92.
- Anderson, Lee G. 2002. A bioeconomic analysis of marine reserves. *Natural Resource Modeling* 15(3): 311-334.
- Apostolaki, P., Eleanor J. Milner-Gulland, Murdoch K. McAllister & Geoff P. Kirkwood. 2002. Modelling effects of establishing a marine reserve for mobile fish species. *Canadian Journal of Fisheries and Aquatic Sciences* 59(3): 405-415.
- Beattie, Alisdair, Ussif Rashid Sumaila, Villy Christensen & Daniel Pauly. 2002. A model for the bioeconomic evaluation of marine protected area size and placement in the North Sea. *Natural Resource Modeling* 15(4): 414-437.
- Béné, Christophe & Alexander Tewfik, A. 2003. Biological evaluation of marine protected area: evidence of crowding effect on a protected population of Queen Conch in the Caribbean. *Marine Ecology* 24(1): 45-58.

- Bennett, B.A. & C.G. Attwood. 1991. Evidence for recovery of a surf-zone fish assemblage following the establishment of a marine reserve on the southern coast of South Africa. *Marine Ecology Progress Series* 75: 179-181.
- Beverton, Raymond J.H. & Sidney J. Holt. 1957. *On the Dynamics of Exploited Fish Populations*. Her Majesty's Stationery Office: London.
- Bhat, Mahadev G. 2003. Application of non-market valuation to the Florida Keys marine reserve management. *Journal of Environmental Management* 67: 315-325.
- Bohnsack, James.A. 1998. Application of marine reserves to reef fisheries management. *Australian Journal of Ecology* 23: 298-304.
- Botsford, Louis.W., Juan Carlos Castilla, & Charles H. Peterson. 1997. The management of fisheries and marine ecosystems. *Science* 277: 509.
- Botsford, Louis.W., Alan Hastings, & Steven D. Gaines. 2001. Dependence of sustainability on the configuration of marine reserves and larval dispersal distance. *Ecology Letters* 4: 144-150.
- Botsford, Louis.W., Fiorenza Micheli, & Alan Hastings. 2003. Principles for the design of marine reserves. *Ecological Applications* 13(1) Supplement: S25-S31.
- Brown, Gardner & Jonathan Roughgarden. 1997. A metapopulation model with private property and a common pool. *Ecological Economics* 22: 65-71.
- Bulte, Erwin H. & G. Cornelis van Kooten. 1999. Metapopulation dynamics and stochastic bioeconomic modelling. *Ecological Economics* 30: 293-299.
- Christie, Patrick, Alan White and Evelyn Deguit. 2002. Starting point or solution? Community-based marine protected areas in the Philippines. *Journal of Environmental Management* 66: 441-454.
- Clark, Colin.W. 1996. Marine reserves and the precautionary management of fisheries. *Ecological Applications* 6(2): 369-370.

- Cohen, Dan. 1966. Optimizing reproduction in a randomly varying environment. *Journal of Theoretical Biology* 12: 119-129.
- Conrad, Jon M. 1999. The bioeconomics of marine sanctuaries. *Journal of Bioeconomics* 1: 205-217.
- Côté, I.M., Mosquiera, I. and Reynolds, J.D. 2001. Effects of marine reserve characteristics on the protection of fish populations: a meta-analysis. *Journal of Fish Biology* 59 (supp. A): 178-189.
- Crowder, L.B., Lyman, S.J., Figueira, W.F. & Priddy, J. 2000. Source-sink population dynamics and the problem of siting marine reserves. *Bulletin of Marine Science* 66 (3): 799-820.
- Davidson, R.J. 2001. Changes in population parameters and behaviour of blue cod (*Paraoercis colias*; Pinguipedidae) in Long Island—Kokomohua Marine Reserve, Marlborough Sounds, New Zealand. *Aquatic Conservation: Marine and Freshwater Ecosystems* 11: 417-435.
- DeMartini, Edward E. 1993. Modeling the potential for fishery reserves for managing Pacific coral reef fishes. *Fishery Bulletin* 91(3): 414-427.
- Doyen, Luc & Christophe Béné. 2003. Sustainability of fisheries through marine reserves: a robust modelling analysis. *Journal of Environmental Management* 69: 1-13.
- Edgar, Graham J. & Neville S. Barrett. 1999. Effects of the declaration of marine reserves on Tasmanian reef fishes, invertebrates and plants. *Journal of Experimental Marine Biology and Ecology* 242: 107-144.
- Francis, Julius, Agneta Nilsson & Dixon Wareunga. 2002. Marine protected areas in Eastern African Region: how successful are they? *Ambio* 31(708): 503-511.
- Gaines, Steven D., Brian Gaylord & John L. Largier. 2003. Avoiding Current Oversights in Marine Reserve Design. *Ecological Applications* 13(1) Supplement: S32-S46.

- Gell, Fiona R. and Callum M. Roberts. 2002. *The fishery effects of marine reserves and fishery closures*. World Wildlife Fund, United States, Washington DC.
- Gell, Fiona.R. & Callum M. Roberts. 2003. Benefits beyond boundaries: the fishery effects of marine reserves. *TRENDS in Ecology and Evolution* 18(9): 448-455.
- Gerber, Leah R., Louis W. Botsford, Alan Hastings, Hugh P. Possingham, Steven D. Gaines, Stephen R. Palumbi, and Sandy Andelman. 2003. Population models for marine reserve design: a retrospective and prospective synthesis. *Ecological Applications* 13(1), supplement: S47-S64.
- Grafton, R. Quentin, Pham Van Ha & Tom Kompas. 2004. Saving the Seas: The Economic Justification for Marine Reserves. Economics and Environment Network Working Paper 0402. http://een/download_files/een0402.pdf
- Guénette, Sylvie, Tim Lauck & Colin Clark. 1998. Marine reserves: from Beverton Holt to the present. *Reviews in Fish Biology and Fisheries* 8: 251-272.
- Guénette, Sylvie & Tony J. Pitcher. 1999. An age-structured model showing the benefits of marine reserves in controlling overexploitation. *Fisheries Research* 39: 295-303.
- Guidetti, Paolo. 2002. The importance of experimental design in detecting the effects of protection measures on fish in Mediterranean MPAs. *Aquatic Conservation: Marine and Freshwater Ecosystems* 12: 619-634.
- Halpern, Benjamin S. 2003. The impact of marine reserves: do reserves work and does reserve size matter? *Ecological Applications* 13(1), supplement: S117-S137.
- Halpern, Benjamin S. & Robert R. Warner. 2002. Marine reserves have rapid and lasting effects. *Ecology Letters* 5: 361-366.
- Halpern, Benjamin S. & Robert R. Warner. 2003. Matching marine reserve design to reserve objectives. *Proceedings of the Royal Society London B* 270: 1871-1878.

- Hannesson, Rögnvaldur. 1998. Marine reserves: what would they accomplish? *Marine Resource Economics* 13: 159-170.
- Hannesson, Rögnvaldur. 2002. The economics of marine reserves. *Natural Resource Modeling* 15(3): 273-290.
- Hastings, Alan & Louis W. Botsford. 1999. Equivalence in yield from marine reserves and traditional fisheries management. *Science* 284: 1537-1538.
- Hastings, Alan & Louis W. Botsford. 2003. Comparing designs of marine reserves for fisheries and biodiversity. *Ecological Applications* 13(1), supplement: S65-S70.
- Helvey, M. 2004. Seeking consensus on designing marine protected areas: keeping the fishing community engaged. *Coastal Management* 32: 173-190.
- Holland, Daniel S. 2000. A bioeconomic model of marine sanctuaries on Georges Bank. *Canadian Journal of Fisheries and Aquatic Sciences* 57(6): 1307-1319.
- Holland, Daniel S. 2002. Integrating marine protected areas. *Natural Resource Modeling* 15(3): 369-386.
- Holland, Daniel S. & Richard J. Brazee. 1996. Marine reserves for fisheries management. *Marine Resource Economics* 11: 157-171.
- Holland, Daniel S. & Jon G. Sutinen. 2000. Location Choice in New England Trawl Fisheries: Old Habits Die Hard. *Land Economics* 76(1): 133-149.
- Hyrenbach, K. David, Karin A. Forney & Paul K. Dayton. 2000. Marine protected areas and ocean basin management. *Aquatic Conservation: Marine and Freshwater Ecosystems* 10: 437-458.
- Inglis, G. 1992. Ambiguities in the identification and selection of representative marine reserves. Pp. 23-28 in C.N. Battershill et al. (eds) *Proceedings of the Second International Temperate Reef Symposium*, 7-10 January 1992, Auckland, New Zealand.

- Jennings, Simon. 2001. Patterns and prediction of population recovery in marine reserves. .
Reviews in Fish Biology and Fisheries 10: 209-231.
- Johannes, Robert Earl. 1978. Traditional marine conservation methods in Oceania and their
demise. Annual Review of Ecology and Systematics 9: 349-364.
- Jones, Peter J.S. 1999. Marine nature reserves in Britain: past lessons, current status and future
issues. Marine Policy 23(4-5): 375-396.
- Kramer, Donald L. & Matthew R. Chapman. 1999. Implications of fish home range size and
relocation for marine reserve function. Environmental Biology of Fishes 55: 65-79.
- Lauck, Tim, Colin W. Clark, Marc Mangel, & Gordon R. Munro. 1998. Implementing the
precautionary principle in fisheries management through marine reserves. Ecological
Applications 8(1), supplement: S72-S78.
- Levins, Richard. 1970. Extinction. In Gerstenhaber, M. (Ed.) *Some Mathematical Problems in
Biology*, American Mathematical Society, Providence Rhode Island, pp. 77-107.
- Lockwood, Dale R., Alan Hastings & Luois W. Botsford. 2002. The effects of dispersal patterns
on marine reserves: does the tail wag the dog? Theoretical Population Biology 61: 297-309.
- Ludwig, Don, Ray Hilborn, & Carl Walters. 1993. Uncertainty, resource exploitation and
conservation: lessons from history. Science 260: 7, 36.
- Mangel, Marc. 1998. No-take areas for sustainability of harvested species and a conservation
invariant for marine reserves. Ecology Letters 1: 87-90.
- Mangel, Marc. 2000a. On the fraction of habitat allocated to marine reserves. Ecology Letters 3:
15-22.
- Mangel, Marc. 2000b. Irreducible uncertainties, sustainable fisheries and marine reserves.
Evolutionary Ecology Research 2: 547-557.

- McClanahan, T.R. & B. Kaunda-Arara. 1996. Fishery recovery in a coral-reef marine park and its effect on the adjacent fishery. *Conservation Biology* 10 (4): 1187-1199.
- McClanahan, T.R. & S. Mangi. 2000. Spillover of exploitable fishes from a marine park and its effect on the adjacent fishery. *Ecological Applications* 10 (6): 1792-1805.
- National Research Council. 2001. *Marine protected areas: tools for sustaining ocean ecosystems*. National Academy Press: Washington, D.C.
- Neubert, Michael G. 2003. Marine reserves and optimal harvesting. *Ecology Letters* 6: 843-849.
- Pauly, Daniel, Villy Christensen Sylvie Gu nette, Tony J. Pitcher, Ussif Rashid Sumaila, Carl Walters, R. Watson, & Dirk Zeller. 2002. Towards sustainability in world fisheries. *Nature* 418: 689-695.
- Pezzey, John C.V., Callum M. Roberts & Bjorn T. Urdal. 2000. A simple bioeconomic model of a marine reserve. *Ecological Economics* 33: 77-91.
- Pimm, Stuart L. 1984. The complexity and stability of ecosystems. *Nature* 307: 321-325.
- Polacheck, Tom. 1990. Year round closed areas as a management tool. *Natural Resource Modeling* 4(3): 327-354.
- Pulliam, H. Ronald. 1988. Source, sinks, and population regulation. *The American Naturalist* 132(5): 652-661.
- Rakitin Ana and Donald L. Kramer. 1996. Effect of a marine reserve on the distribution of coral reef fishes in Barbados. *Marine Ecology Progress Series* 131: 97-113.
- Roberts, C.M., James Bohnsack, Fiona Gell, Julie P. Hawkins & Renate Goodridge. 2001. Effects of marine reserves on adjacent fisheries. *Science* 294: 1920-1923.

- Roberts, Callum .M., George Branch, Rodrigo H. Bustamante, Juan Carlos Castilla, Jenifer Dugan, Benjamin S. Halpern, Kevin D. Lafferty, Heather Leslie, Jane Lubchenco, Deborah McArdle, Mary Ruckelhaus, & Robert R. Warner. 2003. Application of ecological criteria in selecting marine reserves and developing reserve networks. *Ecological Applications* 13(1), supplement: S215-S228.
- Roberts, Callum M. & Helen Sargent. 2002. Fishery benefits of fully protected marine reserves: why habitat and behavior are important. *Natural Resource Modeling* 15(4): 487-507.
- Roughgarden, Jonathan & Yoh Iwasa. 1986. Dynamics of a metapopulation with space-limited subpopulations. *Theoretical Population Biology* 29: 235-261.
- Rowley, Robert J. 1994. Case studies and reviews: marine reserves in fisheries management. *Aquatic Conservation: Marine and Freshwater Ecosystems* 4: 233-254.
- Russ, Garry R. Yet another review of marine reserves as reef management tools, in (Peter F. Sale, Ed.) *Coral Reef Fishes: Dynamics and Diversity in a Complex Ecosystem*, Academic Press: Amsterdam, pp 421-443.
- Sanchirico, James N. & James E. Wilen. 1999. Bioeconomics of spatial exploitation in a patchy environment. *Journal of Environmental Economics and Management* 37: 129-150.
- Sanchirico, James N. & James E. Wilen. 2001. A bioeconomic model of marine reserve creation. *Journal of Environmental Economics and Management* 42: 257-276.
- Sanchirico, James N. & James E. Wilen, J.E. 2002. The impacts of marine reserves on limited-entry fisheries. *Natural Resource Modeling* 15(3): 291-310.
- Shaffer, Mark L. 1981. Minimum population sizes for species conservation. *Bioscience* 31: 131-134.
- Sladek Nowlis, Joshua & Callum M. Roberts. 1998. Fisheries benefits and optimal design of marine reserves. *Fishery Bulletin* 97: 604-616.

- Smith, Martin D. & James E. Wilen. 2003. Economic impacts of marine reserves: the importance of spatial behavior. *Journal of Environmental Economics and Management* 46: 183-206.
- Stamps, J.A., Buechner, M. and V.V. Krishnan. 1987. The effects of edge permeability and habitat geometry on emigration from patches of habitat. *American Naturalist* 129: 533-552.
- Sumaila, Ussif Rashid 1998. Protected marine reserves as fisheries management tools: a bioeconomic analysis. *Fisheries Research* 37: 287-296.
- Sumaila, Ussif Rashid, Sylvie Gu nette, Jackie Alder & Rana Chuenpagdee. 2000. Addressing ecosystem effects of fishing using marine protected areas. *ICES Journal of Marine Science* 57: 752-760.
- Trippel, Edward A. 1995. Age at maturity as a stress indicator in fisheries. *Bioscience* 45: 759-771.
- Tuck, Geoffrey N. & Hugh P. Possingham. 1994. Optimal harvesting strategies for a metapopulation. *Bulletin of Mathematical Biology* 56(1): 107-127.
- Tuck, Geoffrey N. & Hugh P. Possingham. 2000. Marine protected areas for spatially structured exploited stocks. *Marine Ecology Progress Series* 192: 89-101.
- Turner, S.J., Thrush, S.F., Hewitt, J.E., Cummings, V.J. and Funnel, G. 1999. Fishing impacts and the degradation or loss of habitat structure. *Fisheries Management and Ecology* 6: 401-420.
- United Nations. 2002. *World Summit on Sustainable Development Plan of Implementation*. Division for Sustainable Development, http://www.un.org/esa/sustdev/documents/WSSD_POI_PD/English/POIToc.htm.
- Walters, Carl J., Daniel Pauly and Villy Christensen. 1999. Ecospace: prediction of mesoscale spatial patterns in trophic relationships of exploited ecosystems, with emphasis on the impacts of marine protected areas. *Ecosystems* 2: 539-554.

- Walters, Carl J. & Ray Hilborn. 1978. Ecological optimization and adaptive management. *Annual Review of Ecology and Systematics* 9: 157-188.
- Walters, Carl W. 2000. Impacts of dispersal, ecological interactions and fishing effort dynamics on efficacy on marine protected areas: how large should protected areas be? *Bulletin of Marine Science* 66(3):
- Ward, Trevor J., Dennis Heinemann & Nathan Evans. 2001. *The Role of Marine Reserves as Fisheries Management Tools: A Review of Concepts, Evidence and International Experience*. Bureau of Rural Sciences, Canberra, 192 pp.
- Wilen, James, E., Martin D. Smith, Dale Lockwood & Louis W. Botsford. 2002. Avoiding Surprises: Incorporating Fisherman Behavior into Management Models. *Bulletin of Marine Science* 70(2): 553-575.