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MARINE PROTECTED AREAS

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Introduction

Marine protected areas (MPAs) are a regulatory tool for conserving the natural or cultural resources of the ocean and for managing human uses through zoning. MPAs may also be referred to as marine parks, sanctuaries, reserves, or closures; the latter two terms are used most commonly in the context of fisheries management.

Definition

At a conceptual level, zoning in the ocean involves the spatial segregation of a marine area in which certain uses are regulated or prohibited. This general definition might apply to any marine area in which a set of human uses are given preference over others. For example, by law the US President may set aside hydrocarbon deposits on the US outer Continental Shelf as 'petroleum reserves.' However, the typical use of the term 'protected' implies that a primary focus of an MPA is on the conservation of either individual species and their habitats or ecological systems and functions through the regulation of 'extractive' or potentially polluting commercial uses, such as fishery harvests, waste disposal, and mineral development, among others.

MPAs are frequently considered to be a fishery management measure, but they may be used for other purposes as well. For instance, in 1975, the first US national marine sanctuary was created around the wreck of the *U.S.S. Monitor*, a civil war vessel, located off the coast of North Carolina. The sanctuary was established to prevent commercial 'treasure' salvage and looting of the shipwreck, to regulate recreational diving, and to promote archaeological studies. In the discussion below, we focus on the use of MPAs in the field of fishery management because this use represents one of the most relevant and interesting examples.

Size

Although there is no discernible size limitation, the issue of geographic scale may be another defining characteristic of MPAs. On the tidelands of US coastal states, for example, the 'public trust doctrine' gives preference in the common law to transitory public uses, typically navigation, fishing, and hunting, over permanent private uses, such as constructing a dock. Yet the tidelands, which are quite extensive, are not referred to as an MPA. Some fishery closures can be quite large, and we would classify these as one type of MPA. The Great Barrier Reef Marine Park in Australia is the largest MPA in the world, measuring 344 million km^2. Most of the world's existing MPAs are much smaller, however, and focused on unique ocean features or sites, such as coral reefs or underwater banks. The World Bank estimates the median size of a sample of about one thousand of the world's MPAs to be 15 840 km^2 (**Figure 1**).

Number

Worldwide, MPAs have become a popular form of ocean management, and their use has expanded exponentially since they were first introduced in the late nineteenth century (**Figure 2**). The trend in the establishment of MPAs follows on the heels of a more general trend in the regulation of ocean uses, as an MPA represents merely a form of governance distinguishable geographically by type or severity of regulation. Regulation of the ocean has become

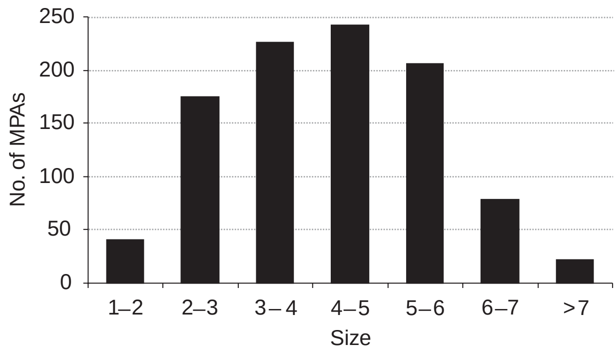

Figure 1 Worldwide size distribution of marine protected areas ($n = 991$). Sizes are grouped by km^2 to the powers of ten.

necessary as human uses of the ocean have increased in scale and variety and as conflicts among mutually exclusive uses and users have arisen.

With the expansion in the establishment of MPAs, marine scientists and policy experts have begun to take a closer look at the likely benefits and opportunity costs associated with zoning the ocean, and several recent studies have emerged. In particular, as ecological models of the marine environment become more realistic, marine policy analysts can begin to make more sophisticated examinations of how to choose among competing human uses, given the constraints presented by the natural system.

Management Objectives

The extent to which an MPA may be considered an effective management tool depends on its management objectives. Here, objectives are classified under the following general categories: Biological (ecological); economic; and distributive (equity). Often, the establishment of an MPA involves objectives from more than one of these categories. To make the discussion in the next three sections more focused,

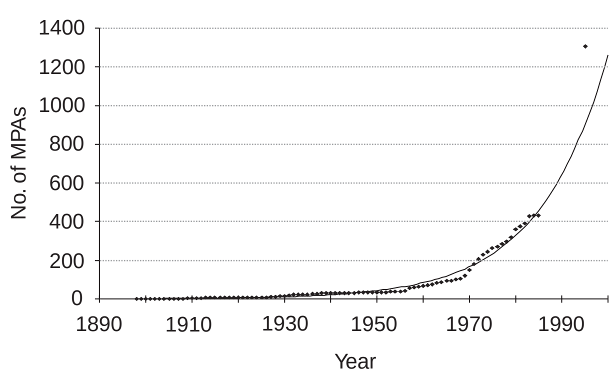

Figure 2 Cumulative worldwide growth in the number of marine protected areas and estimated logarithmic trend 1898–1995.

we ignore the complexities of the subject, and return to them in a later section.

Biology

Consider a single species fishery as a starting point, and assume that a biological objective is to increase stock size or biomass. Restrictions on fishing in certain areas are expected to lead to positive 'refuge' and 'stock' effects. The refuge effect is a static concept implying that some portion of the target stock cannot be harvested because it remains within the MPA. As a consequence, the entire stock is not exploited to the same degree as it would be in the unregulated case. The stock effect is a dynamic concept implying that fish within the MPA will grow and reproduce and that either their larva will drift out beyond the boundary of the MPA and eventually recruit to the fishery or new recruits (or possibly older, larger fish) will 'diffuse' across the boundary into the fishery. Where the behavior patterns of fish stocks are well understood, the careful placement of an MPA may be effective from a biological standpoint. One excellent example is the establishment of an MPA around a spawning aggregation in tropical fisheries.

Economics

The economic implications of an MPA depend critically upon the nature of the institutional framework for managing the fishery. Suppose that a fishery supplies only a small part of a large market and that, initially, it is unregulated. The first assumption implies that seafood consumers are not much affected by changes in the supply of fish from the fishery of concern. Assuming that an equilibrium is reached where harvests balance stock growth, theory suggests, and empirical investigations confirm, that the economic value of the fishery is near zero. In an unregulated fishery, fish are an unpriced factor in the production of seafood, and this implicit subsidy encourages too much fishing effort and, consequently, excessive exploitation. In the jargon of economics, 'resource rents' are dissipated. Depending on the scale of the variable costs of fishing, yields may fall below levels considered to be the maximum sustainable.

Now suppose that an MPA is established. The refuge effect implies that the exploitable stock is smaller for any given level of fishing effort. In the absence of any complementary regulation, fishermen will exit the fishery until an open-access equilibrium sets up for the residual exploitable stock. As before, rents are dissipated at this new equilibrium, and no economic value is created through the establishment of the MPA. Over time, the stock effect might lead to an expansion of the exploitable biomass. Again, the existence of economic rents associated with an expanding biomass will attract fishermen until rents dissipate.

It is conceivable that the exploitable biomass could expand to a level exceeding that in the fishery prior to the establishment of the MPA. This might happen where increasing returns exist in the production of eggs as female fish grow older and larger. A common example is the red snapper (*Lutjanus campechanus*), a reef fish native to the Gulf of Mexico. It has been claimed that a 10 kg red snapper produces in a single spawn more than 200 times the eggs of a fish weighing only 1 kg. Only in cases in which the stock effect more than compensates for the refuge effect and surpluses accrue to consumers due to the absence of close seafood substitutes, can a case be made that the establishment of an MPA in an otherwise unregulated fishery is valuable in an economic sense. And this result is due solely to the expansion of value to the consumer, not to the fisherman.

The establishment of an MPA might be complemented with other forms of regulation. Assuming that the costs of administering fishery regulations are minor, resource rents can be realized through the implementation of management measures in conjunction with an MPA, such as taxes on either fish landings or fishing effort or the introduction of an individual tradeable quota system. However, in theory, the implementation of these alternative management measures by themselves can lead to the capture of resource rents, implying no need for an accompanying MPA. Recent research suggests, however, that, where the stock effect overcomes the refuge effect, the establishment of an MPA can lead to increases in economic value in an otherwise optimally managed fishery.

Distribution of Economic Impacts

The third general category of objectives concerns the distribution of economic benefits and costs across human users. In attempting to achieve either biological or economic objectives, the effects of the establishment of an MPA on individual fishermen are not considered explicitly. For example, an economic decision rule would argue for the creation of an MPA as long as economic benefits exceed economic costs, assuming all relevant sources of benefits and costs are accounted for, without regard for the identities of the recipients of the surplus. Moreover, even if the creation of an MPA results in net benefits, the historical pattern of the distribution of gains may be shifted. One example is the creation of an MPA in the vicinity of a fishing port, forcing fishermen from that port to travel longer distances to fish.

In some circumstances, such as a small fishery in a developed economy, the distributional effects may be minor, as fishermen are able to switch at low cost to other stocks or to other occupations. On the other hand, the distributive effects of an MPA may be more serious for a community that is heavily reliant on a stock for income or as a source of protein. In such cases, an objective of fairness to users may necessitate foregoing potential biological or economic gains through, say, the relocation or reduction in size of an MPA. The political economy of the management regime may dictate such a result, if users are capable of influencing the adoption of an MPA through voting, negotiation, or other means.

In circumstances where some form of regulation must be imposed, it is possible that, on the basis of equity, MPAs may be the preferred choice of fishermen, relative to alternative measures. The reason for this preference is that the establishment of an MPA does not single fishermen out on the basis of gear type or other distinguishing characteristics. Further, it may be difficult to discern *ex ante* which specific fishermen eventually will bear the costs or be forced to exit.

Complexities

There are a number of important issues that increase the complexity of the simple scenarios described above. A few of these issues are touched on here, and the interested reader should refer to the reading list for further detail.

Dynamic Responses

In the discussion above, we have ignored the potential for lags in the response of the system, including the behavior of both fish stocks and fishermen, to the implementation of an MPA. Importantly, it may take more than one fishing season for the stock effect to contribute significantly to recruitment. Further, the refuge effect does not always result in the immediate exit of fishermen from the fishery. When few opportunities exist for redeploying boats and hands elsewhere, fishermen may continue to fish in the short run, as long as they can cover their variable costs (wages, fuel, ice, etc.). In certain circumstances, fishermen might rationally delay exit, expecting the stock effect to lead to a future expansion of the fishery. If fishermen delay exit, the expected stock rebuilding may be prolonged. When environmental conditions and ecological interactions are added in, it is not hard to imagine a scenario in which an MPA appears to have no effect, at least in the short run. The lack of results may lead to political action to remove the MPA.

Both fish stocks and fishing effort may be distributed nonuniformly across the fishery. This spatial distribution can be affected through the establishment of an MPA. As a consequence, location becomes an important consideration when planning an MPA. For example, recent models of plaice fisheries show that a properly located MPA can protect undersized fish when fishing effort becomes redistributed around the borders of the MPA.

Ecological Relationships

MPAs have also been established to protect aggregations of species or components of ecosystems. Even where the management of a single species is of primary concern, a characterization of the biological relationships between the species of focus and other species in the ecosystem is crucial to understanding the biological, economic, and distributional impacts of the establishment of an MPA. Where fishing technologies are nonselective, MPAs may prove beneficial in reducing the by-catch of nontarget species and minimizing the impacts of trawl gear on seafloor habitat.

Biological Diversity

Recent developments in international and domestic law have emphasized the conservation of biological diversity as a biological objective, and MPAs have been suggested as one means of achieving that objective. Although the conservation of biological diversity is an appealing concept at a superficial level, basic definitional questions persist. For example, does biological diversity refer to species richness (i.e., the number of species) or to some other measure, such as the average genetic distance among a set of species? Assuming that an appropriate measure can be agreed upon, economic research has focused on the problem of maximizing a chosen diversity measure subject to limits on financial resources. When coupled with information on species distributions and ecological relationships, this research may be useful in optimizing locations and scaling the size of MPAs.

Insurance and Precaution

The ocean is an uncertain environment. Substantial gaps exist in our understanding of ecological relationships among species, the linkages between environmental conditions and ecosystem states, especially given uncertainties about long-term environmental changes, and the impacts of fishing activity on habitat quality and on ecological relationships. For reasons of tractability, bioeconomic models of fisheries are often based on equilibrium assumptions, when it is not clear that, even if their existence is plausible, steady states can ever materialize. In the context of this uncertainty, MPAs have been touted as a hedge for insuring against stock depletion or collapse.

Although it seems reasonable to conclude that MPAs might be useful as a hedge against uncertainty, we should heed the message of economic theory that, in the long run, some MPAs may not remedy the problem of rent dissipation, especially if they are used as the only means by which to manage fisheries. Furthermore, the presence of ineluctable uncertainty raises the question of the extent of the practical contribution that fisheries scientists and marine ecologists can make to specifying the size and location of MPAs. This issue has led some observers to suggest that ‘picking’ MPAs is akin to picking securities in the stock market. They conclude that, in the long term, it may be sensible to randomly select a portfolio of MPAs that cover some agreed-upon percentage of the geography in a particular ocean region. Making estimates of the proportion of ocean area to be included in an MPA may also be problematic, as models suggest a wide range, 20–90% of the relevant area.

Irreversibilities

Human uses of the ocean can result in ecological impacts that are costly or impossible to reverse. Examples include the extinction of marine fish or protected species, such as mammals or reptiles, and biomass ‘flips,’ in which the collapse of commercially important stock groupings are replaced by others. Concerns about these irreversibilities reflect the notion that there may be preferred states for marine ecosystems. Changed ecosystems could result in smaller potential economic surpluses and a different set of options for the use of the system in the future. The latter may include ‘nonmarket’ damages when protected species or unique ecosystems, such as coral reefs or underwater banks, are affected adversely.

In the presence of uncertainty about human uses or ecosystem states, it may be worthwhile to delay decisions to proceed with human uses, such as fishing, that result in irreversible effects, where the development of new information reduces the uncertainty. The existence of this ‘quasi-option value’ may be a formal justification for taking the so-called ‘precautionary approach’ to fisheries management. The precautionary approach, which has now become embodied in international soft law, argues for the maintenance of commercial fish stocks at relatively high levels because, when accounting for uncertainty, the expected losses due to overexploitation exceed those due to underexploitation. Some analysts have pointed to MPAs as an essential element of a precautionary approach. The value of MPAs in this context may be most apparent when they are employed as a control in a scientific experiment designed to test hypotheses about the impacts of fishing. The partial closure of the US portion of Georges Bank to sea scallop dredging, for example, provided valuable information on the ability of that stock to rebuild in a discrete area.

The designation of an MPA can be conceptualized as a kind of 'administrative' irreversibility, where it may be difficult to modify the designation through political processes. To many observers and interests, this kind of policy inflexibility may be the whole point to designating an MPA. Nevertheless, as environmental conditions change, ecosystems adjust, and it is sensible to have in place a management tool that can also be adjusted. The boundaries of the Canadian 'Endeavor Hot Vents' MPA off the coast of Vancouver, which has been proposed at the site of a deep-sea hydrothermal system, is designed to be adjusted as vents turn on and off and their associated microbial and faunal assemblages appear and disappear.

Administrative Costs

MPAs have been promoted as a management tool that is less costly than alternative measures. Recent research suggests that management costs may decline with the size of an MPA as fixed costs of monitoring and enforcement are spread over larger areas (**Figure 3**). The degree to which MPAs are less costly to manage may depend, however, on the form of management. If MPAs are complemented with other management measures, it may be difficult to argue that the entire management regime is less costly.

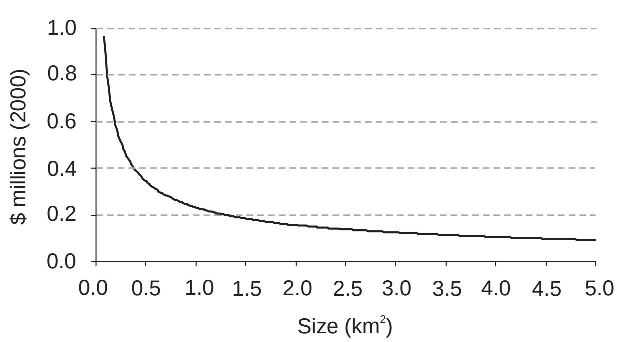

Figure 3 An estimate for small marine protected areas (MPA) of the relationship between size and the average costs of establishing and managing an MPA. The relationship demonstrates economies of scale. Costs include the acquisition of coastal land, demolition of existing structures, development, and operating costs (capitalized at 5%). Average costs are estimated from data pertaining to size alternatives for the proposed Salt River Bay MPA in St Croix, US Virgin Islands.

Many MPAs have been criticized as being 'paper parks' because monitoring and enforcement are minimal. In such cases, the apparent 'savings' in administrative costs relative to other management measures are illusory. Although some users may be dissuaded from breaking the rules inside the boundaries of an MPA, others weigh the product of the probability of apprehension and the penalty, concluding from this calculation that it is rational to ignore the rules. Even in well-monitored and enforced areas, poaching occurs, as enforcement actions in fishery closures in the US Gulf of Maine demonstrate on a regular basis. Limits on government budgets may imply that some portions of very large MPAs are paper parks.

Summary

MPAs clearly hold promise as a rational way of managing ocean resources, but this promise should not be overstated. In particular, MPAs should not be seen as a panacea to all the problems of fisheries management. Indeed, the best way to see MPAs is probably as part of a collection of management tools and measures. As the marine counterpart to systems of national and international parks, they are conceptually easy to understand and naturally appealing to the public. Yet MPAs differ in important ways from land parks because of their relative inaccessibility, the fugitive nature of fish stocks and the physical transport of pollutants and plankton, the legal characteristics of property rights in the ocean, and the costs of monitoring human activities. As we learn more about the ocean and the workings of its environmental and ecological systems, and as demand for the special characteristics of these systems expands with growing coastal populations, we can expect the use of MPAs to grow as well.

See also

Coral Reef and Other Tropical Fisheries. Deep-sea Fishes. Dynamics of Exploited Marine Fish Populations. Ecosystem Effects of Fishing. Fisheries: Multispecies Dynamics. Fishery Management. Fishery Management, Human Dimension. Fishery Manipulation through Stock Enhancement or Restoration.

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MARINE SILICA CYCLE

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Introduction

Silicate, or silicic acid (H_4SiO_4), is a very important nutrient in the ocean. Unlike the other major nutrients such as phosphate, nitrate, or ammonium, which are needed by almost all marine plankton, silicate is an essential chemical requirement only for certain biota such as diatoms, radiolaria, silicoflagellates, and siliceous sponges. The dissolved silicate in the ocean is converted by these various plants and animals into particulate silica (SiO_2), which serves primarily as structural material (i.e., the biota's hard parts). The reason silicate cycling has received significant scientific attention is that some researchers believe that diatoms (one of the silica-secreting biota) are one of the dominant phytoplankton responsible for export production from the surface ocean (Dugdale *et al*., 1995). Export production (sometimes called new production) is the transport of particulate material from the euphotic zone (where photosynthesis occurs) down into the deep ocean. The relevance of this process can be appreciated because it takes dissolved inorganic carbon from surface ocean waters, where it is exchanging with carbon dioxide in the atmosphere, turns it into particulate organic matter, and then transports it to depth, where most of it is regenerated back into the dissolved form. This process, known as the 'biological pump', along with deep-ocean circulation is responsible for the transfer of inorganic carbon into the deep ocean, where it is unable to exchange with the atmosphere for hundreds or even thousands of years. Consequently, silicate and silica play an important role in the global carbon cycle, which affects the world's climate through greenhouse feedback mechanisms. In addition, the accumulation of biogenic silica on the ocean floor can tell us where in the ocean export production has occurred on timescales ranging from hundreds to millions of years, which in turn reveals important information concerning ocean circulation and nutrient distributions.

Basic Concepts

In understanding the cycling of silicate in the oceans, the concept of mean oceanic residence time