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PLUGGING A HOLE IN THE OCEAN: THE EMERGING SCIENCE OF MARINE RESERVES[1]

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Rapid and radical degradation of the world's oceans is triggering increasing calls for more effective approaches to protect, maintain, and restore marine ecosystems (Allison et al. 1998, Murray et al. 1999, NRC 1999*a*, 2000*a*). A broad spectrum of land and ocean-based activities, coupled with continued growth of the human population and migration to coastal areas, is driving unanticipated, unprecedented, and complex changes in the chemistry (Committee on Environment and Natural Resources 2000, NRC 2000*b*, Boesch et al. 2001), physical structure (Lubchenco et al. 1995, Watling and Norse 1998), biology and ecological functioning (Lubchenco et al. 1995, Vitousek et al. 1997, Botsford et al. 1997, Watling and Norse 1998, NRC 1999*b*, NMFS 1999, FAO 2000, Hutchings 2000, Carlton 2001, Jackson et al. 2001) of oceans worldwide. Symptoms of complex and fundamental alterations to marine ecosystems abound, including increases in: coral bleaching, zones of hypoxic or anoxic water, abrupt changes in species composition, habitat degradation, invasive species, harmful algal blooms, marine epidemics, mass mortalities, and fisheries collapses (Botsford et al. 1997, Vitousek et al. 1997, Harvell et al. 1999, NRC 1999*b*, 2000*a*). Fishing practices, coastal development, land-based chemical and nutrient pollution, energy practices, aquaculture, land use and land transformation, water use and shipping practices combine to alter the structure and functioning of marine ecosystems globally (Lubchenco et al. 1995). Fundamental alterations to ecosystem structure include changes in species diversity; population abundance, size structure, sex ratios, and behavior; habitat structure; trophic dynamics; biogeochemistry; biological interactions; and more. These changes in turn affect the functioning of marine ecosystems and the consequent provision of goods and services (Lubchenco et al. 1995, Peterson and Lubchenco 1997). As both the value and vulnerability of marine ecosystems become more broadly recognized, there is an urgent search for effective mechanisms to prevent or reverse widespread declines and to protect, maintain, and restore ocean ecosystems.

Fully protected marine reserves are an emerging tool for marine conservation and management. Defined as ''areas of the ocean completely protected from all extractive and destructive activities,'' fully protected marine reserves (hereafter, simply ''marine reserves'') have explicit prohibitions against fishing and the removal or disturbance of any living or nonliving marine resource, except as necessary for monitoring or research to evaluate reserve effectiveness. Sometimes called ''ecological reserves'' or ''no-take areas,'' marine reserves are a special class of ''marine protected areas,'' (MPAs). MPAs are defined as ''areas of the ocean designated to enhance conservation of marine resources.'' The actual level of protection within MPAs varies considerably; most allow some extractive activities such as fishing, while prohibiting others such as drilling for oil or gas. A third definition will complete the set and allow use of the appropriate terms throughout this special issue. A ''network of marine reserves'' is ''a set of marine reserves within a biogeographic region, connected by larval dispersal and juvenile or adult migration.'' (IUCN 1994, NRC 2000*a*).

By protecting geographical areas, including both resident species and their biophysical environments, marine reserves offer an ecosystem-based approach to conservation or fisheries management, which is distinct from the traditional focus on single species conservation or management (NMFS 1999, NRC 1999*a*). Marine reserves may provide multiple benefits including: protection of habitat; conservation of biodiversity; protection or enhancement of ecosystem services; recovery of depleted stocks of exploited species; export of individuals to fished areas; insurance against environmental or management uncertainty; and sites for scientific investigation, baseline information, education, recreation, and inspiration (Allison et al. 1998, NRC 2000*a*). Research is demonstrating that marine reserves are powerful management and conservation tools, but they are not a panacea; they cannot alleviate all problems, such as pollution, climate change, or overfishing, that originate outside reserve boundaries. Marine reserves are thus emerging as a powerful tool, but one that should be complemented by other approaches.

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Despite keen interest on the part of some, but serious skepticism by others with respect to the potential of marine reserves to protect biodiversity, protect habitats, and restore depleted fisheries, concrete information about marine reserves has been fragmentary until recently. In 1997, few syntheses of results from the various marine reserves around the world existed: modeling studies of marine reserves left critical questions unanswered, similarities and differences between terrestrial parks and marine reserves were fuzzy, and possible conflicts between different goals for marine reserves (e.g., between conservation and fishery enhancement) were unresolved. A symposium on marine reserves at the 1997 Annual Meetings of the American Association for the Advancement of Science, (see Allison et al. 1998) concluded that marine reserves appeared to hold substantial promise, but that progress in evaluating this potential would require a serious effort at analysis, modeling, and synthesis.

As a direct result of that symposium, a Working Group on Marine Reserves was convened in 1999 at the National Center for Ecological Analysis and Synthesis. The work was conducted as part of the 'Developing the Theory of Marine Reserves' Working Group supported by the National Center for Ecological Analysis and Synthesis, a Center funded by NSF (Grant #DEB-0072909), the University of California, and the Santa Barbara campus. Additional support was also provided for the Postdoctoral Associate Sandy Andelman in the Group. The goal of this effort was to advance the theory of marine reserve design, synthesize data on the performance of existing reserves, and develop tools to apply the new theory to practical situations. This Special Issue is one product. The 16 papers herein, all products of the Working Group on Marine Reserves plus a suite of other contributions, have substantially increased our understanding of the role of marine reserves in protecting and restoring marine ecosystems, and allowed us to define the next stages of implementation of this critical management option. In addition to the papers in this volume, see Hastings and Botsford (1999), Barber et al. (2000), Botsford et al. (2001), Palumbi (2001), Palumbi and Hedgecock (2001), and Lubchenco et al. (2002) for other papers from the NCEAS Marine Reserves Working Group.

The papers presented here address three key aspects of marine reserve science. The first set of papers (Allison et al. 2003, Botsford et al. 2003, Gaines et al. 2003, Gerber et al. 2003, Hastings and Botsford 2003, Largier 2003) examines the theoretical underpinning of reserves, especially the relationship between reserve design and fisheries/conservation functions. An important advance is the development of models of networks of reserves that explore how multiple reserves arrayed along a coastline may interact to augment the contributions of individual reserves. Both reviews of existing theory and new models show how dispersal, reserve configuration, catastrophes, climate variability, and fisheries effort interact to influence the value of reserves. A common goal of these theoretical efforts is the search for inherent compromises between reserves designed to meet fisheries vs. conservation goals. Surprisingly few compromises have emerged as many of the design principles that promote population persistence converge on the principles that promote sustainability in fisheries. Oceanography is developing in ways that generate a clearer understanding of how water moves away from and is retained close to shore. This focus on very shallow water is methodologically challenging but crucial to the blending of nearshore marine biology and oceanographic monitoring that reserve science relies upon.

A second set of papers (Carr et al. 2003, Grantham et al. 2003, Halpern 2003, Neigel 2003, Palumbi 2003, Shanks et al. 2003) reviews existing data on several key ecological and life history features of marine species and communities. Data on species–area relationships, dispersal distances, genetic structure and larval developmental periods represent timely contributions that are used to parameterize marine reserve models and to contrast patterns with terrestrial species.

Finally, the third set of papers (Airamé et al. 2003, Leslie et al. 2003, Roberts et al. 2003*a*, *b*) examines the practical application of reserve design criteria in real world settings. These contributions focus on lessons learned from existing reserves as well as on criteria for the design and implementation of marine reserve networks that are "comprehensive, representative and adequate," the three goals identified for terrestrial conservation efforts (Margules and Pressey 2000). Some important examples of the implementation of reserves around the world are included and provide insights into the benefits and challenges of integrating ecological theory into marine reserve policy. The use of mathematical siting algorithms (Possingham et al. 2000, Airamé et al. 2003, Leslie et al. 2003), coupled with geographic information systems, provides an explicit and transparent mechanism for identifying spatially explicit maps of alternative reserve network scenarios that efficiently represent the full range of biodiversity that is characteristic to a region. Such methods provide a level of design flexibility that cannot be obtained through exclusively expert-opinion driven approaches.

Marine reserve research has benefited from a large number of excellent reviews and collections of papers (e.g., Roberts and Polunin 1991, Agardy 1994, 2000, Dayton et al. 1995, Roberts et al. 1995, McManus 1997, Ballantine 1999). The papers published in this special issue represent an incremental contribution that brings together new theory and syntheses of empirical data to advance understanding of the role of marine reserves in protecting and restoring marine ecosystems. More importantly, they demonstrate unequivocally that marine reserves are a viable and useful management tool in a wide variety of different settings.

Based on the reviews just cited and on the findings reported in this issue, a Scientific Consensus Statement on Marine Reserves and Marine Protected Areas was written and released at a symposium entitled ''The Science of Marine Reserves'' at the 2001 American Association for the Advancement of Science. The full statement, its context, statement, and list of 161 signatories are available online from the National Center for Ecological Analysis and Synthesis (NCEAS) in Santa Barbara, California, USA.[6] The core of the statement was a new consensus by marine scientists about marine reserves that was endorsed by all of the authors of papers in this special issue as well as a large number of other scientists with expertise in marine reserves. The scientific consensus statement synthesizes the findings reported in this issue in language that is useful to scientists and nonscientists alike:

THE SCIENTIFIC CONSENSUS

The first formal marine reserves were established more than two decades ago. Recent analyses of the changes occurring within these marine reserves allow us to make the following conclusions:

Ecological effects *within* reserve boundaries:

1) Reserves result in long-lasting and often rapid increases in the abundance, diversity and productivity of marine organisms.
2) These changes are due to decreased mortality, decreased habitat destruction and to indirect ecosystem effects.
3) Reserves reduce the probability of extinction for marine species resident within them.
4) Increased reserve size results in increased benefits, but even small reserves have positive effects.
5) Full protection (which usually requires adequate enforcement and public involvement) is critical to achieve this full range of benefits. Marine protected areas do not provide the same benefits as marine reserves.

Ecological effects *outside* reserve boundaries:

1) In the few studies that have examined spillover effects, the size and abundance of exploited species increase in areas adjacent to reserves.
2) There is increasing evidence that reserves replenish populations regionally via larval export.

Ecological effects of reserve networks:

1) There is increasing evidence that a network of reserves buffers against the vagaries of environmental variability and provides significantly greater protection for marine communities than a single reserve.
2) An effective network needs to span large geographic distances and encompass a substantial area to protect against catastrophes and provide a stable platform for the long-term persistence of marine communities.

ANALYSES OF THE BEST AVAILABLE EVIDENCE LEADS US TO CONCLUDE THAT:

- Reserves conserve both fisheries and biodiversity.
- Reserves must encompass the diversity of marine habitats in order to meet goals for fisheries and biodiversity conservation.
- Reserves are the best way to protect resident species and provide heritage protection to important habitats.
- Reserves must be established and operated in the context of other management tools.
- Reserves need a dedicated program to monitor and evaluate their impacts both within and outside their boundaries.
- Reserves provide a critical benchmark for the evaluation of threats to ocean communities.
- Networks of reserves will be necessary for long-term fishery and conservation benefits.
- Existing scientific information justifies the immediate application of fully protected marine reserves as a central management tool.

This statement and the papers in this issue on which it is based demonstrate the emergence of a science of marine reserves, a dynamic discipline that has made major strides in the past five years. This increase in knowledge allows us to see where the next phases of critical research lie. Two are worth highlighting—one biological, the other socioeconomic. Even though marine reserves are inherently a multispecies, ecosystem-based approach to management, the theoretical basis for their design remains largely focused on single species. Considerations of multispecies responses continue to rest on simple extrapolations from single species predictions. Although empirical studies have shown important consequences of ecological interactions following the establishment of reserves, our understanding of how such interactions affect the design principles of reserves is still rudimentary. Perhaps an even greater need lies in the interface between ecological and socioeconomic disciplines. Our workshops only began to address the crucial interaction between the broad range of human stakeholders and reserve success (see Roberts et al. 2003*b*), or the best methodologies for engaging

[6] URL: ⟨http://www.nceas.ucsb.edu/consensus⟩

different interest groups in the process of marine reserve research and design. The various socioeconomic disciplines have much to offer to the topic of marine reserves.

The design and implementation of comprehensive, representative, and adequate reserve networks is the next great challenge for marine policy and resource management. Current information suggests that several features of marine ecosystems will dominate design principles. Although the topology of a network of marine protected areas can be complex, and there can be many differences between potential network designs, all networks have four key features that play fundamental roles in their functioning. These include (1) the span of the network (the length of coastline or area of habitat between the most distant protected units), (2) the size and shape of individual reserve units, (3) their number, and (4) their placement. Together these features determine other critical network features like the amount of area dedicated to protection and connectivity among reserve units. There are of course important network features that are unique to particular settings, but the above features seem to be common to most if not all networks, and provide useful focus to crystallize generalizations.

The answer to the question, ''how much is enough'' is the holy grail of conservation in both marine and terrestrial ecosystems. The goal of marine reserves is to ensure the persistence of the full range of marine biodiversity—from gene pools to populations, to species and whole ecosystems—and the full functioning of the ecosystem in providing goods and services for present and future generations. Because there will always be opportunity costs to conservation, there is a limit to how much we can conserve. Hence the crucial need to identify and debate criteria for adequacy. In the context of designing and managing marine reserve networks, decisions about adequacy are particularly challenging, given the complex life histories of many marine organisms, and our limited ecological knowledge of marine ecosystems. Although we cannot yet offer definitive answers to the question of adequacy, some important new insights have emerged from the body of work in this volume.

A century ago, T. H. Huxley stated that the oceans were an inexhaustible source of food and industrial products for humans to use with confidence. Our challenge today is to help ensure that this statement becomes true by building a heritage of reserve networks that will safeguard marine communities and will complement more traditional fisheries management tools, making it more likely that future generations will inherit the beauty and productivity of the oceans.

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