Marine Reserves

A TOOL FOR ECOSYSTEM MANAGEMENT AND CONSERVATION

Prepared for the
Pew Oceans Commission by

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PEW OCEANS COMMISSION

Front and Back Cover: *Waving sea fans and octocorals frame a blue angelfish,* **Holacanthus bermudensis,** *on a coral reef in the waters of Florida Keys National Marine Sanctuary. Every marine ecosystem houses a complex assortment of species that have a wide variety of habitat needs, life strategies, and value to humans. Current scientific knowledge suggests that the best way to protect and preserve living marine resources and create a legacy in the oceans for future generations is to establish dense networks of fully protected marine reserves—areas in which no extractive use of any living, fossil, or mineral resource, nor any habitat destruction is allowed.*

Opposite: *Orca,* **Orcinus orca,** *North Pacific Ocean*

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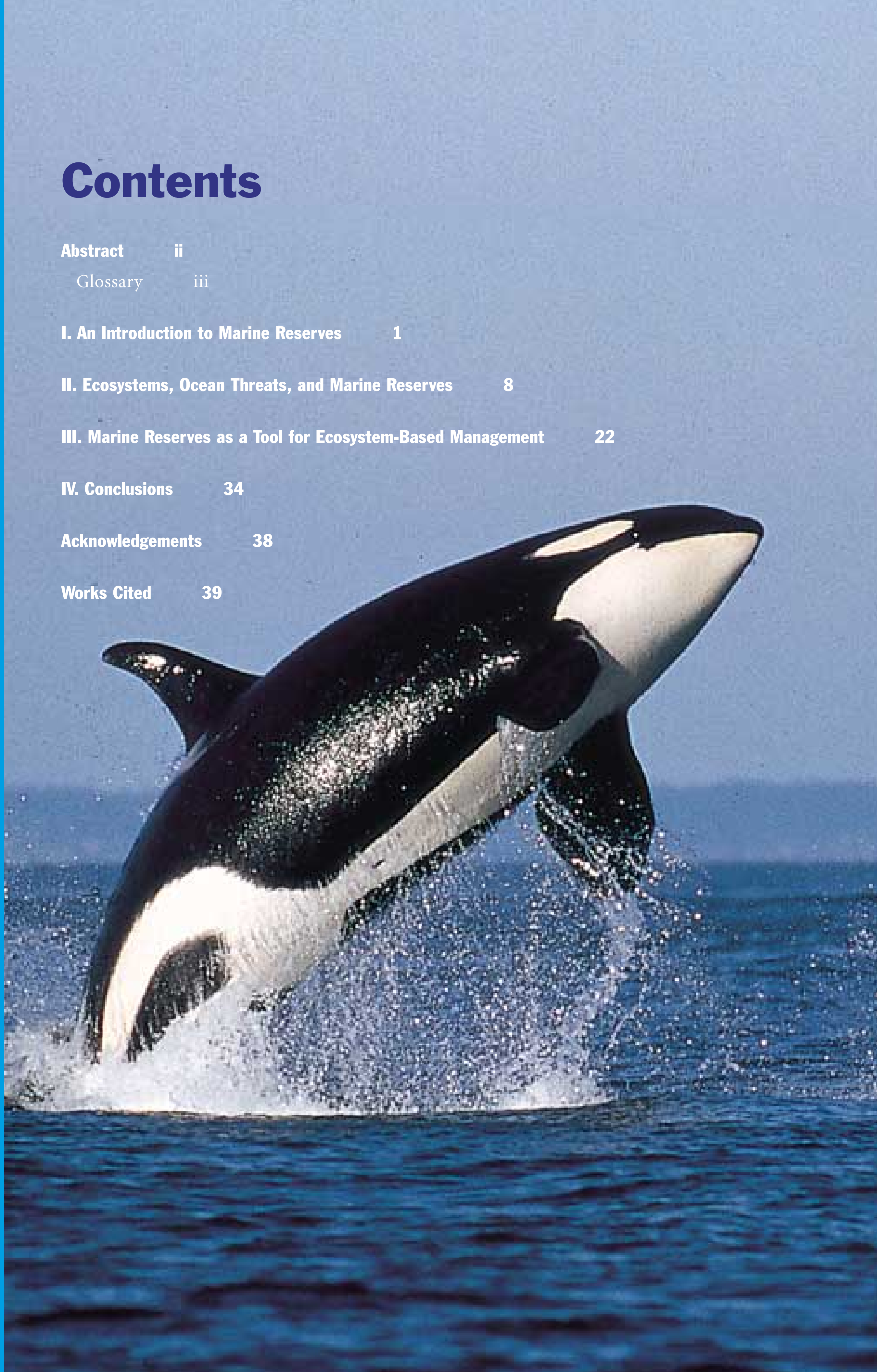


Abstract

Chuck Davis

Bat Stars, *Asterina miniata,* Point Pinos, California

Marine ecosystems around the United States are the targets of intensive alteration by coastal development, pollution, commercial fishing, recreational fishing, tourism, and a host of other human-mediated activities. Ecosystems are breaking down, giving way to invading organisms and losing important commercial species, and they are failing to replenish themselves at the same rate they are being damaged or exploited. Fishing as a commercial lifestyle is under threat almost everywhere in the U.S., and the seas are crowded with competing users.

Although threats as different as pollution and overfishing may seem unrelated, they all affect ecosystems in the same basic way—through negative impacts on marine populations. In turn, each affected population perturbs others around it because populations in ecosystems are linked by species interactions. When different impacts pour into one ecosystem, many of the species and their interactions are damaged, in some cases resulting in an ecosystem collapse. As a result, whole ecosystems absorb and integrate the spectrum of varied ocean threats and have become critical foci for marine management.

To date, networks of fully protected marine reserves are the best-understood tool for managing marine ecosystems. Over the last 15 years, study of more than one hundred reserves shows that reserves usually augment population numbers and the individual size of overexploited species. Reserves provide protection from three major consequences of overfishing. First, they protect individual species of commercial or recreational importance from harvest inside reserve bounderies. Second, they reduce habitat damage caused by fishing practices that alter biological structures, such as oyster reefs, necessary to maintain marine ecosystems. Third, reserves protect from ecosystem overfishing, in which removal of ecologically pivotal species throws an ecosystem out of balance and alters its diversity and productivity. Within reserves, protection from all three types of overfishing is well known to spark ecosystem rebounds. Examples of these rebounds form a solid empirical backdrop for the use of reserves as a management tool.

However, there are limits to how well reserves can effect ecosystem rebounds, and these limits are becoming better understood. The conservation value of reserves is best demonstrated by the fact that reserves augment population size and biomass within their borders. Fisheries benefits can accrue through spillover into surrounding local communities, a facet of reserve function that is increasingly documented at local levels but not yet at the regional level. Currently, effects of reserves on regional marine ecosystems are poorly known, except through results of mathematical models.

Based on current knowledge, the best way to protect and preserve marine resources and create a legacy in the oceans for future generations is to establish dense networks of marine reserves of

varying sizes and spacing. Reserve systems intended to help sustain healthy ecosystems must include representatives of all habitat types, and have sufficient enforcement and monitoring. Continuing research should include social and economic effects of reserves as well as their impact on regional marine ecosystems. Marine reserves should be part of an overall coordinated plan to protect and utilize sustainable marine ecosystems throughout the U.S. In the future, oceans must be alive with fish, algae, mammals, and invertebrates, while remaining the commercial and recreational center for an exploding coastal population. Achieving this vision requires extensive efforts, and marine reserves are a fundamental part of those efforts.

Glossary

Biodiversity is the variety of life, often divided into three hierarchical levels: genetic diversity (genetic variation within an individual species), species diversity (the number of species within an ecosystem), and ecosystem diversity (a variety of different types of ecosystems).

Biomass is the measure of the amount of living matter that exists in an area.

Dispersal potential is the intrinsic ability of a single animal to travel away from its parents. This potential is not always realized because it depends on ocean currents and other environmental variables. For example, species with a long planktonic phase in their early life have a high dispersal potential because they can potentially drift long distances.

An **ecosystem** is an integrated system of living species, their habitat, and their interaction with other species and environmental factors.

Ecosystem health refers to the capability of an ecosystem to support and maintain a productive and resilient community of organisms that has a species composition, diversity, and functional organization comparable to the natural habitat of the region. Such an ecosystem is capable of providing a range of ecological goods and services to people and other species in amounts and at rates comparable to those that could be provided by a similar undisturbed ecosystem.

Ecosystem overfishing is the fishing-induced impact on an ecosystem, including a reduction in species diversity and a change in community composition; a large variation in abundance, biomass, and production in some of the species; a decline in mean trophic levels within ecological systems; and significant habitat modification or destruction. Catch levels considered sustainable under traditional single-species management may adversely affect other living marine resources, creating ecosystem overfishing.

Ecosystem resilience is the ability of an ecosystem to resist change and recover after a disturbance.

A **keystone species** is a species whose absence has a dramatic affect on the distribution or abundance of other important species in the community. The sea otter is a classic marine keystone species.

A **marine protected area** is any area of the ocean designated by law, regulation, or other authority, to provide any of a variety of levels of protection to the enclosed environment, including flora, fauna, and historical and cultural resources.

A **marine reserve** is a marine protected area in which no extractive use of any resource—living, fossil, or mineral—nor any habitat destruction is allowed.

Ocean zoning is a management approach in which discrete regions of the ocean are identified for specific human uses that are permitted or prohibited by law, regulation, or other authority on a temporary or permanent basis.

A **self-seeding reserve** is a reserve that maintains steady populations of species because the offspring of adults in the reserve repopulate the reserve each generation.

Single-species management focuses on the benefits and impacts of only one species during the development of a management plan. In this traditional approach to fisheries management, little or no consideration is given to impacts on other species in an ecosystem or to an ecosystem as a whole.

Spinner Dolphins, *Stenella longirostris,* off Hawaii

I. An Introduction to Marine Reserves

The ocean is a global highway, a self-filling pantry, and the Earth's lungs. Its influence rises far above high tide, washing into the lives of every human—even those with homes in communities far inland. However, it isn't the sea itself that does yeoman's duty in supporting human populations—it is the life of the sea. Without the sea's microbial plant and animal species to produce oxygen, absorb CO_2, produce food, break down wastes, stabilize coastlines, and aerate sediments, life above sea level would be greatly different. For centuries, the vastness of the sea and the bounty of its life made any human-induced deterioration nearly unthinkable. "I believe, then, …that probably all the great sea fisheries, are inexhaustible…" reassured nineteenth-century biologist Thomas Huxley (Huxley, 1883). Unfortunately, they are not. Entire marine ecosystems are affected at nearly every level by a variety of threats—from overfishing to chemical pollution and physical alterations. The ability of ecosystems to absorb these impacts is pivotal to the long-term health of the oceans. Evaluating and responding to these threats in an integrated fashion is the most critical management challenge.

The goal of this report is to summarize current information on one emerging tool in marine ecosystem management—fully protected marine reserves. To place this tool in its biological perspective requires an additional focus on marine ecosystems, how they function, the types of threats they face, and how reserves can address them. Topics such as the mechanisms that governments have used to establish reserves and new social and economic approaches to evaluating them are introduced but comprehensive treatment of these is outside the scope of this report. The following chapters focus on the biology of reserves, how they fit into current management schemes, how they differ from traditional management, and the hope they bring to solving daunting problems. The diversity of ways reserves can function in marine management is one of their principal virtues. However, some management goals cannot be reached with reserves, and these need to be noted as well.

The scientific evidence on the benefits of reserves is overwhelming in some areas, currently emerging in others, and frustratingly poor at some crucial junctures. An important goal of the report is to highlight these different levels of knowledge in order to foster a sense of the practical utility of reserves in future management of the oceans.

The Nature of Reserves

Marine reserves are a special category of marine protected areas. Whereas any marine habitat in which human activity is managed is


Steve Simonsen/Marine Scenes

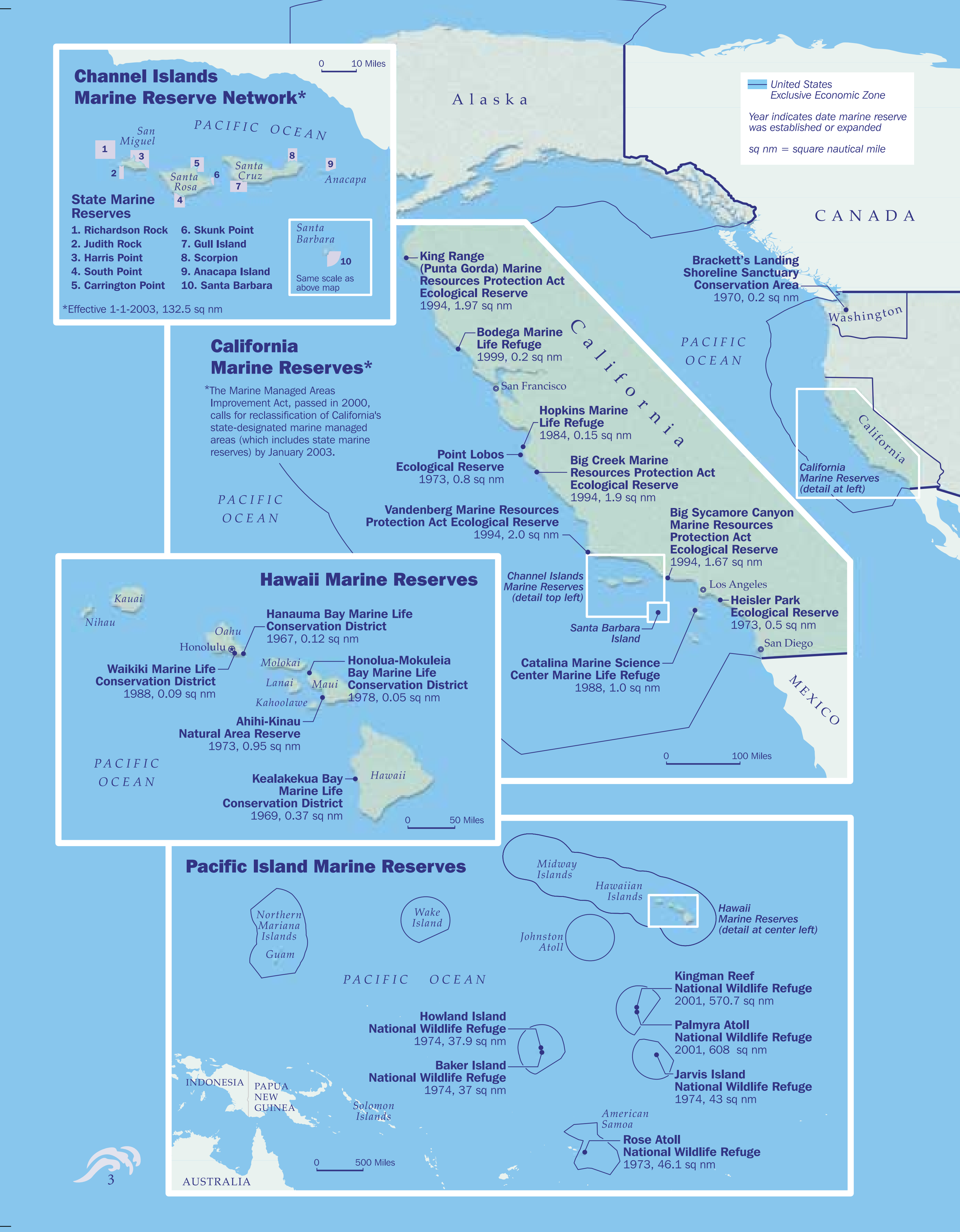
Reef in waters near Solomon Islands

a marine protected area, marine reserves are areas in which no extractive use of any resource—living, fossil, or mineral—nor any habitat destruction is allowed. These areas are generally called fully protected marine reserves, and they represent the major management tool discussed in this report. Other, less comprehensive levels of protection from extraction—seasonal closures, bans on taking reproductive individuals, and catch limits—are common in U.S. marine habitats. There are also areas in which mineral extraction or waste disposal is restricted. Any area in which these types of habitat or species protection occur can be called a marine protected area.

Because there are so many different types of marine protected areas, a map of their placement can be confusing or even misleading. Large areas of seemingly protected coast may, in fact, provide poor comprehensive protection. For example, the large expanses of the 13 national marine sanctuaries seem to be the crown jewel of the U.S. marine reserve system. However, these sanctuaries provide protection mostly against oil and gas development. Fully protected marine reserves only exist where they have been carefully negotiated with the local community (Figure One, page 3–4). Even large numbers of marine protected areas may include few reserves: marine protected areas in California number over 100, but less than a quarter of one percent of their combined area is completely protected from fishing (McArdle, 1997). In the Gulf of Maine, there is an impressive mosaic of protected areas (The Ocean Conservancy, 2002), but full protection is implemented in only three tiny wildlife refuges. In most areas, protection is limited to a single species or is focused on a single activity such as oil exploration.

Where Are Marine Reserves?

The scientific and marine management literature sports abundant examples of fully protected marine reserves—hereafter, simply called marine reserves—established along many different coastlines around the world. Over the last 30 years, reserves have been established along coral reefs, temperate shores, in estuaries, mangroves, and many other habitats (Agardy, 1997). Despite these examples, the area protected in marine reserves is still a tiny fraction of one percent of the world's oceans (NRC, 1999), a small figure compared to the four percent of global land area protected in terrestrial parks (Primack, 2000). Across North America, the area protected in state and federal parks outstrips the area in marine reserves by a ratio of 100 to 1 (Primack, 2000; Roberts and Hawkins, 2000). Marine reserves

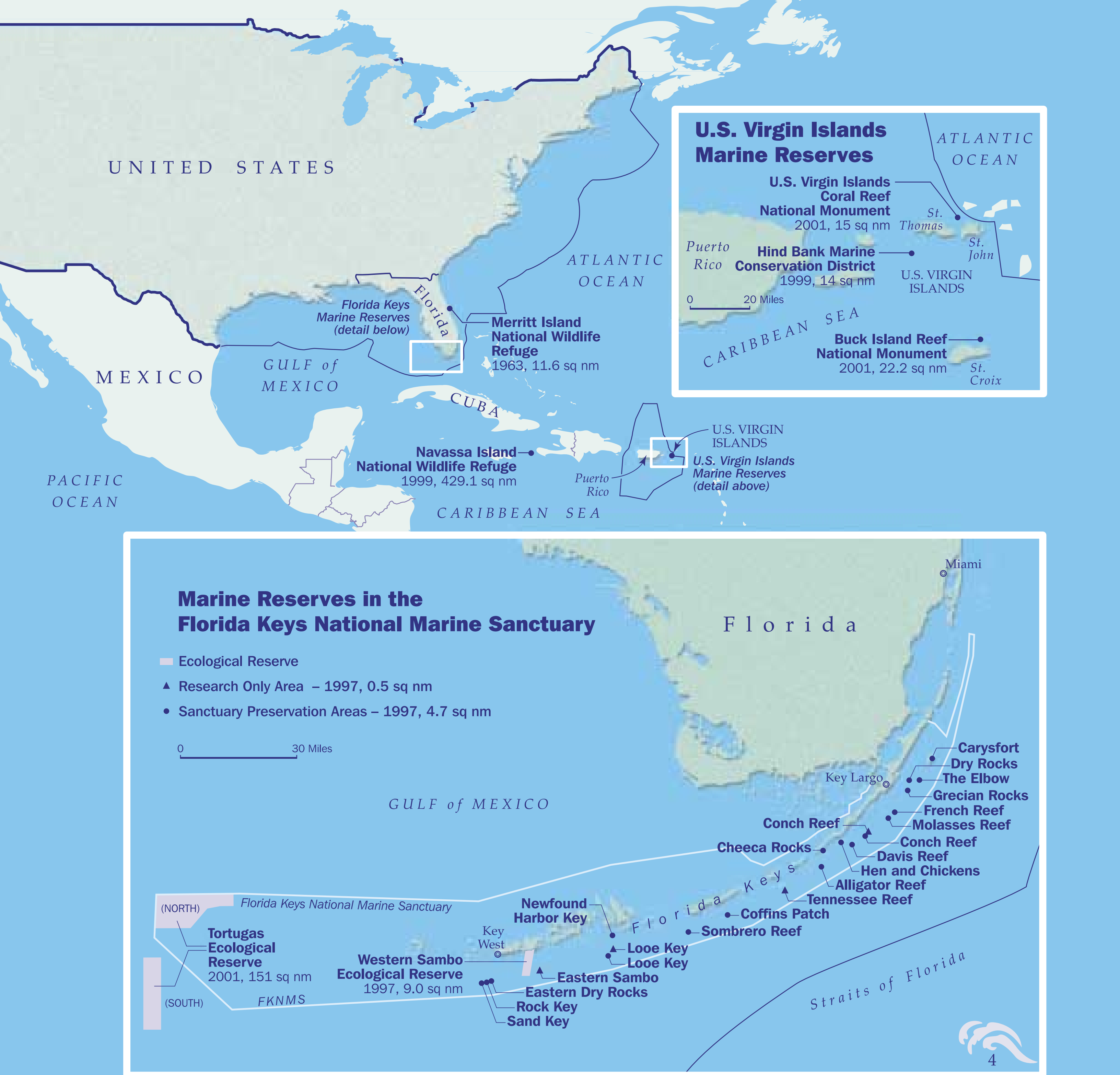


Channel Islands
Marine Reserve Network*
0 10 Miles
PACIFIC OCEAN
San Miguel
Santa Rosa
Santa Cruz
Anacapa
1
2
3
4
5
6
7
8
9
State Marine Reserves
1. Richardson Rock
2. Judith Rock
3. Harris Point
4. South Point
5. Carrington Point
6. Skunk Point
7. Gull Island
8. Scorpion
9. Anacapa Island
10. Santa Barbara
Santa Barbara
10
Same scale as above map
*Effective 1-1-2003, 132.5 sq nm
Alaska
CANADA
United States Exclusive Economic Zone
Year indicates date marine reserve was established or expanded
sq nm = square nautical mile
California
Marine Reserves*
*The Marine Managed Areas Improvement Act, passed in 2000, calls for reclassification of California's state-designated marine managed areas (which includes state marine reserves) by January 2003.
King Range (Punta Gorda) Marine Resources Protection Act Ecological Reserve
1994, 1.97 sq nm
Bodega Marine Life Refuge
1999, 0.2 sq nm
San Francisco
Hopkins Marine Life Refuge
1984, 0.15 sq nm
Point Lobos Ecological Reserve
1973, 0.8 sq nm
Big Creek Marine Resources Protection Act Ecological Reserve
1994, 1.9 sq nm
Vandenberg Marine Resources Protection Act Ecological Reserve
1994, 2.0 sq nm
Big Sycamore Canyon Marine Resources Protection Act Ecological Reserve
1994, 1.67 sq nm
Channel Islands Marine Reserves (detail top left)
Los Angeles
Heisler Park Ecological Reserve
1973, 0.5 sq nm
Santa Barbara Island
San Diego
Catalina Marine Science Center Marine Life Refuge
1988, 1.0 sq nm
California
PACIFIC OCEAN
MEXICO
0 100 Miles
Brackett's Landing Shoreline Sanctuary Conservation Area
1970, 0.2 sq nm
Washington
PACIFIC OCEAN
California
California Marine Reserves (detail at left)
Hawaii Marine Reserves
Kauai
Nihau
Oahu
Honolulu
Hanauma Bay Marine Life Conservation District
1967, 0.12 sq nm
Waikiki Marine Life Conservation District
1988, 0.09 sq nm
Molokai
Lanai
Maui
Kahoolawe
Honolua-Mokuleia Bay Marine Life Conservation District
1978, 0.05 sq nm
Ahihi-Kinau Natural Area Reserve
1973, 0.95 sq nm
PACIFIC OCEAN
Kealakekua Bay Marine Life Conservation District
1969, 0.37 sq nm
Hawaii
0 50 Miles
Pacific Island Marine Reserves
Midway Islands
Hawaiian Islands
Hawaii Marine Reserves (detail at center left)
Northern Mariana Islands
Guam
Wake Island
Johnston Atoll
PACIFIC OCEAN
Kingman Reef National Wildlife Refuge
2001, 570.7 sq nm
Palmyra Atoll National Wildlife Refuge
2001, 608 sq nm
Howland Island National Wildlife Refuge
1974, 37.9 sq nm
Baker Island National Wildlife Refuge
1974, 37 sq nm
Jarvis Island National Wildlife Refuge
1974, 43 sq nm
INDONESIA
PAPUA NEW GUINEA
Solomon Islands
American Samoa
Rose Atoll National Wildlife Refuge
1973, 46.1 sq nm
0 500 Miles
AUSTRALIA

Figure One

Fully Protected Marine Reserves in U.S. Waters

Fully protected marine reserves protect all species within their borders from exploitation. They are a subset of marine protected areas, which generally provide lower levels of protection. Reserves in U.S. waters occur on coral reefs, kelp beds, rocky reefs, estuaries, and sand flats. Nationally, however, reserves make up a tiny fraction—less than one percent—of marine environments. Yet, these reserves have already increased abundance of exploited fish and invertebrates, protected slow-growing biological structures like reefs, and provided enhanced fishing and recreational opportunities. Reserves have helped restore kelp beds in California, increased lobster size and abundance in Florida, and provided home for large lingcod in Washington. The seeds of a U.S. marine reserve network (shown on the map on these pages) have already formed through the dedicated action of local communities and governmental agencies.



Lucidity Information Design, LLC

Yellowtail Snapper, *Ocyurus chrysurus,* off Florida

also tend to be small—the vast majority are one square kilometer (0.39 mi^2) or less in area (Halpern, 2002). Brackett's Landing Shoreline Sanctuary Conservation Area (formerly named Edmonds Underwater Park) in Puget Sound, Washington, one of the oldest marine reserves in the U.S., contains just 0.04 square miles (0.10 km^2). By contrast, the De Hoop reserve in South Africa spans about 150 square miles (388.4 km^2).

Marine reserves in the U.S. are limited to a thinly scattered set of research and recreational sites, such as the Big Creek Marine Resources Protection Act Ecological Reserve, in California, or the Brackett's Landing Shoreline Sanctuary Conservation Area, in Washington (Figure One, page 3–4). Larger reserves occur in the Florida Keys National Marine Sanctuary, where the Western Sambo Ecological Research Reserve is about 12 square miles (31 km^2) of seagrass, coral, sand, and reef. The newly designated Tortugas Ecological Reserve weighs in at 200 square miles (518 km^2) and is the largest in the U.S. Although a comprehensive list of U.S. marine reserves does not yet exist, a review of the literature and current websites turns up only about two dozen fully protected marine reserves. (Figure One, page 3–4).

Authority to Create Reserves

The authority to create marine reserves remains unclear for the vast majority of U.S ocean waters. The National Marine Sanctuary Program provides a process for establishing reserves within a sanctuary boundary, with implementation and enforcement through existing state and federal agencies. The regional fishery management councils can restrict removal of species within their control, but they cannot set aside an area as a closure for all species. The lack of clear authority can also be found at the state level. A notable exception is the state of California, which passed the Marine Life Protection Act to provide the governance framework for marine reserves. Other states and the U.S. federal government do not have such a blueprint, making the process for establishment of marine reserves unclear.

The lack of clear authority to establish marine reserves makes their implementation as tools for ecosystem-based management more difficult. This confusion can obscure a critical point agreed on by virtually all proponents of marine reserves—that the public, as stakeholders for marine ecosystems, must be involved at the early stages of any plan to implement reserves. Without clear guidelines for where the authority to establish reserves exists, involving stakeholders becomes more difficult.

Comprehensive discussion of the legal framework of reserves is outside the focus of this report, but currently, at least four different legislative or executive mechanisms allow for the establishment of marine reserves or other marine protected areas (Box One).

Box One

Some Laws and Executive Orders Providing the Authority to Establish Marine Protected Areas and Reserves

Magnuson-Stevens Fishery Conservation and Management Act

This law established federal fishery management authority in 1976, mainly to stop fishing by foreign fleets in U.S. waters, protect habitat, and prevent bycatch and overfishing (NEFSC, 2002). In 1996, the Sustainable Fisheries Act was passed and integrated into the Magnuson-Stevens Act. Regional fishery management councils must plan to rebuild fisheries that are overfished. In addition, the councils must make regulations to reduce bycatch and minimize the mortality of bycatch. They are required to protect "essential fish habitat," water and substrate for fish spawning, breeding, feeding, and growth to maturity (NMFS, 2002).

National Marine Sanctuaries Act

This act was created by Title III of the Marine Protection, Research, and Sanctuaries Act of 1972, which was renamed The National Marine Sanctuaries Act in 1992. The mission of the National Marine Sanctuary Program is to serve as the trustee for a national system of marine protected areas (marine sanctuaries) in order to conserve, protect, and enhance their biodiversity, ecological integrity, and cultural legacy. The National Oceanic and Atmospheric Administration (NOAA) manages the sanctuaries and is responsible for compiling lists of potential marine sanctuaries from which future sanctuaries might be chosen. Protection for natural resources varies, but generally, dredging, dumping, placing structures on the seabed, mining, and oil and gas exploration and production are restricted or prohibited in all sanctuaries. The removal of historic artifacts and certain valuable natural resources is not allowed without permits. Each sanctuary also has site-specific regulations tailored to its individual needs and resources. Sanctuaries typically do not prohibit fishing (NOS, 2002).

Coastal Zone Management Act

Passed in 1972 and amended in 1996, the law established the National Estuarine Research Reserve System. Twenty-five sites have been designated and are suitable for long-term research, conservation, and education. Restoration is a goal at many of these sites. The act provides a system that can be used for coordinated and comparative research of coastal waters around the U.S. (OCRM, 2002).

Executive Order No. 13158
Marine Protected Areas, 2000

The Bush Administration endorsed this executive order, which was initially issued by the Clinton Administration, in June 2001. The order reiterated a request for three million dollars to support marine protected areas as part of Department of Commerce (DOC) budget. The executive order directs DOC and other agencies to expand and strengthen a national system of marine protected areas by working with state, territorial, tribal, and other stakeholders. Designation and management of marine protected areas remain with existing authorities. NOAA is responsible for implementing the executive order for DOC (MPA, 2002b).

The Ecosystem Context of Reserves

"...ecosystems are more than just the sum of their parts...."

Marine reserves were designed to reduce the impact of human activity on marine ecosystems, particularly the ecological damage caused by overfishing of some coastal areas. Focus on single species is the traditional method of fisheries management. Recent collapses of important U.S. fisheries such as New England cod *(Gadus morhua)* and the struggle of many U.S. fishing communities have prompted a call for evaluation of alternative methods (NRC, 1999). Because they protect habitats and all the species that use them, marine reserves are a management tool that affects representative parts of whole ecosystems. The value of this approach comes from the differences between protecting all the species in a functioning ecosystem versus protecting a few species through focused management. A core understanding of why ecosystems are more than just the sum of their parts requires a glimpse into how ecosystems work, and what maintains them. The past few decades have witnessed enormous advances in the understanding of marine ecosystem function, and this timely information can be brought to bear on the issue of marine reserves.

Summary

Fully protected marine reserves are rare in the U.S. but are more common elsewhere along the world's coastlines. However, there is a complex suite of protections currently applied to species and habitats along the U.S. coasts. Protection tends to focus on very specific threats (e.g., oil and gas exploration), or on a single species of particular fishery interest (e.g., cod in the Northeast). As a management tool, marine reserves differ from these approaches because they protect all the elements of a marine ecosystem, and their goal is to preserve ecosystem function.

II. Ecosystems, Ocean Threats, and Marine Reserves

An ecosystem is the sum total of the organisms living in a particular place, the interactions between these organisms, and the physical environment in which they interact. Ecosystem boundaries are as ill defined as good fashion sense, and ecosystem definitions vary. Estuarine ecosystems clearly must involve the fresh-saline water gradient typical of these areas, as well as the fish, marsh plants, invertebrates, birds, and marine mammals found there. The ecosystem also includes the bacteria and nematodes that live in the sediments, the parasites living in the birds, the algae drifting in from the sea, alien species clinging to pier pilings and the non-native oysters that may be growing on shore-based farms. It does not include tuna that never venture into brackish water, the rocky shore inhabitants of the marine coast outside the estuary mouth, or a host of other species that do not rely on estuarine production. However, it might include migrating whales that spend only part of their time there, or seabirds that nest near its shores yet forage out at sea.

The definition of an ecosystem thus encompasses all elements thought to play a role in the lives of organisms living in a particular place. The importance of this concept is that it emphasizes the linkages among species, and their connections to common environmental features such as weather and topography. Ecosystems also include species interactions—the way some species influence the distribution and abundance of others. Some biological interactions are strong and obvious—such as the predation of orcas *(Orcinus orca)* on otters

Gerry Ellis/Minden Pictures

Sea Otter, *Enhydra lutris,* North Pacific Ocean

(Enhydra lutris) (Estes et al., 1998)—and numerous cases show how such predation plays a major role in controlling populations in marine ecosystems (Paine, 1966; Menge, 1976; Lubchenco, 1978; Lewis, 1986). Other species interactions such as competition, facilitation (one species enhancing the growth or survival of another), or mutualism (one species depending on another) are more difficult to discern but play decisive roles in many ecosystems (Connell, 1961; Dayton, 1975; Woodin, 1978; Bertness and Hacker, 1994).

Patterns of primary productivity—the growth of plants using environmental nutrients and photosynthesis—can also determine ecosystem properties. Ecosystem productivity helps determine biodiversity in an ecosystem. However, the reverse is also true: for grasslands and wetlands, more highly diverse communities have higher rates of productivity and lower rates of nutrient loss (Tilman, 1999; Engelhard and Ritchie, 2001). Higher diversity also stems the rate of invasion of exotic species into marine communities (Stachowicz et al., 1999) and increases the efficiency of resource use (Emmerson et al., 2001). In some cases, particular species contribute disproportionately to this effect (Engelhard and Ritchie, 2001). However, in most cases, multiple species contribute to the overall impact of diversity on ecosystem function (Herbert et al., 2001).

Green Sea Turtle, *Chelonia mydas,* Goldring Surgeonfish, *Ctenochaetus strigosus,* and Yellow Tang, *Zebrasoma flavescens* (yellow fish), Honokohau Harbor, Hawaii

The Functioning of Marine Ecosystems

A marine community is more than the sum of its parts (Box Two, page 11–12). Removing predators can have an effect that ripples down through the community—changing abundances of all of the hundreds of species that rely on primary producers like kelp or structure-producing species like coral or oyster reefs. Ecologists tend to call this top-down control of an ecosystem because animals high in the food chain control the abundances of organisms at lower levels, such as herbivores and primary producers like plants. Other ecosystem shifts occur when competition for space is changed—say, through the introduction of a new species that outcompetes an established, native species. Still other changes may occur by changing the primary produc-

Jim Knowlton

Garibaldi, *Hypsypops rubicundus,* in kelp forest off California

tion of an area—for example, by the dumping of sewage into coastal environments. In all these cases, changes to whole ecosystems can result from smaller changes to a few particular species because these species have strong impacts on other species in the ecosystem.

The Value of Everything Wet

In a paper called "The value of the world's ecosystem services and natural capital," conservation biologist Robert Costanza and colleagues (1997) tried to estimate the value of natural ecosystems in a new way. It had long been possible to value a fishery by the amount the standing stock of the fishery would be worth if sold on open markets. Such analyses—totaling up the poundage of a fishery resource and estimating its net worth—almost always concluded that the best economic strategy was to sell off the entire resource all at once, and bank the proceeds, letting the cash equivalent of the resource grow monetarily (Clark, 1973).

Under this economic model of the value of species, conservation of any population for future use is discouraged (Pimm, 1997). In the last decade, however, many environmental economists have pointed out another way to treat this question. For example, Gretchen Daily and others have emphasized that ecosystems perform important services to local and global economies that, if they had to be replaced by technology, would be very costly (Daily, 1997; Daily and Ellison, 2002). Thus, an important value of an ecosystem is the replacement value of the services it provides for free. Marine ecosystems provide many such services, including capture of sediments by wetlands, protection from coastal storm damage by reefs or mangroves, production of oxygen, and sequestration of carbon dioxide (Costanza, 1999).

"...ecosystems perform important services to local and global economies...."

Costanza and others (1997) estimate the value of ecosystem services provided by the global biosphere is about 30 trillion dollars per year, higher than the value of the globe's entire industrial output. The bulk of this value is derived from marine ecosystems, with the open ocean accounting for eight trillion dollars, and coastal ecosystems providing over 12 trillion dollars in services that would have to be provided should these ecosystems com-

Box Two

Crucial Ecological Interactions in Kelp Forests

The tower of California kelp *(Macrocystis pyrifera)* begins life as a spore smaller than the period finishing this sentence. Attaching to the seabed, the sprouting spore extends a series of tiny blades fast enough that a kelp forest ranks among the world's most productive plant communities. Growing over several seasons, the kelp reaches up to spread across the sea surface, forming the basis of one of the most complex and integrated coastal ecosystems on Earth.

A host of herbivores has evolved to take advantage of the productivity of kelp ecosystems. Sea urchins *(Strongylocentrotus purpuratus and S. franciscanus)* scour the seabed with star-shaped grinding maws that can devour young kelp blades and chew through mature stems. The steady grazing of a dense population of sea urchins can generate a hard-packed seabed devoid of fleshy algae. These urchin barrens are parking lots of sea urchins, living off algae drifting in from elsewhere.

Predators prowl the vertical relief of the kelp forest, too, and play a crucial role in the balance between plants and herbivores. Rockfish *(Sebastes spp.),*

Richard Herrmann

Vermillion Rockfish, *Sebastes miniatus,* near San Miguel Island, California

garibaldi *(Hypsypops rubicundus),* and scores of other fish are the chief predators of this forest, consuming smaller fish and the myriad invertebrate herbivores. Some kelp forests house predators that feed directly on sea urchins. For example, in the *Macrocystis* beds of California, urchin abundance is kept low by the foraging of sea otters and spiny lobsters *(Panulirus interruptus).* Where common, otters are known to reduce urchin populations by several orders of magnitude (Duggins, 1980; Estes and Palmisano, 1974). Historical hunting of otters by native Americans along shores of the Pacific Northwest led to local extinction of these animals, followed by increases in herbivore density and a reduction in kelp-associated fish and invertebrates (Simenstad et al., 1978). Herbivores, in turn, ate away at the kelp beds, reducing them in density and extent. This ecosystem shift—from the alternative stable states of kelp forest to urchin barrens—was repeated in the nineteenth century along the west coast of the U.S. as otter pelts became valuable commodities (Simenstad et al., 1978) and as other urchin predators like spiny lobsters and sheephead wrasses *(Semicossyphus pulcher)* were overfished (Steneck and Carlton, 2001). The

Fred Bavendam/Minden Pictures

Purple and Red Sea Urchin, *Strongylocentrotus purpuratus* and *S. franciscanus,* near Channel Islands National Marine Sanctuary, California

California Spiny Lobster, *Panulirus interruptus,* near Anacapa Island, California

return of otters, after protection in Alaska and in central California, has seen the reversal of this ecosystem shift (Estes and Duggins, 1995). Kelp beds quickly grow back in areas where otters have returned.

However, otters are not safe in kelp beds. In the 1990s, environmental shifts in the North Pacific, exacerbated by a lack of prey, drove a major new predator into the balanced kelp-urchin-otter system. By 1997, orcas returned, prowling the coastal areas of Alaska, attacking otters inside kelp beds (Estes et al., 1998). Within a few months, otter populations had plummeted. Again, the gears of ecological change were engaged, and urchin populations climbed at the expense of kelp. This dynamic shift in one species because of change in others is a hallmark of ecosystems.

pletely disappear (Pimm, 1997). These numbers are preliminary estimates of extremely complex issues. For instance, there are many ecosystem services that cannot be substituted by artificial or industrial processes at this time, and so they cannot be assigned a replacement cost. Nevertheless, these efforts underscore the huge value of the Earth's living veneer.

The value of healthy ecosystems also arises from the tourist dollars they generate. For instance, one study of the value of wetlands based on recreational fishing in Florida estimated each wetland acre along the East Coast contributes about 6 thousand dollars to local economies each year (Bell, 1997). Other kinds of local values for marine ecosystems derive from the value of waterfront property, erosion control, and water quality. Measurement of these values can be explored through surveys of the public's willingness to pay to ensure the preservation of marine ecosystems. The former was the basis for valuation of damage caused by the *Exxon Valdez* oil spill, in which a settlement of 2 billion dollars pivoted on an average willingness of U.S. households to pay 31 dollars a year for access to clean coasts (Carson et al., 1995). The Environmental Protection Agency and other regulatory agencies responsible for Superfund, the Oil Pollution Act, and other environmental laws routinely use such willingness-to-pay methods to assess amounts for compensation for oil spills or waste spillage.

Should marine management focus on the

health of an entire ecosystem? Alternatively, should management focus on individual species? Largely, this depends on how much healthy marine ecosystems are worth and how their value is blended into economic management decisions. In the past, this type of valuation would consider only the extractive value of exploited species (e.g., comparing the extractive value of sea urchins versus the value of the kelp). Increasingly, however, it has become apparent that extractive value is only a small part of the worth of an ecosystem.

"At least five main elements contribute to ecosystem health: resilience, stability, diversity, productivity, and services provision."

Ecosystem Health

As an analogy to human health, the concept of ecosystem health can be a useful way to summarize the status of the elements of an ecosystem and to define key management goals. Although we each intuitively know what we mean by "human health," defining health of an ecosystem in an unambiguous and comprehensive way is difficult (Rapport et al., 1998). For instance, one concise definition proposes that an ecosystem is healthy if it is stable and sustainable, but this applies to agricultural fields as well as native forests (Rapport et al., 1998).

At least five main elements contribute to ecosystem health: resilience, stability, diversity, productivity, and services provision (Box Three). Resilience is the ability of an ecosystem to recover from a perturbation. In general, resilient ecosystems are also more stable in population numbers of most species. Diversity as a criterion of ecosystem health is obviously a relative one. Although a pristine ecosystem may have few species naturally, it could be considered healthier than a higher diversity area that has been extensively perturbed. A healthier ecosystem might also be more productive (Tilman, 1999), although many highly perturbed ecosystems—like salmon farms—have high productivity. A final relative measure of ecosystem health might be the level of ecosystem services provided compared to nat-

Box Three
What Is Ecosystem Health?

The concept of ecosystem health has been fundamental to legislation considered to be at the heart of environmental investment in the U.S. because it is central to the 1972 U.S. Water Pollution Control Act Amendments (now called the Clean Water Act). Section 101(a) set a standard for answering the question, "What is river health?" The act seeks to restore and maintain the chemical, physical, and biological integrity of the nation's waters. By integrity, Congress meant to "convey a concept that refers to a condition in which the natural structure and function of ecosystems is maintained" (Karr, 1999). In 1972, Senator Edmund S. Muskie of Maine summarized the value of this point of view during debate when he asked: "Can we afford clean water? Can we afford rivers and lakes and streams and oceans, which continue to make life possible on this planet? Can we afford life itself?...These questions answer themselves." (quote excerpted from Karr, 1999) ural ecosystems. Such services might be the degree of shoreline protection afforded by salt-marsh or sand-dune communities or the sheltering of juvenile fish by mangrove or estuarine habitats. A decline in services may be a signal of poorer health.

It should be clear that these health indicators for ecosystems are not infallible. For example, a coral reef inundated by excess nutrients may show artificially high primary productivity that allows algae to quickly smother coral growth. Nor are these indicators independent—high diversity and productivity may go hand in hand (Tilman, 1999), and resilience and stability are related concepts. Moreover, it may be very difficult to define a baseline health for an ecosystem because its natural state may be unknown (Jackson, 2001; Dayton et al., 1998). Even in these cases, however, it might be valuable to monitor *future* ecosystem health with these measures in order to monitor response to management interventions.

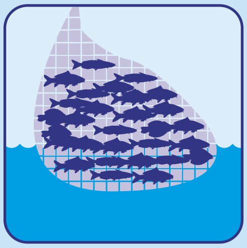
Threats to the Oceans

Threats to the oceans and the life they harbor have been extensively described in other Pew Oceans Commission reports. Major categories of threat include overfishing, habitat alteration, pollution, terrestrial runoff, aquaculture, invasive species, coastal development, and climate change (see Box Four for an overview). These threats differ in several important ways from those that have affected many terrestrial systems. First, many of these threats go unnoticed because they are beneath the surface—where casual eyes do not penetrate. On land, for example, one can easily notice clear-cutting: a drive through the Pacific Northwest reveals an obvious quilt of partially clear-cut forests. However, an area equivalent in size to the nations of Brazil, Congo, and India combined is trawled every year, resulting in massive changes to the seafloor (Watling and Norse, 1998). Because this area lies far below our usual gaze, the extent of trawling and its environmental consequences are only now becoming clear (Watling and Norse, 1998). Second, the dilution power of the sea is vast and many pollutants diffuse away quickly enough to curtail local buildup. Where dilution wafts the waste away, local communities do not complain about dumping until the local problem becomes severe (Boesch et al., 2001). Third, the sea is still used as a hunting ground for wild animal protein, though most terrestrial protein comes from farmed plants and animals. Marine management is expected to sustain and improve the yield of hunted animals in a way seldom encountered in management of terrestrial parks and wildlife refuges. Lastly, threats to the oceans are more difficult to establish because existing baseline data on the normal denizens of the sea are poor. The discovery of a new bird or mammal species is a rare, heralded event (MacKinnon, 2000; Alonso and Whitney, 2001). By contrast, new phyla and classes are still being discovered in the sea. Uncertainty about what species actually inhabit the sea clouds the ability to fully understand the scope of recent oceanic changes.

"...many of these threats go unnoticed because they are beneath the surface...."

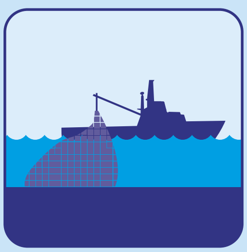
Box Four

Threats to the World's Oceans



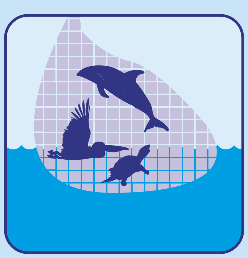
Overfishing

The 80 million metric tons (88,160,000 short tons) of food pulled from the sea each year (Botsford et al., 1997) comprises hundreds of species. However, most of the world's fisheries are at or above sustainable levels (Vitousek et al., 1997; FAO, 2000; Watson and Pauly, 2001), and the species caught are getting smaller and farther down the food chain (Pauly et al., 1998). Extracting food from the sea has so eroded some ecosystems that ocean observers have largely forgotten how these areas teemed with life in past centuries (Jackson et al., 2001).



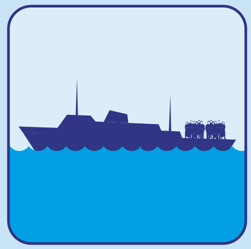
Habitat Alteration

Heavy fishing pressure can cause ecological problems by altering habitats, a threat defined as habitat overfishing. Some types of fishing gear dig into seabeds. In places where bottom-dwelling invertebrates cover the natural bottom, recovery from one pass of a dredge can take more than five years. Sandy or muddy bottoms recover over time scales of three to 12 months—but even this shortened time frame is long enough that the sea bottom can be in a perpetual state of disturbance (Peterson and Estes, 2001).



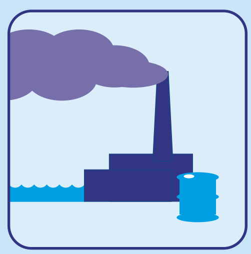
Bycatch

Animals caught as bycatch—species caught unintentionally and subsequently discarded—can outnumber those kept for sale in longline or trawl fisheries. Bycatch of dolphins, turtles, and seabirds has been of enough consumer and governmental concern that new gear has been required to limit mortality of these species.



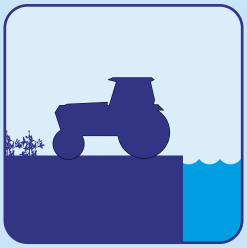
Recreational Threats

Tourism can harm marine ecosystems in various ways, such as physical damage to kelp or corals by divers or boat anchors, sewage discharges by cruise ships, harassment of marine mammals or turtles by tour boats or beach driving, or sand pumping by beach communities. Two-cycle outboard engines are a significant source of oil and gas discharge into marine waters. Recreational fishing by line or spear can remove substantial numbers of some target species. Impacts from such activities can degrade ecosystems protected for their tourism value.



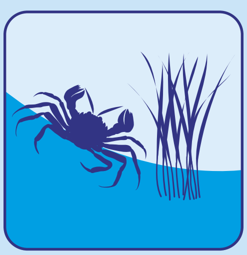
Pollutants

Coastal populations affect the world's oceans through terrestrial runoff and the dumping of waste products. Oceans are used to dilute and disperse sewage, chemicals, waste heat from power plants, and waste from domestic and industrial sources. Chemical pollutants include PCBs, dioxins, DDT, excess nutrients, petroleum derivatives, organics, and heavy metals. Some of these chemicals can accumulate in the bodies of top bird and fish predators. Elsewhere, ocean depths have been suggested for storage of atomic waste and excess CO_2 (Nadis, 1996). Substantial progress has been made in controlling some forms of marine pollution (Boesch et al., 2001). However, other forms, like excess nutrients from nonpoint sources, are such growing problems that they affect up to two-thirds of the U.S. coast.



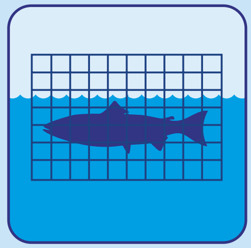
Runoff from Land

Inputs that flow from the land through streams, rivers, and storm drains are increasing problems for ocean ecosystems. Not only does much of the oil pollution on U.S. coasts come from runoff, but farm and sewage effluent brings in a huge pulse of nutrients that powers the growth of planktonic algae. When introduction of excess nutrients is severe, planktonic algae vigorously bloom, creating a huge biomass that can sink and decay on the sea floor. This decay consumes so much oxygen that the ocean layer near the bottom becomes oxygen-depleted, forming an anoxic layer noxious to bottom-dwelling invertebrates and fish. A huge anoxic mantle covers the sea floor near the mouth of the Mississippi River in summer months, but many other smaller anoxic events have been recorded in the U.S.—particularly in shallow estuaries and embayments along the southeastern coast (Peterson and Estes, 2001).



Introduced Species

International commerce provides a major conveyor for marine species. Some transport is intentional—as for aquatic pets and bait—but most marine exotics are transported accidentally, in ballast water of ships or packed into the algae used to ship live bait or seafood. Such introductions cause widespread damage, and disrupt freshwater ecosystems. For example, the European green crab *(Carcinus maenus)* now dominates the ecology of some West Coast bays (Groszholz et al., 2000). Populations of burrowing Chinese mitten crabs *(Eriocheir sinensis)* and weedy salt marsh grass *(Spartina alterniflora)* have grown so large that they have altered the shape of coastlines (for details, see Carlton, 2001).



Aquaculture

Farming in the sea has a number of ecological impacts that alter the overall economic balance sheet (Naylor et al., 2000). Intensive feeding, especially of carnivorous fish, often requires massive amounts of fish meal or fish oil, and produces large quantities of waste products (Goldburg et al., 2001). Aquaculture can also introduce exotic species, diseases, and exotic genes. In Hawaii, algae imported for aquaculture development escaped and grew rampantly over patch reef corals (Rodgers and Cox, 1999). Escapes of Atlantic salmon *(Salmo salar)* from farms have introduced this species to west coast streams.

Climate Change

In the past century, sea level has risen between 10 and 25 centimeters (4 and 9.8 in), associated with a dramatic rise in concentrations of carbon dioxide, methane, and nitrous oxide in the atmosphere (IPCC, 2001). The impact of global climate change on marine ecosystems is expected to be large, with changes in the extent and placement of wetlands, river deltas, coral reefs, and other coastal habitats. In addition, runoff from land and the evaporation rate are expected to change.

Coastal Development

Today, 53 percent of the total U.S. population lives in coastal counties. The U.S. Census Bureau predicts that this percentage will remain constant through 2025. Human activity at the ocean interface includes dredging and filling, changing coastal hydrology through changes in land use and increases in impervious surface, altering vegetation, building sea walls and harbors, and a myriad other impacts of intense urbanization.

Art: Widmeyer Communications

"The snarl of interfering regulations is an inevitable result of relying on single-species management schemes."

Eating Ecosystems: The Challenge of Single-Species Management

Whole ecosystems are a critical focus of ocean management. Because such a large variety of food is taken from the sea, whole ecosystems, in effect, are being harvested, not just single species. As traditional fisheries have become depleted, fishing has focused on fish further down the food chain (Pauly et al., 1998). In addition, as U.S. prices for invertebrate seafoods have increased, traditional finfish fisheries have lost their place as the top income generators. Although marine resource management is usually called fisheries management, increasingly the most important fisheries species are not fish at all. In the three most populous western states—California, Oregon, and Washington—as well as in the New England area, marine invertebrates, not finfish, are by far the most valuable commercial fisheries. These invertebrates dramatically increase fisheries revenues and diversity. Overall, there are 41 different invertebrate and fish species that each generate more than one million dollars a year in the fisheries of the northeastern U.S. Across the four western continental states, there are 55 species yeilding at least a million dollars in revenue yearly (NMFS website: data from 2001).

Why does fisheries diversity matter in fisheries management? Traditional fisheries management considers just one species at a time. Few single-species plans will work on any but the most similar and closely related species. In the face of mounting modern fisheries diversity—of finfish and invertebrates—multiple, overlapping single-species management plans can become cumbersome and difficult to implement. For example, single-species regulations led to the closure of large areas in the Gulf of Maine to bottom fishing for cod. Because these closures were only for cod, dredging for scallops *(Placopecten magellanicus)* was not prevented throughout these areas. Such dredging could damage not only cod but other fish as well (such as yellowtail flounder *[Limanda ferrugine]*), placing management of these three species potentially in conflict.

The snarl of interfering regulations is an inevitable result of relying on single-species management schemes. The Magnuson-Stevens Fishery Conservation and Management Act clearly demands that managers seek "the optimum yield from each fishery in the United States" (16 U.S.C. 1851(a)(1), Goldberg, 2002). This means an optimum of cod *and* scallops *and* flounder at the same time. Would an ecosystem be able to support optimum levels of all species at the same time when management falls under numerous single-species plans? Moreover, how well could the fishing community follow multiple and conflicting regulations generated by single-species plans? An alternative to the coordination of optimal single-species plans for scores of species is to take an ecosystem-based or area-based management approach.

Integrating Ocean Threats and Ocean Use with an Ecosystem View

Threats to the oceans affect the species that make up marine ecosystems in multiple ways. The linkages that exist among species in ecosys-


Bill Harrigan/The Waterhouse

Elkhorn Coral, *Acropora palmata,* South Carysfort Reef, Florida Keys National Marine Sanctuary

tems guarantee that these impacts are not limited to a single species but can reverberate through the ecosystem, changing it in unexpected ways. A focus on the interactions of species within ecosystems provides a framework in which to see that various threats to the oceans need to be considered at the same time. Although pollutants, excess nutrients, and overfishing seem to be very different ocean threats, they interact with one another because they all affect ecosystems. These threats can be evaluated relative to one another in the currency of their effect on ecosystem health.

For example, excess nutrients from coastal sewage promote algal growth on Hawaiian coral reefs. Sewage input was reduced through sewage treatment in the 1980s, but at the same time, reduction in herbivory through overfishing allowed algae to continue to be a problem. Moreover, an introduced but highly palatable alga attracts the few herbivores left, allowing less palatable coral-smothering algae to grow larger (Stimson et al., 2000). In this case, reef coral abundance is the integrator of many diverse ocean threats. Similar linkages and threat accumulations probably occur in most ecosystems.

In the southeastern U.S., nutrients create algal blooms in coastal waters that, in turn, generate local dead zones of bottom water with low oxygen concentration (Peterson and Estes, 2001). These dead zones kill bottom invertebrates and force mobile animals to forage in concentrated areas, where they deplete food. Thus, a nutrient pulse works its way through the local ecosystem and may result in changed patterns of fish abundance. A healthy ecosystem replete with filter feeders like oysters *(Crassostrea virginica)* may buffer an area from such dead zones by preventing algal blooms. The services provided by filter feeders are thought to have kept the Chesapeake Bay productive despite nutrient overloading in the nineteenth century (Jackson et al., 2001).

"Although pollutants, excess nutrients, and overfishing seem to be very different ocean threats, they interact with one another because they all affect ecosystems."

John Michael Yanson

"Most of the big fish and turtles were gone from Jamaica by the early 1900s."

An example of the failure of an entire ecosystem through accumulation of threats from overfishing and other environmental perturbations emerges from the reefs of Jamaica (see ecosystem time line above). Most of the big fish and turtles were gone from Jamaica by the early 1900s (Jackson, 1997). Reef fish decline continued, with the focus shifting to smaller and smaller fish. By the latter half of the twentieth century, Jamaican reef fish were no longer abundant enough to play a significant ecological role on reefs.

Unlike most temperate coastal fish, many coral reef fish are herbivores, pecking away at strands of algae that grow among the coral heads. These reef vegetarians have competition, and in Jamaica, the decline of reef fish opened up an opportunity for sea urchins to become the reef's dominant algae eaters. Such ecological redundancy is common in complex ecosystems. Often, several species play similar ecological roles. Such redundancy can sometimes buffer an ecosystem from the removal of just a single species and adds to ecosystem resiliency.

In Jamaica, the herbivore guild suffered a serious second blow in 1983 when the urchins began to die from a fatal wasting disease (Lessios, 1988). After the demise of urchins, algal abundance in reefs skyrocketed (Hughes, 1994) because the herbivore guild was gone. Since reef algae are powerful competitors for space against slow-growing reef corals, rapidly growing algae quickly began overgrowing the corals in Jamaica. A steady decline in coral cover matched the steady increase in algal cover. Additional reef stresses may have been imposed through the increase in nutrients from increased runoff from streams with deforested banks, and through untreated sewage. In addition, a series of devastating hurricanes pounded the reefs in the middle 1980s. Although hurricanes are natural disturbances, normal reef recovery has not occurred. In addition to the increase in algal cover, worm predators prevented regrowth of coral fragments (Knowlton et al., 1990). The latest blow came in the form of a virulent coral disease, white band disease, that devastated stands of the dominant staghorn and elkhorn corals *(Acropora cervicornis* and *A. palmata)*, leaving crumbling skeletons in its wake (Harvell et al., 1999).

Examination of fossil coral reefs in this area shows that such a die-off of corals is unprecedented, even though hurricanes are a natural part of the Caribbean climate (Pandolfi and Jackson, 2001). One possibility is that Jamaican reefs were uncharacteristically sensitive to hurricane damage because of the reduction of normal ecosystem services, such as erosion control from forests, water purification from filter-feeding reef organisms, and reduction in algal growth by herbivores. Without these services, the ecosystem may have been more sensitive to the removal of an ecological guild and the effects of storm stress.

Such situations may be operating in other reef environments as well, where small changes in summertime seawater temperature have led to massive coral bleaching events. Coral bleaching occurs when physiologically stressed corals expel the single-cell, symbiotic algae they use to photosynthesize (Brown, 1996). Marine disease outbreaks and toxic algal blooms may also reflect breakdown in normal ecosystem hygiene provided by natural ecosystem services, although few studies address this issue (Harvell et al., 1999).

Reserves and Diverse Ocean Threats

Overfishing generates three major types of ecosystem damage. First, overfished species are depleted. Second, habitat alteration from fishing activity can cause large-scale ecosystem shift by removing biological structure such as oyster reefs. Third, ecological shifts resulting from the removal of important species (ecosystem overfishing) can restructure whole ecosystems such as kelp forests. Reserves help protect ecosystems by protecting all the species within their borders, and the stable functioning of these ecosystems is thought to yield enormous potential advantages.

"Reserves help protect ecosystems by protecting all the species within their borders,...."

Marine management strategies that include reserves may be more efficient at protecting many species in situations where fishing targets a large number of species (such as the herbivorous reef fish assemblage in Jamaica or the large number of commercial species in the northeastern U.S.) or where fishing for one species causes habitat damage that affects other species. In simpler situations, single-species management may be as beneficial a solution from a fisheries yield perspective, but even in these cases, reserves provide concomitant conservation benefits through habitat protection (Hastings and Botsford, 1999). Because the ecological damage from some kinds of overfishing is so clear—especially when biological structures such as kelp beds or living reefs are damaged—this reserve benefit is likely to be of primary importance in such cases.

"...many marine ecosystems—such as coral or oyster reefs and kelp beds—depend on biological structures...."

It may seem that reserves can do little to limit ocean dumping, eutrophication from terrestrial runoff, or the need to trawl in at least some part of the sea. However, benefit also derives from marine protected areas when they protect marine habitats from damaging activities such as aquaculture and mining. For example, protection from oil and gas development is a major value provided by the U.S. national marine sanctuaries. Pollutants and damaging terrestrial runoff would not be prohibited in a reserve as defined in this report. However, a broader definition of a fully protected marine reserve could be envisioned that includes coordinated protection against these threats as well.

Likewise, other threats such as global climate change will not honor reserve boundaries. It is possible that a healthy marine ecosystem is more resilient to pollution damage or climate change than one that has suffered extensive habitat or ecological alteration. Currently, this question cannot be answered because there are very few data that examine the relative resilience of marine habitats inside and outside reserves, nor are there comprehensive studies available that address whether ecosystems inside reserves can better weather climate shifts. One study shows that species-rich marine systems are more capable of resisting colonization by invading species (Stachowicz et al., 1999), but this single study needs confirmation in other habitats. Overall, it is reasonable to expect healthy marine ecosystems to be more resistant to perturbation, but this must be tested in existing reserve systems.

Summary

Ecosystems are more than species lists. The ecological links among species and their links with the environment create a complex tapestry of threads that connect and support life on Earth. One of the most important ecological lessons of the past 40 years has been that changing abundance of some keystone species can completely alter marine ecosystems. Furthermore, many marine ecosystems—such as coral or oyster reefs and kelp beds—depend on biological structures without which the nature of the ecosystem changes fundamentally.

Because responses to most ocean threats require some level of ecosystem protection regardless of the type of threat, it makes sense to combine ocean protection measures into coordinated plans that take into account the ways the ecosystem responds as a unit. Marine reserves are one management tool that intrinsically helps protect ecosystems from overexploitation that reduces populations, alters habitats, and causes widespread ecological change. Although the combined impact of many ecosystem stressors has seldom been evaluated rigorously, a perspective that includes the ecosystem as a major client may allow a more straightforward integration of different management goals.

III. Marine Reserves as a Tool for Ecosystem-Based Management

Although reserves are rare in U.S. waters, careful study of the result of high levels of protection in several U.S. MPAs, and a deluge of data from marine reserves in other countries, has shown that reserves function to enhance marine ecosystems. Tabulation of more than a hundred examples provides evidence of the consistent impact of reserves on marine communities. Overall, full protection of a marine community typically results in an increase in size and numbers of heavily exploited species within the reserve. These changes can have important effects on the entire marine community.

Stephen Frink/The Waterhouse

Bluestriped Grunts, *Haemulon sciurus,* French Grunts, *Haemulon flavolineatum,* and Yellow Goatfish, *Mulloidichthys martinicus,* Florida Keys National Marine Sanctuary

A few examples show these trends in detail. In Caribbean reserves on the islands of Saba and St. Lucia, reef protection led to increases in size and biomass of about a third of resident fish species. Those for which there was no change tended to be the species that were initially rare (Roberts, 1995). In a series of replicate reserves in St. Lucia, fish biomass inside reserves was 50 percent higher than outside, and was almost triple the values seen at the beginning of protection (Roberts et al., 2001). Similar results have been reported for the Florida Keys National Marine Sanctuary, which measured increases in fish and lobster abundance and size over the past three years (FKNMS, 1999; FKNMS, 2002; <http://www.fknms.nos.noaa.gov/research_monitoring/presentations/year3/1.html>). Larger and more numerous fish have also been reported from Brackett's Landing Shoreline Sanctuary Conservation Area in Washington and outside the Merritt Island National Wildlife Refuge in Florida (Johnson et al., 1999). A recent review (Halpern, in press) found five cases of marine reserves in the U.S. that had been monitored for at least one species. Evidence for significant density increases was seen in all of these studies.

Reefs in Kenya, the Pacific Ocean and the Mediterranean Sea, temperate bays and estuaries, rocky subtidal kelp forests, and subtropical coasts all show strong evidence that reserves function to increase the abundance and size of exploited species within their borders. To estimate the magnitude of this effect, the data that Halpern (2002)

"...density increases averaged between 60 percent and 150 percent across a wide range of countries in North America, the tropical Pacific, and Africa."

presents for 104 reserve studies were screened, and studies that were published in the peer-reviewed literature were used for analysis. Among these 56 studies, density increases averaged between 60 percent and 150 percent across a wide range of countries in North America, the tropical Pacific, and Africa. Lower values (increases of 20 percent to 35 percent) have been reported for the Mediterranean and the temperate South Pacific. Likewise, biomass inside reserves increased in most studies reported, usually at least doubling no matter whether the studies were conducted in the Philippines, Africa, or temperate shores (Figure Two).

Increased fish populations have been noted within a few years of reserve implementation (Russ and Alcala, 1996). Although longer-term protection can lead to incremental increases in biomass and density (Russ and Alcala, 1996; McClanahan and Arthur, 2001), most reserves have generated substantial increases in short-lived, fast-growing species within five years of protection.

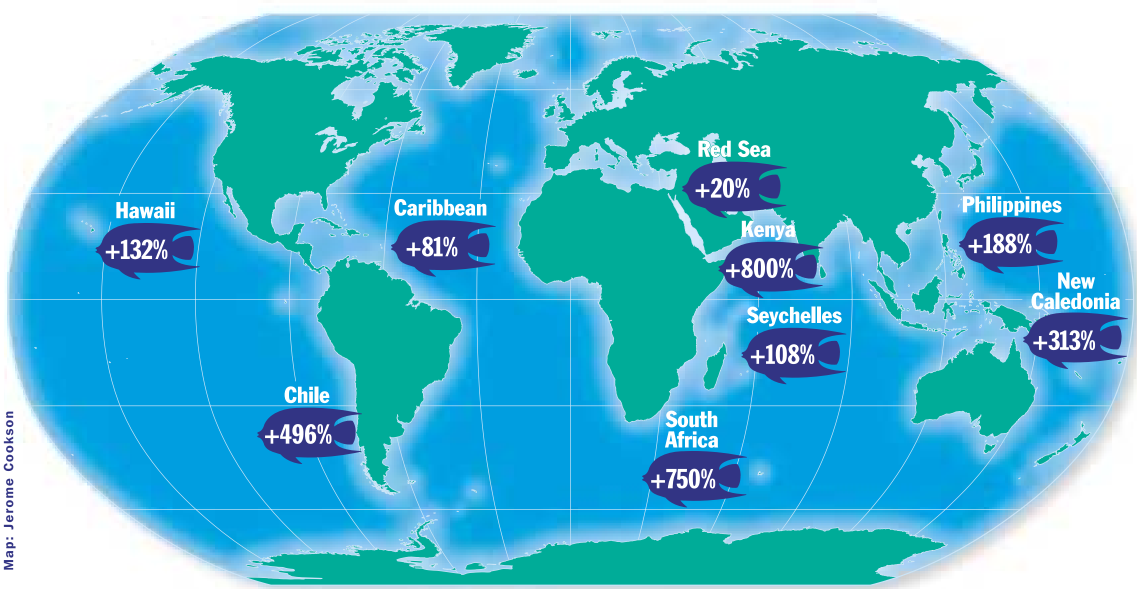
Limits to Response in Reserves

Not all species increase in abundance in reserves. Most reserve studies show some species that decline (Ruckelshaus and Hays, 1998), perhaps because some are prey for the larger, predatory fish that prowl protected areas. Species that are not heavily exploited outside reserves tend not to increase inside them unless they respond to overall ecosystem changes sparked by protection. In addition, highly mobile fish, for which a small individual reserve is a tiny fraction of home range, may require larger reserves. Long-lived, rarely recruiting species such as corals (FKNMS, 2002) or perhaps deep-sea fish (Roberts, 2002) probably will respond to reserve protection more slowly than species with shorter life cycles. By

Figure Two

Marine Reserves Increase Fish Biomass

Around the world, marine reserves have demonstrated the ability to increase fish biomass inside their borders. The numbers on the map below represent the average increases of fish biomass inside reserves after the reserves were established.



Map: Jerome Cookson

Source: Data are from 32 studies summarized by Halpern (2002) that were published in peer-reviewed journals.

themselves, reserves do not protect habitats from threats by invasive species or global warming. Finally, reserves with little enforcement do not provide any benefit. This was clearly shown in the collapse of reserve enforcement in the Philippines, where a scramble to take fish in the previously enforced reserve wiped out all previous gains (Russ and Alcala, 1996).

The overwhelming result of decades of study of reserves is that heavily exploited species recover within reserve borders, becoming more numerous and larger (Alcala 1988; Roberts and Polunin, 1991; 1993; Agardy, 1997; Roberts and Hawkins, 2000; Halpern, 2002). This effect is clearer for sedentary species, but applies in many cases to pelagic fish where spawning grounds or juvenile nursery areas are protected (Roberts and Hawkins, 2000). Although the local conditions of a reserve (access to recruits from outside, reserve size in relation to mobility, enforcement, etc.) may strongly affect how it changes after protection, the value of reserves in generating broad changes within their boundaries has been demonstrated in scores of well-documented cases in virtually all settings in which they have been studied.

Ecosystem Changes within Marine Reserves

Enhancement of particular overfished species is not the only way reserves help. They also address two other kinds of threats. One of the most dramatic reserve effects occurs when habitat protection leads to a wholesale ecosystem shift. On the coast of New Zealand, where fishing for spiny lobsters *(Jasus edwardsii)* has been severe, urchin populations have exploded and kelp almost disappeared. Halting the exploitation of lobsters in New Zealand marine reserves brought the kelp back, along with the fish that inhabit kelp forests, reconstituting a whole ecosystem (Babcock et al., 1999). In this case, lobster exploitation cost the marine ecosystem much more than this one species, and protection restored the ecosystem by limiting biological habitat destruction caused by overabundant urchins.

This is a simple case because only one pivotal species, the spiny lobster, is present, and it could be argued that single-species management would do the job as well. The otter example in Chapter Two also shows the ecological effects of single-species management as opposed to marine reserves. However, the ecological ramifications of these management strategies derive from the special role these species play in their ecosystems. When a species plays an overarching role in determining the abundance of others, it is called a keystone species (Power et al., 1996). In such cases, determined management of a keystone species will have a strong ecosystem impact. However, in many marine ecosystems, critical roles are played by larger numbers of species and in these cases, ecosystem impact will require management of many species. For example, restoring herbivores to reefs overgrown by algae would not be possible without protection of many individual fish species. This can be accomplished most easily through simultaneous protection of all of them in reserves. In some cases the relevant, ecologically pivotal species are not known (perhaps because they are no longer very common, Jackson et al., 2001), and it is impossible to use single-species management to restore such poorly understood ecosystems.

"Halting the exploitation of lobsters in New Zealand marine reserves brought the kelp back,...."

“Without seasonal bottom trawling for cod, scallop populations bloomed in the closed areas.”

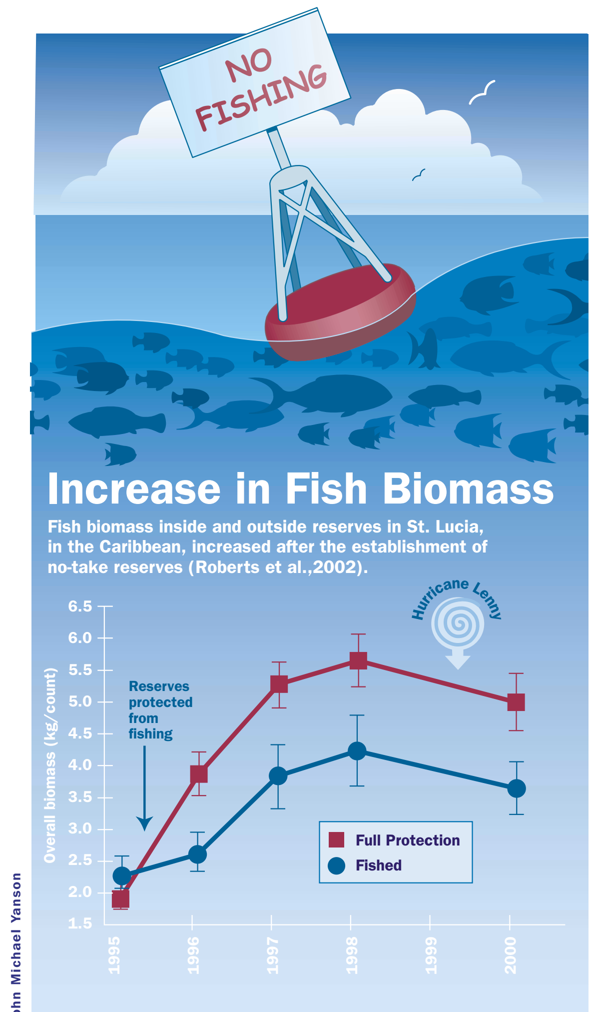
Other community-level effects of reserves rely on the protection of bottom habitats or biological structures—such as oyster and scallop beds, coral reefs, or giant kelps—that take years or even decades to grow. Bottom protection can have unexpected benefits. When cod stocks on Georges Bank off Cape Cod collapsed in the early 1990s, large seasonal closures—designed to protect spawning stocks—were changed to become year-round cod closures. Without seasonal bottom trawling for cod, scallop populations bloomed in the closed areas. Scallops are now the second largest fishery in New England (in dollar amounts), increasing from 91 million dollars in 1995 to 123 million dollars in 1999.

Spillover Effects

Although a major role of reserves is to protect habitats and ecosystems within their borders, the benefits of reserves increase if they export species or populations to surrounding areas. This can happen two ways. For most fish, algae, and invertebrates, eggs develop into tiny larvae that disperse from their parents. This dispersal phase may last months, or only minutes, and can export larvae and eggs from a reserve through water currents and sometimes the swimming of larvae. After settlement, juveniles and adults can move from place to place. Although some fish and invertebrates such as tuna and squid have large home ranges, some are dedicated to one bit of habitat for nearly their entire lives.

Evidence of spillover comes from repeated observation of fishing success around existing reserves. Where reserves have been established in heavily fished environments, fishers commonly change locations to fish along the reserve boundary. For example, the greatest density of fish traps is seen just meters from the borders of a marine park in Kenya, with a dramatic drop in traps found more than 500 meters (547 yards) away (McClanahan and Mangi, 2000). “Fishing the line” in Kenyan reef reserves has been shown through careful study

Figure Three



to yield higher catches for the same effort than fishing farther from the reserve (McClanahan and Kaunda-Arara, 1996; McClanahan and Mangi, 2000). Roberts and others (2001) showed that total catch increased outside reserves in the Caribbean island of St. Lucia at the same time as fish abundance increased inside reserves (Figure Three). Overall, fish biomass was almost three times higher outside reserves after five years of protection.

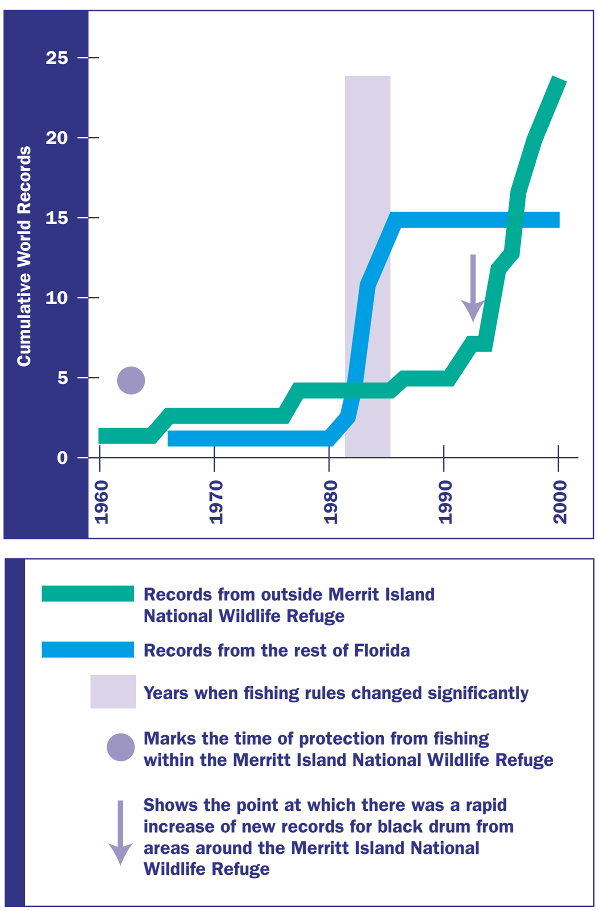
Dramatic evidence of spillover can be seen in the increase in large fish caught in the estuary neighboring the Merritt Island National Wildlife Reserve near Cape Canaveral, Florida (Figure Four). World-record-size fish now tend to come from areas just outside this reserve, showing spillover of large fish of at least three species to adjacent habitats.

Complex changes in rules governing record-size fish and the impact of stringent tra-

Figure Four

World Record Sizes for Black Drum

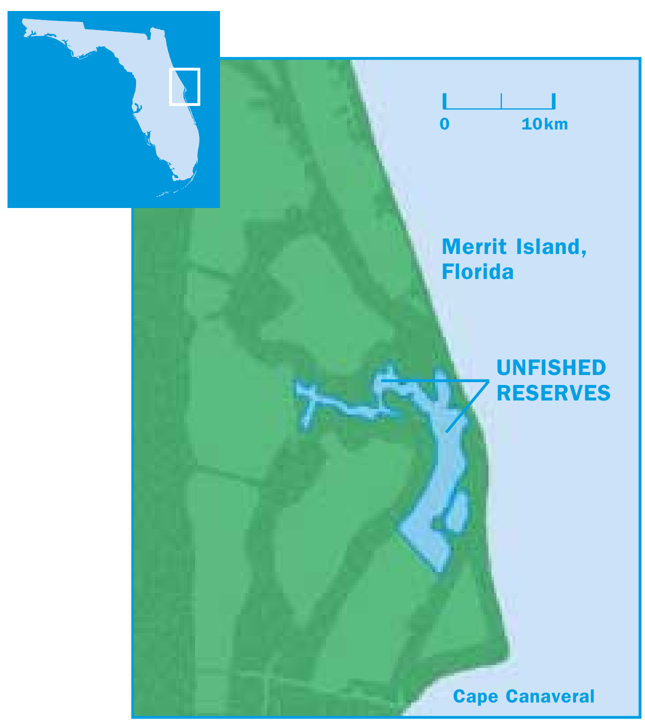
World size records for black drum *(Pogonias cromis)* from Florida and from outside the Merrit Island National Wildlife Refuge. Fish caught outside the refuge now dominate the world-record category (Roberts et al., 2001).



John Michael Yanson

A black drum is about to be released back into the water after being caught in a catch-and-release fishery in the South Banana River at Cape Canaveral, Florida.

Susan Cocking



Maps: Widmeyer Communications

ditional fisheries management (Tupper, 2002; Wickstrom, 2002) are unlikely to explain the spillover results. The increase of record-size fish was quickest for the fastest-growing fish and slowest for the slowest-growing fish, patterns that strongly suggest an impact of protection of fish inside the reserve (Roberts et al., 2002). In addition, fisheries regulations are enforced statewide and there is no reason to suspect they have a bigger impact near Merritt Island than elsewhere (Roberts et al., 2002).

"In Brackett's Landing Shoreline Sanctuary Conservation Area, large lingcod have been estimated to produce 20 times more eggs than in similar areas outside the reserve."

Does spillover from reserves make up for the decrease in area open to fishing? There are extremely few comparative data that can be used to answer this question, but the St. Lucia study suggests that these reserves have improved overall catches. Similar socioeconomic data from the Florida Keys National Marine Sanctuary reserve at Western Sambo show increases in local fishing around the reserve, and no drop in fish catch due to the implementation of the reserve (FKNMS, 2002). In Kenya, total catch has stabilized, becoming less variable over time than it was before reserve establishment, and catch per fisher, per day has increased 30 to 50 percent (McClanahan and Mangi, 2000).

Larval Spillover and Replenishment of Natural Ecosystems

These examples show that spillover of adults or juveniles out of reserves is possible, but what about the export of eggs and larvae? Many species of marine fish and invertebrates produce planktonic eggs or larvae that drift in water currents for weeks or months before metamorphosing into bottom-dwelling juveniles. These eggs and larvae can be important export products from reserves if the production of eggs and larvae outside the reserves is limiting to the size of the next generation. This is likely to be true in extremely overexploited species, or species for which habitat loss has dramatically reduced reproductive potential (e.g., some turtles), but it is not clear which of the moderately exploited species in the U.S. fishery fall under this category (Myers et al., 1994).

Lingcod, *Ophiodon elongatus,* Pacific Northwest

The larger biomass of fished species inside reserves will have a large effect on potential egg production, and this larger production could have an effect on availability of eggs and larvae outside reserves. In Brackett's Landing Shoreline Sanctuary Conservation Area, large lingcod have been estimated to produce 20 times more eggs than in similar areas outside the reserve. If reserves typically produce 20 times more eggs than outside areas, then establishing reserves in 10 percent of an area will triple egg production. Although these estimates are easy to make, any serious effect outside reserves depends on reserve sizes large enough to add substantially to regional egg production.

Thus, scientific study of this issue is hampered by lack of study systems in the U.S., and is limited by a fundamental gap in our understanding of the early life cycles of most commercial marine species.

To date, the best large-scale (but accidental) example of larval export derives from the fishing closures on the Georges Bank off Cape Cod (Murawski, 2000). These closures protected the sea bottom from bottom trawling, resulting in a dense population of scallops producing a cloud of larvae that has drifted downstream, densely seeding areas of the Bank outside of the closure (Murawski, 2000). The closure that produced this effect is large, and the scallop population probably numbers in the millions, so these results may be difficult to replicate soon.

Marine Reserve Models

Key questions in marine reserve research and design are: How much area in a region should be devoted to reserves, and how big should individual reserves be? Field studies show that if the goal of a reserve is to buttress the density and diversity of species inside, then even small reserves (under one square kilometer) can be effective (Halpern, 2002). Models and empirical investigations suggest that larger reserves will protect more species than smaller reserves (Neigel, in press; McClanhan and Mangi, 2000). It is clear that some species of highly mobile fish, such as bluefin tuna *(Thunnus thynnus),* will never spend their whole lives in a reserve unless it is enormous. However, even for these species, the existence of healthy ecosystems in reserves is beneficial if they provide islands of normal habitat or protect spawning and nursery grounds (Roberts and Hawkins, 2000). Fisheries benefits for such species are not likely to be the most important reason to establish reserves.

If reserves are meant to play a role in fisheries, the effectiveness of export becomes a critical issue (Roberts et al., 2001). However, there are few U.S. studies of reserves in a fisheries context. Instead, guidance stems from mathematical models of reserves. In such models, reserves and effort control through regular fisheries management are similar in impact, but reserves also provide benefits to more than a single species (Hastings and Botsford, 1999). There are many different reserve configurations for a given set of

"To date, the best large-scale (but accidental) example of larval export derives from the fishing closures on the Georges Bank off Cape Cod."

Richard Herrmann

Bluefin Tuna, *Thunnus thynnus,* off Baja California parameters that can provide similar levels of fisheries benefit, but substantial fisheries benefit typically requires substantial investment in reserves—20 to 50 percent in various models (Hastings and Botsford, 1999; Botsford et al., 2001; Hastings and Botsford, in press; Botsford et al., in press). The amount of area required in reserves varies, but very few models show significant fisheries benefit at low coverage (<10 percent).

"...substantial fisheries benefit typically requires substantial investment in reserves...."

In addition, the configuration of reserves—and their size—matters. A reserve that is too small will not be self-sustaining because most larvae produced in it are transported elsewhere. Thus, a small, isolated reserve must be seeded from a fished area in order to have any resident population. By contrast, a large reserve will retain too much of the reserve's productivity, releasing too little at the edges to effectively enhance the fishery. For any virtual coastline, intermediate reserve sizes enhance fisheries the most with the least overall reserve area (Botsford et al., 2001 and in press). The best size depends on the species modeled.

The models do not provide single answers to obvious and crucial questions about the density and spacing of marine reserves. Instead, the models provide a range of answers for different situations. Answers to such questions will vary depending on the ecosystem, the marine community being protected, and the human community being asked to support the network of reserves. Answers also depend on the degree to which reserves are being used as a habitat-protection tool, an ecosystem-management tool, a conservation tool, or a fisheries tool.

Reserve Networks

Models also suggest that there are attractive alternatives to single, self-seeding reserves. Reserve networks—a series of reserves that are individually too small to be self-seeding, but that are close enough together so that one reserve can seed another—can fulfill the need to have high spillover into adjacent fished areas (because the reserves are small). These networks can also provide an overall boost to regional egg and larval production (if there are enough reserves). Networks of smaller reserves—rather than one big reserve—provide other benefits as well. For example, they spread the risk of catastrophic habitat loss due to natural or anthropogenic disturbances such as hurricanes or oil spills (Allison et al., in press).

Networks are very poorly studied. Little is known about how far marine species are transported from place to place and about how reserve networks are likely to function for a particular species. However, because most current marine reserves are not big enough to be self-seeding, they must be receiving eggs and larvae from elsewhere. This shows that networking between reserves and fished areas is currently occurring. Studies of this phenomenon will greatly expand the ability to engineer appropriate reserve networks.

Dispersal Variability and Design

Although models show that dispersal is a key feature of reserve function, quantitative dispersal estimates are still rare in marine taxa. However, qualitative knowledge suggests a key feature of virtually all marine ecosystems: they are made up of species with a wide variety of dispersal profiles. Every marine community has species with extremely low dispersal potential (e.g., most algae, colonial tunicates, sponges, some snails), some with moderate dispersal potential whose larvae spend weeks in the plankton, and some with high rates of movement as adults or larvae. Because the models show that these different types of species require reserves with different spacing, the simple conclusion is that reserve networks should have a variety of spacing—from quite low to high—in order to accommodate the whole community. Likewise, it is unlikely that a single reserve size will be optimal for all species. The same is true for terrestrial parks where home-range needs are very different for insects, passerine birds, and large predatory mammals. In terrestrial cases, parks are sometimes designed around the range needs of the largest animals. Is this strategy appropriate for marine reserves? Will reserves designed to be large enough for the species with the largest range adequately protect all other species? How large will those reserves need to be? Current knowledge about marine reserves does not provide unambiguous answers to these questions. However, further exploration of the results of reserve modeling studies shows that reserve networks provide an alternative to the deployment of large, self-seeding reserves.

Research, Education, and Stewardship

Modeling efforts and design criteria for reserves should not focus exclusively on fisheries goals because reserves play strong roles in other areas of marine management. The conservation value of reserves is addressed above. Additional value is in the stabilization and restoration of marine ecosystems for public education, public enjoyment, research, and stewardship. The high existence value of healthy marine ecosystems (see Chapter Two) shows that public interest in maintaining wilderness areas is not limited to the land. Interest in the sea continues to be high, and the thriving ecosystems within reserves can be inspirational to students, tourists, and fishers. Research within reserves continues to generate surprises about how marine ecosystems function (Babcock et al., 1999), and focused studies on existing U.S. reserves (FKNMS, 2002) are providing a great deal more information about the biological, economic, and social impact of reserves as tools for ecosystem-based management.

Research and education are needed for the long-term operation of a reserve. Research is necessary to understand the biological and social impact of the reserve after it is established (for an example, see Roberts et al., 2001), and education is needed to continue to update local communities about the progress of reserve protection and its impact.

"...public interest in maintaining wilderness areas is not limited to the land."

Criteria for Reserve Placement

Over the past ten years, examples of successful—and unsuccessful—implementation of reserves has provided a much-needed reference for the biological criteria on which to base reserve designation, and the processes through which community engagement in reserves can be successful. Although each situation is different, several common features of marine ecosystems are important aspects of reserve placement. According to the review by Roberts and others (2002), reserves with conservation and fisheries goals should consider ten major criteria:

"Although each situation is different, several common features of marine ecosystems are important aspects of reserve placement."

- **Biogeographic representation**—inclusion of reserves in many different biogeographic zones.
- **Habitat representation and heterogeneity**—inclusion of all different habitat types.
- **Human threats**—protection of a reserve from non-extractive human threats, such as pollution.
- **Natural catastrophes**—whether a reserve is subject to severe natural catastrophes.
- **Size**—whether the reserve's size will meet its goals.
- **Connectivity**—whether the reserve is connected by dispersal to other reserves or the rest of the ecosystem.
- **Vulnerable habitats, life stages, or populations**—whether the reserve includes these.
- **Species of particular concern**—whether threatened species are present in the reserve.
- **Exploitable species**—whether the reserve harbors species exploited outside.
- **Ecological services for humans**—whether the reserve area provides substantial ecological services.

These criteria have been implemented in different ways in different parts of the world, including the Tortugas 2000 process that resulted in the Tortugas Ecological Reserve, in Florida, and countrywide efforts in South Africa. The weights given each criterion vary depending on the circumstances. In addition, social and economic factors play a role.

Computer Tools for Mapmaking

The combination of Geographical Information Systems (GIS) databases and computerized map evaluation techniques provides a much-needed new tool in reserve design. GIS databases provide explicit maps of different habitat types along a stretch of coast, and they can be augmented to provide information such as species occurrences and anthropogenic influence. The maps and overlays are the raw material to estimate placement of reserves.

Once criteria and maps are supplied, new computer algorithms search for solutions. In practice, the computer starts with a random map of reserve placement, and then improves it slightly, stage by stage, searching progressively for maps that are closer to the stated criteria.

For example, one criterion might be for a set of reserves that protects 20 percent of each of several habitat types in an ecosystem. The Florida Keys includes habitats as diverse as seagrass beds, sand flats, coral rubble, reefs, and deep channels. All these habitats are mapped into a GIS database (Florida Marine Research Institute and U.S. National Ocean Service). From these maps, the computer can choose potential reserve sites that meet the criteria input into the program.

Leslie and others (in press) found many reserve configurations that would work in the Florida Keys. In fact, the computer program does not produce one map, but several hundred that are all consistent with the input requirements. Other criteria can be added to this computer system, allowing the design of reserves that satisfy many seemingly incompatible requirements. For example, distance from pollution sources, marinas, or fishing grounds can be input as factors favorable or unfavorable to choosing an area as a reserve. The output can be used as a starting place in discussion with different stakeholders, allowing a flexible dialogue about reserve implementation. This approach has been used in part by the Channel Islands National Marine Sanctuary and the California Department of Fish and Game.

Chuck Davis

Blue Shark, *Prionace glauca,* Anacapa Passage, near Santa Cruz Island, California

The Larger Context of Reserves

Reserves are a tool for ecosystem-based management, but there is a tendency to think about them on a traditional single-species basis by asking, Will they work for cod? striped bass? blue sharks? Although these questions are important, they represent the wrong approach to reserves. The correct questions are, "Will they work for the ecosystem in which cod live? in which striped bass live? in which blue sharks live?" Without asking questions about the ecosystem goals of reserves, it is too easy to fall into the trap of viewing them as another single-species management tool.

As a tool for ecosystem-based management, reserves should be approached based on what is known about marine ecosystems. There are a number of known characteristics of marine ecosystems:

- Every marine ecosystem houses a complex assortment of species that have a wide variety of habitat needs, life strategies, and value to humans.
- Interactions within ecosystems are intense and strong impacts on one part of the species assemblage usually ripple through the ecosystem, causing concomitant changes in other species.
- Every ecosystem experiences multiple conflicting uses, from recreation to pollution to extraction of mineral and biological wealth.
- Multiple threats to oceans stem from natural and anthropogenic impacts on habitats and populations.
- Some ocean threats, such as the effects of dredging, are local, but some, such as nutrient runoff and overexploitation of pelagic fishes, occur far from the source of the problem.
- Every call for biodiversity preservation and better management of fisheries stocks includes protecting habitats for adults, juveniles, or spawners.
- Climate variability—both natural and enhanced by global change—can impair ecosystem function at some places and times so that protected habitats must be duplicated for insurance against disaster.
- No single management tool—even preserving habitats—by itself can address all threats to the oceans at the same time.

"Without asking questions about the ecosystem goals of reserves, it is too easy to fall into the trap of viewing them as another single-species management tool."

“Tools that address all the species of an ecosystem are rare, but one of the most powerful is marine reserves.”

The conclusion from these facts is that responding to ocean threats requires multidimensional thinking and deployment of tools that are broadly useful in a variety of settings and for a variety of impacted species. Coordinated amelioration of multiple threats requires the realization that these threats are integrated by ecosystems and that ecosystem health could be a powerful focus of a multidimensional solution to ocean problems. Tools that address all the species of an ecosystem are rare, but one of the most powerful is marine reserves. The impact of this tool can be adjusted by changing how reserves are implemented: strong impacts can be had through commitment of large areas to reserves. Smaller, boutique-level impact can derive from small reserves. New reserve implementation tools allow local communities to evaluate many different possibilities for reserve design and can smooth the process of community involvement. Even small reserves can function to enhance ecosystems, but if these local reserves are to be more than merely a monument to diversity lost elsewhere, they should be implemented with enough area to allow substantial spillover into local surrounding communities. Whether this spillover is enough to solve regional fisheries problems depends on the focal species, the area invested in reserves, and whether reserves export substantial adults, eggs, or larvae.

Most alternatives to reserves require extensive knowledge of how to precisely manage marine ecosystems through overlapping single-species fisheries plans. In effect, current fisheries science has few tools to protect ecosystems without reserves. Reserves allow ecosystems to recover and to be sustained at the same time that other ecosystem-based management tools are invented and deployed, while greatly easing compliance and enforcement efforts.

Summary

Abundant evidence indicates that for heavily fished species, reserves typically increase biomass, density, and size within their borders. Although not every species shows this effect, it is rare that a reserve does not show increases for one or more species. Habitat protection is a major benefit of reserves in situations where exploitation alters habitat characters. Spillover of a fraction of these larger populations is increasingly apparent from field studies of reserves. Far less well known are the regional effects of reserves on egg and larval abundance. Although it is reasonable that the manyfold increase in spawning biomass within reserves will augment the reproductive capacity of many species, proof is rare. The area in reserve determines the degree to which a reserve functions as fishery tool—there is a continuum from scant fishery effect to major fishery effect. Although small reserves are known to afford protection and show increased densities inside their borders, they probably rely on import of larvae from elsewhere. A self-seeding, stable reserve requires a large area because of the dispersal potential of many marine species. Reserve networks, comprising a series of small reserves that are close enough to seed one another, provide alternative configurations.

Results from existing reserves and models show that conservation benefits from reserves accrue easily, and that local augmentation of exploited species just outside reserve boundaries will probably be common. The current fashion of establishing small reserves could be built into a functioning tool for ecosystem-based management if these reserves are numerous. These reserves fulfill several major goals, including conservation of biodiversity, restoration of ecosystems, local to regional spillover, and provision of educational and research sites.

IV. Conclusions

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Clown Nudibranch, *Triopha catalinae,* near San Juan Islands, Washington

Marine reserve research delivers several consistent messages about our ability to affect and manage marine ecosystems. The most important is that enforced no-take marine reserves generate powerful changes in local ecosystems that can dramatically alter the abundance and size of species that are overexploited outside. Reserves function well, and they are empirically vetted as an ecosystem-based management tool in a wide variety of settings. Reserves are particularly powerful in situations where biological habitats are severely disrupted by overfishing and where local populations of fished species rely on these habitats. Especially in these settings, or where exploited populations are severely depleted, reserves are in the vanguard of marine management success stories and should be considered an integral part of any comprehensive plan to respond to current threats facing the oceans.

Effects outside reserve borders vary with size and habitat, and with overall area committed to reserves. To broadly enhance regional ecosystems, reserves need to be implemented densely enough to substantially contribute to species diversity and recruitment outside their borders. Mathematical models conclude with near unanimity that benefits to major regional fisheries can only be expected from reserves if a substantial amount of area is in reserves, and that small investment in reserves will reduce their contribution to regional fisheries. However, small reserves may still supplement local fisheries and function as important conservation tools. Small reserves may also provide a disproportional benefit to fisheries if they protect critical habitat, such as nursery grounds or spawning aggregations. Regional effects depend on export of production outside reserves, and this will be variable from species to species. Self-seeding reserves will have to either be large for many high-dispersal species, or be implemented as a series of networks scattered across the seascape.

Use of the oceans has expanded to the point that virtually no marine ecosystem remains pristine (Jackson et al., 2001). So many different marine species are consumed, so many others used in food processing, and so much discarded in bycatch that entire natural ecosystems are harvested in the sea to an extent unthinkable on land in the U.S. However, exploitation is not the sole threat facing the oceans. By themselves, reserves will not solve problems of terrestrial runoff, the ecological effects of aquaculture or of invasive species. Yet, they can stem habitat destruction, alleviate the local effects of overfishing, protect areas from mining, simplify the simultaneous management of multiple species, and restore biodiversity within their borders. The ten-year clinical trial of marine reserves, conducted intensively throughout the 1990s, shows the oceans need this medicine.

Recommendations

Recommendations for the use of marine reserves as an ecosystem-based management tool fall into three broad categories.

"The ten-year clinical trial of marine reserves, conducted intensively throughout the 1990s, shows the oceans need this medicine."

Reserves and Ecosystem Management

Implement reserves for all major biological habitats in coastal U.S. waters. These habitats are under so many simultaneous threats that immediate protection is paramount. A network of reserves will enhance local ecosystems and provide substantial legacy and conservation value. Habitat protection will enhance recovery of biological structure fundamental to maintenance of marine biodiversity. Reserves placed within all major habitat types are crucial to protection of many species that use multiple habitats.

This action requires summary of major marine habitats on a regional basis throughout the U.S., and an initial designation of several reserves within each type. The recent designation of ten state marine reserves in the Channel Islands should be a national model for the growth of a network of marine reserves in the U.S. Current knowledge of the major marine biogeographical provinces, as well as information on bottom topography and substrate, will help inventory these habitats.

Designating even a single reserve in each of these habitats will require coordination between local, state, and federal governments, and a process of coordination with local communities. These governance challenges may be greater than any biological uncertainties surrounding the impact of reserves. Solving these challenges, starting with lessons learned by National Marine Sanctuaries on implementing reserves, will be an investment in the future of community and ecosystem-based marine management.

Incremental, Adaptive Growth of Reserve Systems

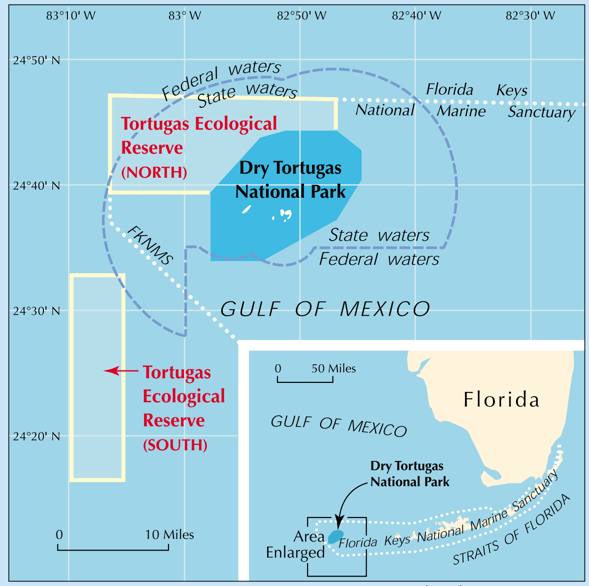
The design and implementation of multiple reserves in a habitat should be done adaptively, using early efforts to inform better design for network expansion, and using the expertise and experience of local stakeholders to guide and enhance reserve effectiveness. This requires consultation with local communities on a continuing basis and suggests the need for a coordinating group to oversee reserves. In addition, reserves and nonreserve areas need to be monitored for performance and effect. Such monitoring should be done in the context of testing hypotheses about reserve impact within and outside reserve borders. In addition, socioeconomic monitoring should be conducted to understand the complex interactions of reserves and local economies. Enforcement of reserve borders is a fundamental part of management, and needs to be included in the monitoring schemes.

It is highly unlikely that any rigid formula for implementing multiple reserves will work for all kinds of marine habitats. The nature of marine ecosystems is diversity and variability—in the number and lifestyles of species, and in local environmental conditions. Protecting this diversity with reserves will require reserves of different sizes and varied spacing. A grid of same-size reserves should not be the goal. Rather, a seascape

Profile of a Marine Reserve

Tortugas Ecological Reserve

- The Tortugas Ecological Reserve was implemented on July 1, 2001, after four years of planning and development.
- The reserve is divided into two parts: Tortugas North (91 square nautical miles) and Tortugas South (60 square nautical miles).
- The Dry Tortugas is a remote area in the western part of the Florida Keys National Marine Sanctuary (FKNMS).
- The reserve was created to protect the diverse habitats—such as corals and sea grasses—and spawning grounds for marine life of the coral reef ecosystem of the Tortugas.
- Numerous state and federal agencies play important roles in the cooperative planning and management of the Tortugas region, including Florida Keys National Marine Sanctuary, the state of Florida, National Park Service, and National Marine Fisheries Service.



Lucidity Information Design, LLC

Development and Implementation of the Reserve's Management

The planning and development process consisted of three phases:

1. Designing alternatives for the reserve boundaries, applying the best available science;
2. Soliciting and maximizing comments from the public; and
3. Refining and implementing an ecological reserve.

Throughout the planning process, Billy Causey (Superintendent of the FKNMS) placed strong emphasis on consensus building. The sanctuary convened a 25-member working group composed of commercial and recreational fishers, divers, conservationists, scientists, concerned citizens, and government agencies to develop a preferred alternative. The process used to develop the reserve serves as a model for collaborative reserve design.

©Marc Muench

Yellow goatfish, *Mulloidichthys martinicus,* Dry Tortugas National Park

The management plan is currently implemented cooperatively by state and federal agencies. The FKNMS will continue to review the plan and, if necessary, revise it on a five-year cycle. Populations and communities are being monitored in this, the largest marine reserve in the U.S., so that scientists can determine whether improvements in ecosystem health accrue over time.

populated by a fleet of reserves of different shapes and sizes is the most useful conceptual model for reserve networks.

Comprehensive Ocean-Use Planning

Reserves do not operate in a vacuum, and the recommendation to move forward with marine reserve implementation does not imply that other management efforts should stop. Reserves provide a unique ecosystem-based management tool to add to the current suite of management options and should be part of a comprehensive effort to manage multiple uses of ocean habitats for multiple goals. There are some threats for which reserves provide no intrinsic solution (e.g., invasive species). For other threats such as pollution, area-based protection provided by reserves could be expanded to include enhanced local control over toxic emissions. In addition, not all uses of the oceans are threats. In some cases, reserves may enhance ocean use, such as in areas with coastal tourism. Wherever multiple uses of community resources occur, conflicts increase with the rate of ocean use. Reserves could increase those conflicts unless they are planned well. Future increases in the multiple-use of all coastal and ocean areas will require a coordinated effort to reduce conflicts through zone management.

"...marine reserves will need to be an integrated part of the eventual seascape."

Achieving coordinated multiple-use of coastal and ocean areas will require a fundamental reorganization of the role of governments in marine activities. As in the inventorying of marine habitats suggested in recommendation one, ocean zoning requires a summary of different ocean uses and their impacts on one another in order for any ocean-use planning to proceed. However, as this new planning capacity is born, marine reserves will need to be an integrated part of the eventual seascape.

A View of the Future

These considerations suggest that a future for the oceans includes a dense network of fully protect-

Recommendations for Action

Marine reserves have become a proven tool in marine management. They should be an integral part of all future efforts to protect marine ecosystems and coordinate ocean use.

Reserves and Ecosystem Management: Acting as part of a larger scheme of marine ecosystem monitoring and management, reserves should be implemented immediately in all major marine habitats in U.S. coastal waters.

Incremental, Adaptive Growth of Reserve Systems: Building a system of reserves in each habitat will require careful consideration by local groups focusing on all aspects of ocean use. Monitoring inside and outside existing reserves will help inform decisions about reserve system growth. A fleet of reserves of different shapes and sizes is the most useful conceptual model for reserve networks.

Comprehensive Ocean-Use Planning: Increased use and reliance on the sea for multiple, potentially conflicting purposes requires a move toward integration of all ocean uses in a comprehensive planning framework. The scale of ocean ecosystems suggests that planning cannot be done solely at the local level, but must be integrated at state and national levels.

ed marine reserves that sits within a regulatory framework of local communities and agencies with regional responsibility. Reserve systems should be self-seeding regionally and have the potential to export significant diversity and biomass into surrounding seas. There should be enough replication of reserves so that their diversity is buffered against local human-caused impacts and natural disasters. Reserve design should allow for enforcement and monitoring, with the potential for non-damaging recreational and professional use. The same regional and local authorities should address other threats to ocean ecosystems in a coordinated way.

Reserves have the potential to preserve and invigorate marine ecosystems in ways that may strengthen ecosystem resilience in the face of other impacts such as global change and increased human population. At the same time, reserves address the needs of hundreds of species that humans eat, as well as the needs of thousands more. By protecting habitats, reserves protect the underlying structure of some of the premier coastal ecosystems in the U.S., from kelp forests to oyster beds to coral reefs. These complex structures nurture the ecosystems that humans rely upon, and like other natural wonders, some habitats are slow to be re-created once destroyed.

In many ways, this is a special time in the history of the sea. Humans have developed the ability to disrupt entire seas and oceans. Yet, when human impact ceases, many marine ecosystems rebound prodigiously. It is unclear how long this good luck will continue. Some rebounds, such as those of turtles or sharks, may never occur. However, if the sea is protected now, it is reasonable to expect that it will recover a substantial part of its former glory. Capturing that glory is a legacy for the future—not only in terms of the species it protects but also in terms of the human lifestyles it will preserve. The tool to protect the future of our oceans is marine reserves.

"...this is a special time in the history of the sea."

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The Pew Oceans Commission is an independent group of American leaders conducting a national dialogue on the policies needed to restore and protect living marine resources in U.S. waters. After reviewing the best scientific information available, the Commission will make its formal recommendations in a report to Congress and the nation in early 2003.

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