The Science of
Marine Reserves

PISCO Partnership for Interdisciplinary Studies of Coastal Oceans

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The Partnership for Interdisciplinary Studies of Coastal Oceans (PISCO) *produced this report in collaboration with SeaWeb, Communication Partnership for Science and the Sea (COMPASS), and the National Center for Ecological Analysis and Synthesis (NCEAS).*

PISCO is a consortium of academic scientists at Oregon State University, University of California at Santa Barbara, University of California at Santa Cruz, and Stanford University. PISCO is dedicated to advancing the understanding of coastal marine ecosystems and to communicating scientific knowledge to diverse audiences.

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A companion 15-minute film, The Science of Marine Reserves produced by Sea Studios Foundation, is available from the PISCO Web site.

Senior Editors
Jane Lubchenco, Professor, Oregon State University
Steven Gaines, Professor, University of California at Santa Barbara
Robert Warner, Professor, University of California at Santa Barbara
Satie Airamé, University of California at Santa Barbara
Brooke Simler, Oregon State University

Senior Writer: Peter H. Taylor
Creative Director: Jeff Jones
Senior Designer: Monica Pessino
Designer: Josh Temkin

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Overview:

Marine environments worldwide are in the midst of a transformation. There is increasing evidence that ocean ecosystems are being altered beyond their range of natural variability by a combination of human activities, including fishing, pollution, and coastal development. Because of these changes, a growing portion of the global community is inquiring about alternative management options for ocean environments.

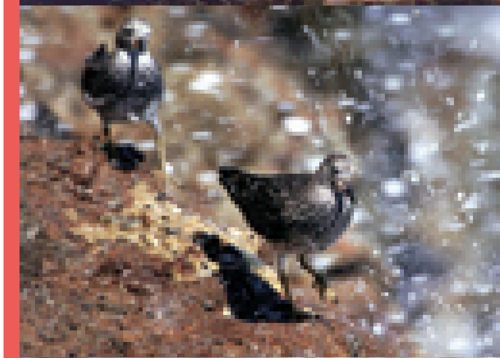
Research shows that marine reserves are one tool that can help to prevent, slow, or reverse negative changes in the ocean. Marine reserves are places in the ocean that are completely and permanently protected from uses that remove animals and plants or alter their habitats. Increasingly, the public, governmental agencies, commercial groups, and scientists are discussing the idea of establishing more marine reserves to complement existing ocean management. The purpose of this report is to provide a summary of the latest scientific information about marine reserves.

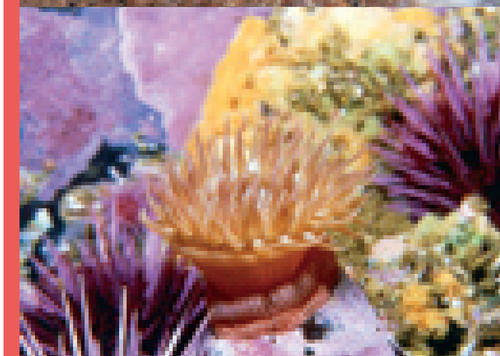
Marine reserves produce different outcomes from other types of management. Reserves protect marine habitats in a particular place and the diversity of animals and plants that live in those habitats. Consequently, many animals and plants in reserves tend to live in greater numbers, grow larger, and reproduce more than their counterparts outside reserves. In contrast, other management strategies attempt to control only some activities or protect only a few species.

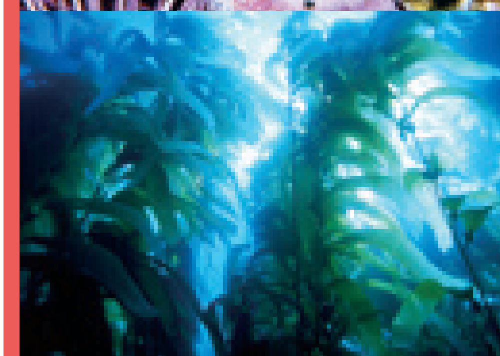
Many other kinds of marine protected areas – with names such as marine parks, marine refuges, or marine sanctuaries – exclude some, but often very few, extractive activities. Those areas do not generate the same effects as marine reserves because they provide far less protection.

Marine reserves are one tool for managing ocean ecosystems, but they cannot protect oceans from all human influences. Reserves alone may not address such pervasive problems as pollution and climate change, and they may have fewer direct benefits to some fishes and mammals that move long distances. However, the most recent scientific research shows that marine reserves usually boost the abundance, diversity, and size of marine species living within their borders. This booklet examines the causes and potential consequences of these biological changes.

what is a marine reserve?



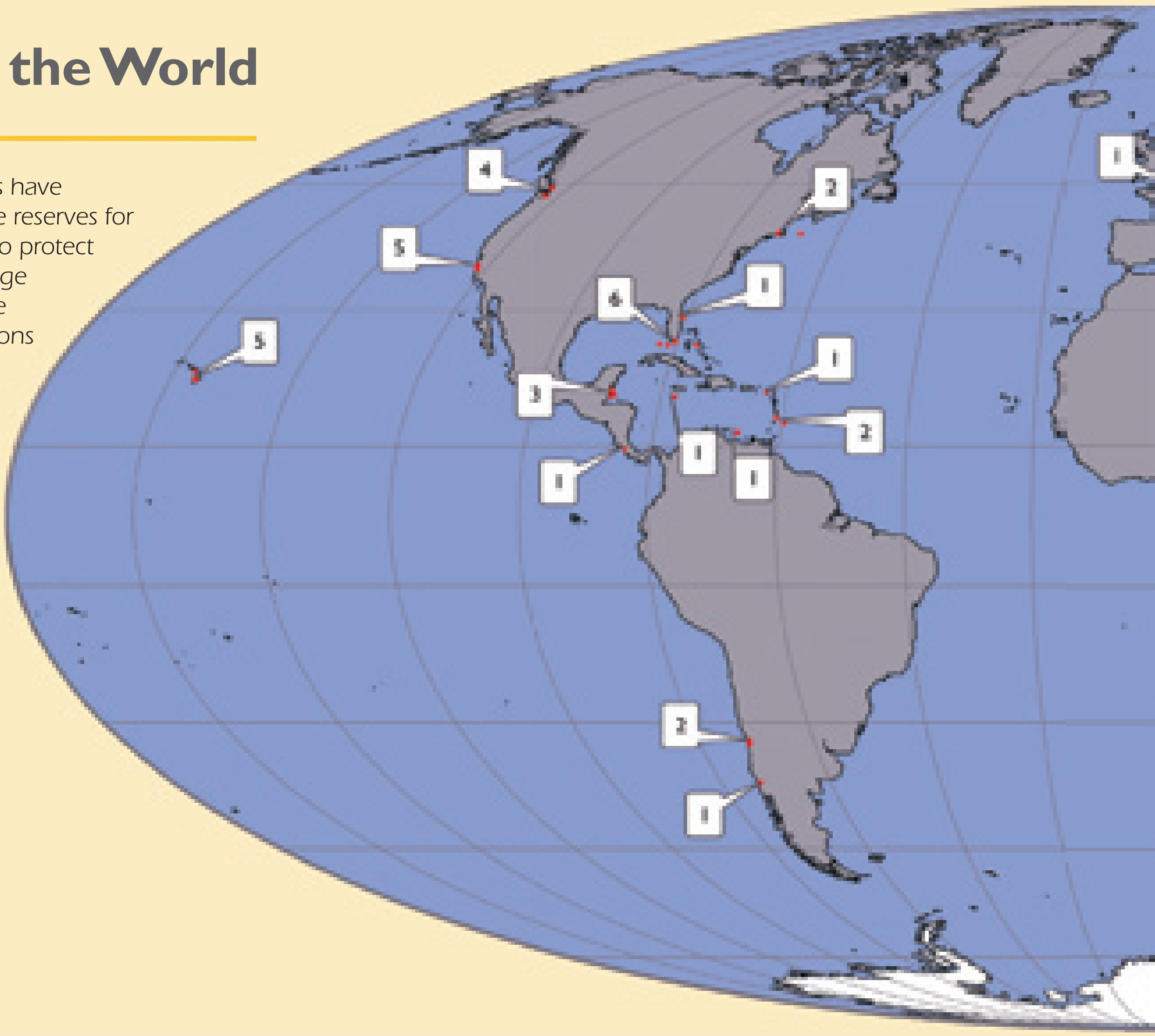




around the World

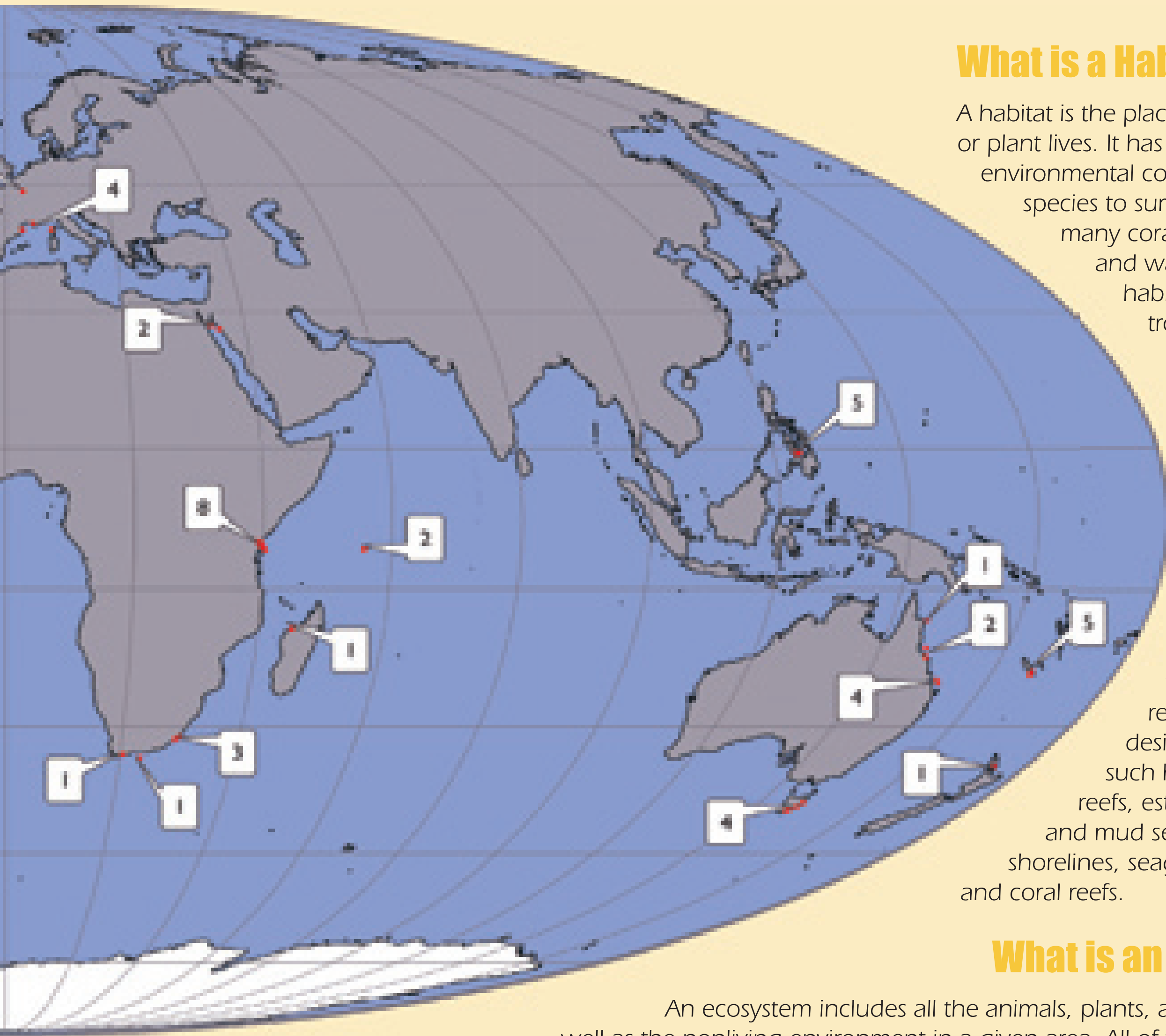
- At least 23 nations have established marine reserves for various reasons - to protect biodiversity, manage fisheries, or restore depleted populations of marine animals and plants.

Australia
Bahamas
Barbados
Belize
Canada
Chile
Costa Rica
Egypt
Fiji
France
Japan
Kenya
Madagascar
New Caledonia
New Zealand
Philippines
Saba (Netherlands Antilles)
Saint Lucia
Seychelles
South Africa
Spain
United States
Venezuela



- **More than 100 marine reserves have been established worldwide.**
- **Marine reserves encompass much less than 1 percent of the world's oceans and less than 0.01 percent of U.S. waters.**
- **Marine reserves range in size from less than a square mile to hundreds of square miles. Currently, most reserves are quite small, and the median reserve size is less than 1.5 square miles.**

marine reserves studied around the world



What is a Habitat?

A habitat is the place where an animal or plant lives. It has all the necessary environmental conditions for that species to survive. For example, many corals require sunlight and warm water. Their habitats are in shallow tropical seas. Habitats support many different communities of animals and plants. Natural or human-caused activities may change habitats and the species living there. Marine reserves have been designed to protect such habitats as rocky reefs, estuaries, sand and mud seafloors, rocky shorelines, seagrass meadows, and coral reefs.

What is an Ecosystem?

An ecosystem includes all the animals, plants, and microbes as well as the nonliving environment in a given area. All of these elements are connected through biological, chemical, and physical processes. Each species plays a role in an ecosystem. For example, algae, fishes, invertebrates, mammals, and microbes in a kelp forest interact to form a rich marine ecosystem. When one species is reduced or removed, others may be affected. Ecosystems can be large or small. The Gulf of Maine is an example of a very large ecosystem that includes diverse habitats across thousands of square miles.

Scientists have studied some marine reserves extensively. Their findings provide considerable information about the effects of reserves. The above map shows the locations of 80 fully protected marine reserves. Scientists have analyzed data from these reserves and published the results in scientific journals. Approximately 40 percent of these reserves are in temperate waters, while the others are in tropical waters. Many other marine reserves exist but have not been monitored effectively, making it difficult to evaluate their effects.

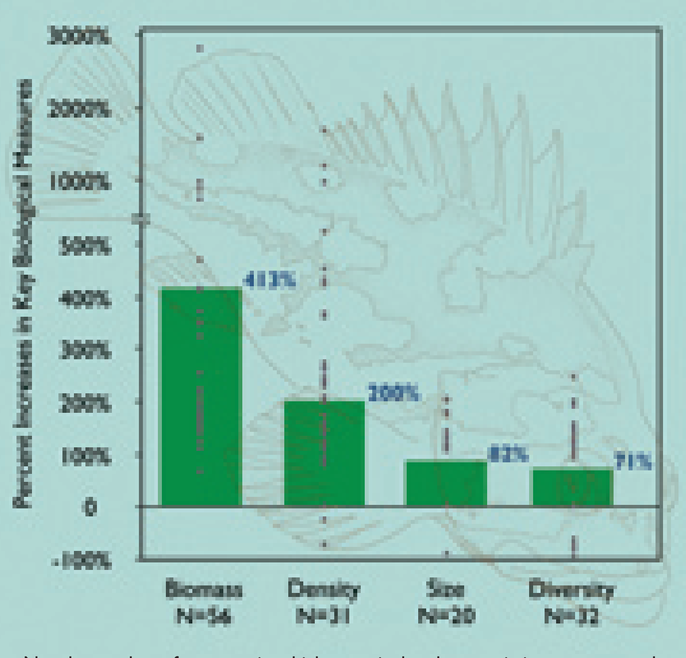
can reserves produce benefits inside their boundaries?

A major purpose for establishing marine reserves is to protect the habitats and to restore animals and plants in particular sites.

Do marine reserves typically accomplish these goals? Scientists have studied the performance of more than 80 marine reserves of many different sizes in a variety of temperate and tropical habitats. A comprehensive review of these studies reveals that most well-enforced marine reserves result in relatively large, rapid, and long-lasting increases in the population sizes, numbers of species, and reproductive output of marine animals and plants. The review found that the average biomass, or weight of all animals and plants studied, is more than four times larger in reserves than in unprotected areas nearby. On average, the density, or number of animals in an area, triples, and the number of species is 1.7 times higher in marine reserves than in unprotected areas. In addition, the average body size of animals is 1.8 times larger in reserves than in fished areas. These findings include not just fished species but other plants, invertebrates, and fishes.

Why do these changes occur within reserves? First, protection from fishing allows animals in reserves to survive longer and grow larger. Second, habitats can recover inside reserves and better sustain the plants and animals that rely on them. Third, the plentiful prey in reserves can support more predators. Marine reserves are currently the only marine management tool that provides this unique combination of effects, promoting the recovery of entire ecosystems.

Why are large populations important? Small populations are more likely to be driven extinct by unpredictable catastrophes, such as oil spills. Large populations include more individuals, so they are more likely to contain individuals that are capable of surviving various stresses. In addition, population size can influence the reproductive success of animals that release their eggs and sperm into the water, such as abalone and sea cucumbers; when these animals are rare, their eggs and sperm can become so diluted that little or no fertilization occurs.

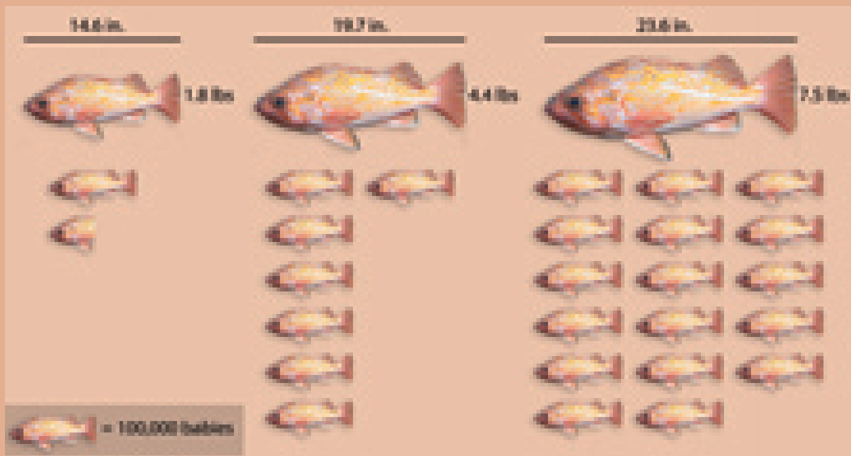


N = the number of reserves in which a particular characteristic was measured

Marine reserves usually increase the biomass, density, size, and diversity of species living within their boundaries. The bar graph (modified from Halpern, in press, and Palumbi, in press) indicates the percent change in key biological measures inside marine reserves. The average increases (green bars) are based on data from marine reserves around the world. The actual changes at particular reserves varied (gray dots), but the vast majority of all reserves showed positive responses in all biological variables.

Key Findings

- In marine reserves, animals and plants usually increase in their biomass, abundance, numbers of species, and body size — factors that can increase ecosystem resilience and productivity.
- Biological changes in marine reserves occur because individuals are not killed by fishing, and because their habitat is protected.
- Larger fishes and invertebrates typically produce substantially more young.
- Many species, not just those that are fished, respond positively to the protection of entire ecosystems in marine reserves.



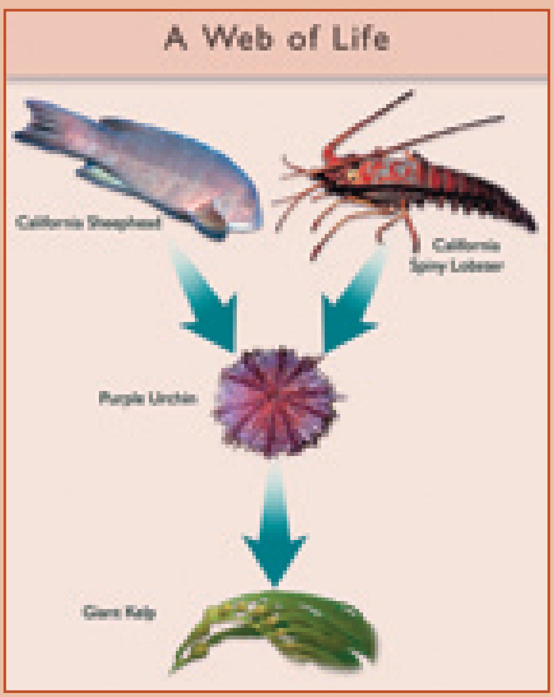
Average numbers of babies produced by three different sizes of vermilion rockfish.

Bigger body size is one of the most important biological changes in marine reserves, because large fishes and invertebrates can produce enormous numbers of young. The relationship between body size and the number of young is well known. For many marine fishes and invertebrates, small increases in body size can lead to large increases in the number of eggs produced. For example, a 23-inch vermilion rockfish can produce 17 times more young than a 14-inch fish. The bigger and more abundant animals living in a marine reserve can produce far more young than their smaller neighbors in unprotected waters. As a result, marine reserves can support higher growth rates.

Will reserves increase the abundance of all species?

Although many fished and nonfished animals and plants become more plentiful within newly established marine reserves, some decline. For example, a fished animal, such as lobster, may increase in number and size in marine reserves and consequently reduce the number of its prey, such as sea urchins (see illustration). In addition, some species that were absent may not become reestablished in a reserve if no viable populations remain nearby.

Although it is difficult to predict the exact changes for any particular species or location, the data from existing reserves show that, on average, increases in abundance, body size, biomass, and the number of species are common outcomes after marine reserves are established.



A food web shows the feeding (or trophic) relationships among species. In southern California, sheephead and lobster eat purple urchins, which consume giant kelp.

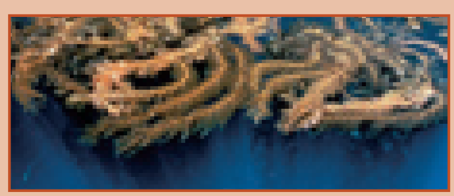
References: 1, 2, 6, 7, 8, 9.

The Importance of Healthy Ecosystems

Healthy ecosystems are the building blocks of productive and resilient oceans. People depend on productive oceans for "goods," such as food and medicines, and essential "services," such as the detoxification of pollutants, recycling of nutrients, control of pest outbreaks and diseases, and regulation of climate, atmospheric gases, and the water cycle. These essentials are called "ecosystem goods and services." Healthy ocean ecosystems provide these goods and services for free. If the ecosystem is damaged, for example by habitat destruction, pollution, or overfishing, the delivery of goods and services is impaired. As a result there may be a loss of productivity, increases in outbreaks of undesirable species, and less resilience to disasters.

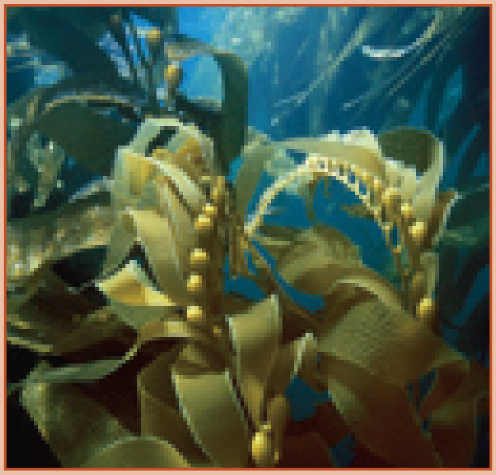
Essential goods and services are provided by many types of ocean ecosystems: coral reefs, kelp forests, mangroves, salt marshes, mud flats, estuaries, rocky shores, sandy beaches, sea mounts, continental shelves, abyssal plains, and open oceans. Each ecosystem contains many types of species that interact with each other and influence the physical and chemical environment. Goods and services are simply byproducts of the functioning of intact ecosystems.

Unlike other management tools, marine reserves protect major portions of an ecosystem, including all the habitats, plants, and animals. This protection allows the environment, the species, and their interactions to function in a manner that provides the ecosystem goods and services that humanity wants and needs.

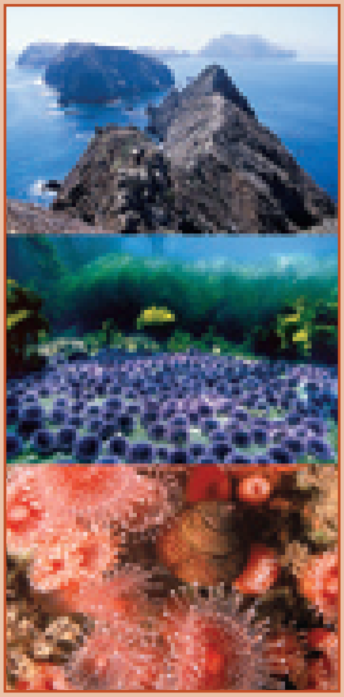


Case Study: Anacapa Island, California, USA

Anacapa Island Natural Area



Ecosystem Responses in a Marine Reserve



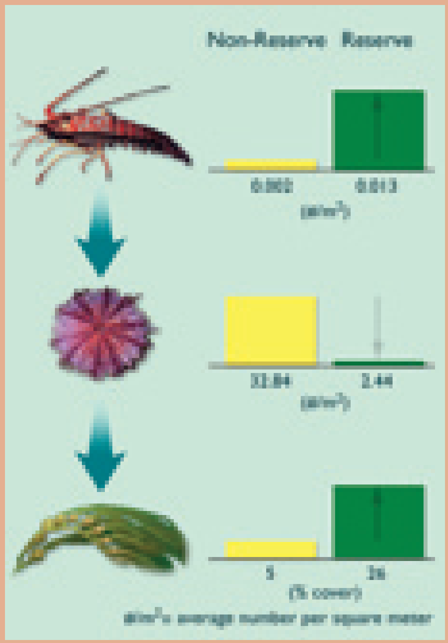
In 1978, the National Park Service established a closed area in the Anacapa Island Ecological Reserve in southern California. The ban on all fishing in the reserve protects lobsters, fish, sea urchins, and many other species living in the rocky reefs and kelp forest habitats of the reserve.

Since 1980, the National Park Service and partner agencies have collected biological data from the Anacapa Island reserve and unprotected areas nearby. The data show that the marine reserve supports some of the richest kelp forests in California's Channel Islands. Lobsters are six times more numerous, red urchins grow 1.7 times larger, and sheephead fish are three times more plentiful in the reserve than in nearby fished waters. Kelp plants, which form crucial habitats for other species, grow five times more densely and persist longer in the reserve than in waters nearby.

Lessons Learned

- Some important species, such as lobster and California sheephead, are larger and more abundant in the Anacapa Island marine reserve than in surrounding fished waters.
- Inside the reserve, kelp forests flourish because lobsters and sheephead, which are predators, reduce populations of kelp-eating purple urchins.
- As a result, the kelp forest ecosystem in the reserve is more productive and stable over time than kelp forests outside. Outside the Anacapa Island reserve, purple sea urchins have periodically destroyed kelp forests.
- Similar effects through the food web are likely to occur in other reserves because marine animals and plants often strongly affect one another.

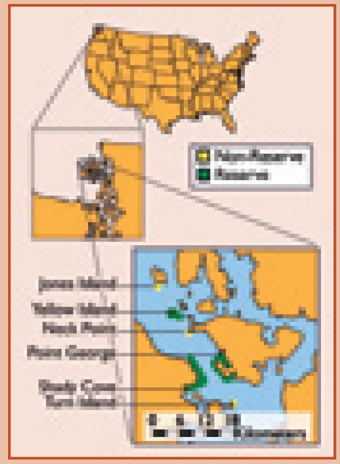
The ecosystem protected in the Anacapa Island reserve now contains most of its animals and plants in a relatively natural state. The populations in the reserve remain more stable over time than those outside the reserve, because interactions among species are not affected by fishing. Lobster and California sheephead protected inside this reserve feed on sea urchins, thereby keeping urchin numbers in check. Reduced numbers of urchins allow stands of kelp to flourish, which in turn support many other species inside the reserve. In contrast, outside reserves where lobster and sheephead are fished, large numbers of urchins periodically overgraze kelp forests, turning reefs into rocky "barrens."



When one species in the food web is fished, other species are affected. For example, when lobsters are fished, sea urchins become abundant and kelp declines. In a reserve, lobsters grow larger and more abundant, keeping the urchin population down and allowing the kelp to grow. K. Lafferty/M. Behrens (USGS/UCSB) analysis of NPS data.

Reference: 16.

Case Study: San Juan Islands, Washington, USA



San Juan Islands Marine Preserves

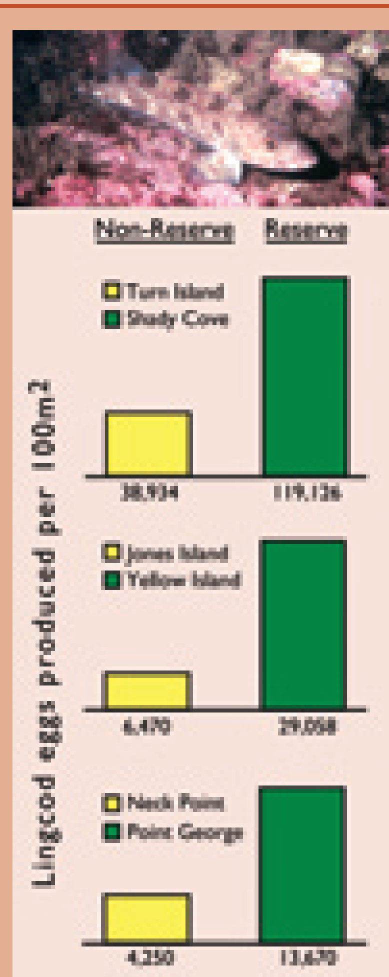
Reserves Boost Abundance, Size & Reproduction

In 1990, the Washington Department of Fish and Wildlife and the University of Washington established five small marine reserves in the San Juan Islands of Puget Sound. They took this action to protect marine biodiversity and to provide undisturbed habitats for scientific research in a region heavily affected by fishing. A decade later, studies show that the San Juan Islands Marine Preserves contain larger and more plentiful fish than unprotected areas. Production of young fish is much greater in the reserves, because both the number and size of fish are larger.

Since establishment of the reserves, lingcod, which had dropped to low levels by the early 1990s because of intensive recreational fishing, increased tremendously. Their biomass is two to four times greater inside the protected areas than outside. Lingcod that are old enough to reproduce are ten times more abundant in reserves. In recent surveys, the biggest lingcod found in a reserve was 110 cm, compared to only 70 cm outside. Each lingcod in the reserves produces an estimated three times as many eggs as those outside.

Quillback and black rockfish have not yet recovered in the reserves. Because of intense fishing, these species are extremely rare in the region. Without breeding stock to provide young to settle in reserves, reserves can offer little immediate aid. However, small numbers of young rockfish have begun to appear in the past few years, offering the potential for future recovery.

Striped surfperch, which are not fished, show no difference in size or abundance inside and outside the reserves. Three times more Puget Sound rockfish, which also are not fished, live outside the reserves than inside. However, lingcod and other large fish eat these small fish. Therefore, rising numbers of lingcod may account for the observed declines of Puget Sound rockfish in the reserves.



The estimated number of lingcod eggs produced per 100 square meters was much larger in marine reserves than in unprotected areas around the San Juan Islands. The total numbers of eggs varied with habitat quality, but habitats in reserves and paired uprotected areas were similar.
Data: E. Eisenhardt (U. Washington)

Lessons Learned

- Lingcod are much bigger and more abundant inside the San Juan Islands Marine Preserves than outside.
- Because of their size and abundance, lingcod in the reserves produce large quantities of young, many more than the number produced in fished areas.
- Quillback and black rockfish are extremely rare in the region. These species have not yet recovered in reserves, probably because they lack breeding stock in the region.

References: 14, 18.

can reserves produce benefits outside their boundaries?

Marine reserves not only affect populations living within their borders but may also influence populations in adjacent waters. Adults and juveniles from a reserve may swim or crawl into neighboring areas. This process is known as "spillover." In addition, tiny newly born animals, called "larvae," and plant "propagules" may drift out of a reserve and "seed" the surrounding waters. This process is called "export." Spillover and export may enable marine reserves to replenish nearby populations. Although not widely documented, spillover and export from reserves are believed to occur commonly.

Key Findings

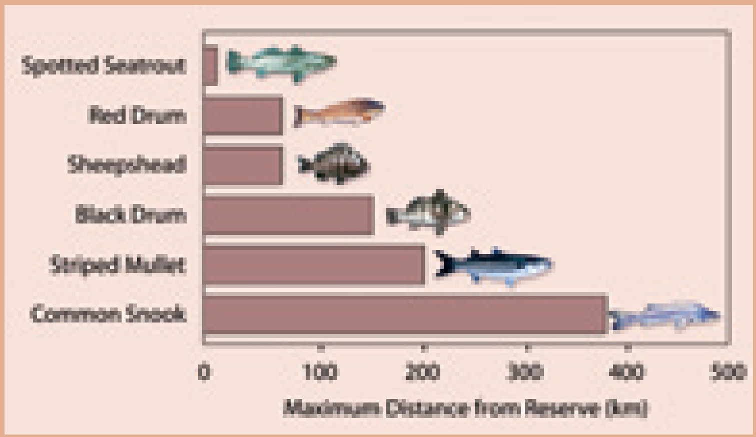
- Animals from marine reserves may swim or crawl outside to supplement surrounding populations.
- Larvae and plant propagules that disperse out of reserves may seed and boost populations in surrounding waters.

Spillover: Movement of Adult & Juvenile Animals

Because marine reserves tend to harbor larger populations than surrounding waters, some animals may move into less-crowded areas nearby to avoid competition for resources such as food and living space. The rate of spillover of adults and juveniles increases with time after reserve establishment as populations become increasingly dense in the protected area. In addition, some fishes, such as rockfishes and lingcod, move from one habitat to another as they grow, regardless of population size, and may leave a reserve for this reason.

Whether or not spillover happens for a given species depends in part on its mobility. Species that are attached to the seafloor as adults, such as mussels and clams, cannot migrate outside reserve boundaries, but swimming and crawling species like fish and crabs can. Transient animals, such as migratory fish, may merely pass through reserves. Thus, their populations are unlikely to build up in reserves and contribute to increased population sizes in adjacent waters.

Studies of animal movement from reserves provide direct evidence that fish and invertebrates spill over. For example, many species of fish tagged in the marine reserve at Florida's Merritt Island National Wildlife Refuge were later caught outside by recreational anglers. Some species, such as the spotted seatrout, moved only short distances from the reserve. However, most species, including two popular sport fish, black drum and red drum, moved between 50 and 200 km from the reserve. A few species, such as common snook, exhibited even longer distance dispersal.

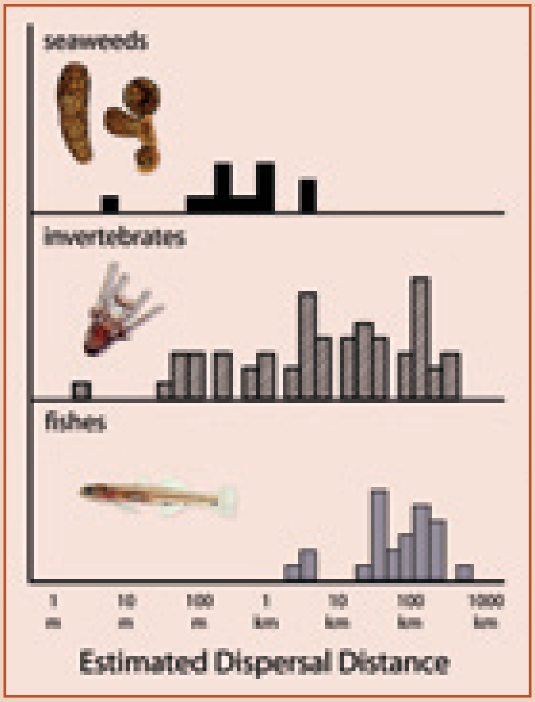


The graph shows the maximum distance traveled (km) by over 125 sport fish tagged in the Merritt Island National Wildlife Refuge. Some species (e.g., spotted seatrout) move only short distances, while others (e.g., common snook) travel much farther. Many tagged fish moved out of the Merritt Island reserve into nearby fishing grounds.

Does spillover actually augment populations outside reserves?

If so, animals should be most abundant inside reserves and just across their boundaries. Indeed, this pattern has been found for fishes and invertebrates at several marine reserves in the United States, Kenya, Barbados, Philippines, Japan, and elsewhere. Moreover, fishing boats often congregate along the borders of marine reserves, because that is where catches are highest. This practice of "fishing the line" has been observed at marine reserves in California, Florida, New England, Spain, Belize, New Zealand, and other places.

References: 10, 11, 12, 13.



This graph shows the average dispersal distance for young marine plants, invertebrates, and fish, estimated from genetic data. In general, plants do not disperse as widely as animals. Young invertebrates exhibit a wide range of dispersal distances. Some young invertebrates do not disperse more than a few hundred feet from their parents. In contrast, sea urchin larvae can move distances over 100 kilometers. Young fish tend to have higher dispersal; some kinds move more than 100 kilometers, on average. Data: B. Kinlan & S. Gaines (UCSB)

Export: Dispersal of Young from Reserves

Fishes and invertebrates typically produce hundreds of thousands of microscopic young that drift on ocean currents for weeks or months, potentially traveling hundreds of miles. Most fishes, mussels, clams, sea urchins, and numerous other animals pass through this early life stage of dispersal. Eventually, some of the larvae settle onto a reef, or other appropriate habitat, where they can grow into juveniles and adults. Most marine plants also produce microscopic young that can be dispersed by currents.

Species vary in how far their larvae travel (see graph). Distances that larvae go depend on their behavior, how long they drift, and the prevailing currents. Depending on the species and the local conditions, larvae may stay close to their parents or they may disperse far away. Because of larval and propagule dispersal, marine reserves can seed populations in surrounding regions.

For example, reserves in the coastal waters of Nova Scotia and the Bay of Fundy protect just 10 percent of the lobster population, but these protected animals are estimated to account for over 50 percent of the larvae produced in the entire region. Currents distribute the larvae across the region, and many of the young lobsters settle in places outside the reserve.

Can Reserves Benefit Migratory Fish?

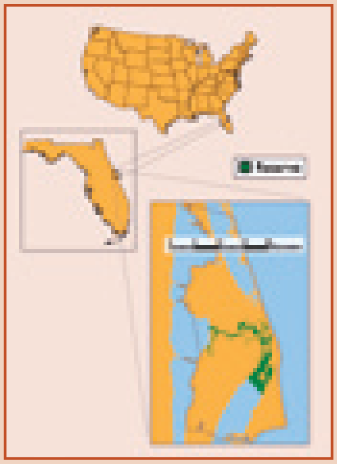
Some fish are homebodies. But others swim dozens, hundreds, or even thousands of miles each year depending on their breeding and feeding habits. How can marine reserves, which are fixed in certain locations, play a role in aiding animals that may routinely enter and leave the protected areas?

Although migratory fish move great distances and can be distributed across expanses of ocean, entire populations become extremely vulnerable to fishing when they aggregate in spawning grounds, migratory pathways, nursery areas, or other sites. Because the animals come together in large numbers in such places, often returning to the same locations year after year, fishermen can catch them more readily, and a large fraction of a population can be killed in a short period of time.

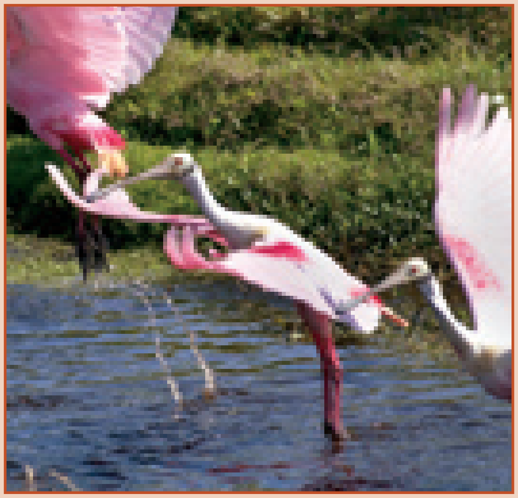
If reserves are established at key locations, they can protect migratory fish during these vulnerable stages. Wildlife refuges on land protect migratory birds at breeding and feeding sites in a similar manner. Marine reserves have the potential to enhance catches of migratory fish in unprotected areas. For example, the nursery grounds of the migratory, flat-bodied fish called plaice were protected in the North Sea for over ten years and catches in the large region outside these protected zones increased an estimated eight percent. Similar measures to protect spawning grounds of Nassau groupers in the Caribbean are currently underway in the Bahamas. Tuna are another migratory fish that could benefit greatly from protection of their breeding grounds.

Marine reserves provide outcomes that supplement those of traditional fisheries measures. In some cases, marine reserves might be unable to protect fish that swim frequently out of the reserves. However, if reserves are large enough, or interconnected in a network of reserves that protects critical habitats, mobile species may benefit by spending a substantial portion of time in reserves.

Case Study: Merritt Island, Florida, USA



Merritt Island
National Wildlife Refuge



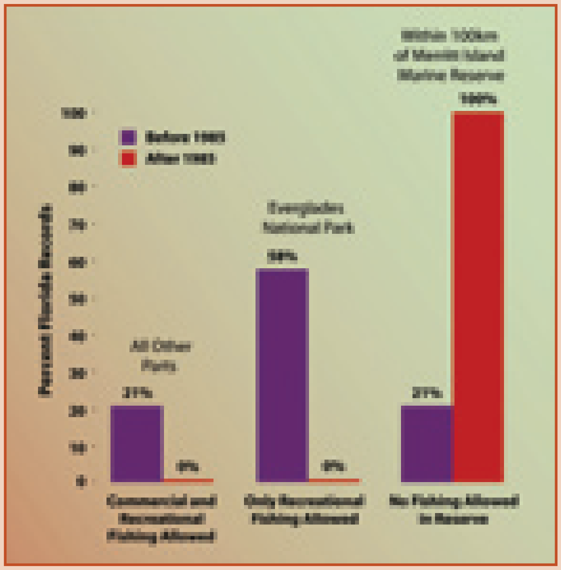
Lessons Learned

- The Merritt Island marine reserve has older, bigger, and more abundant game fish than fished waters outside the reserve.
- Several decades after the reserve was established, recreational fishermen are catching more world-record game fish near the reserve.
- Today, the majority of Florida's record-breaking fish are caught near the reserve.

Spillover: Reserve Supplies Trophy Fishes

Historically, the estuaries at Merritt Island were popular places for recreational fishing. In 1962, the U.S. government banned all access to portions of the Merritt Island National Wildlife Refuge to create a security zone at Cape Canaveral. Today the site on the Atlantic Coast of Florida is one of the oldest fully protected marine reserves in the United States. Studies show the protected zone now produces enormous game fish that live in and move outside the reserve into nearby fishing grounds.

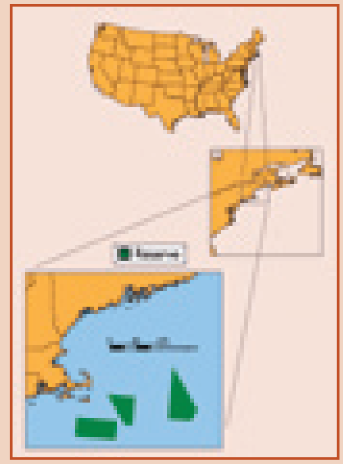
The changes at Merritt Island developed over a period of decades after protection, because the game fish are slow growing and long lived. In the late 1980s, biologists compared the marine reserve to nearby fished waters and found that fish in the reserve were older, bigger, and 2 to 13 times more abundant. Fish tagged inside the reserve were recaptured outside, demonstrating spillover of adults and juveniles. More world records of some popular sport fish are caught near marine reserves than in all other areas of Florida combined. The rest of the state has yielded no new world records for black drum since 1985, despite a variety of statewide management measures, while areas near the reserve continue to produce bigger and bigger fish. Red drum and spotted seatrout show similar results; a disproportionate number of Florida's recent record-breaking fish come from waters near the reserve.



In recent years, far more world-record fish have been caught near the Merritt Island marine reserve than in the Everglades National Park, where only recreational fishing is allowed. Similar habitats in other places in Florida, where both commercial and recreational fishing are allowed, have produced even fewer world records.

References: 15, 19, 20.

Case Study: Georges Bank, New England, USA



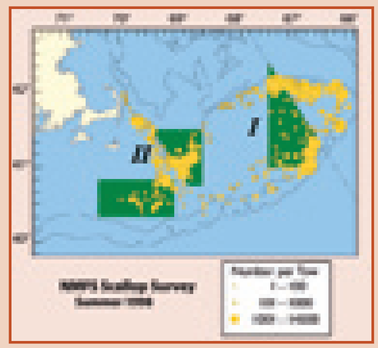
Georges Bank Closed Areas

Middle photograph, above left: Scallops caught inside and outside closed areas on Georges Bank.

Export: Closed Areas Boost Scallop Fishery

Georges Bank rises from the continental shelf to form the southeastern boundary of the Gulf of Maine. For centuries the area has ranked among the world's premier fishing grounds for cod, haddock, scallops, and numerous other species. However, by the early 1990s catches of cod and other groundfish in the region had decreased considerably. Resource managers and fishermen suspected that fishing gear used to catch groundfish and scallops contributed to this decline by damaging habitats of the seafloor. These places supported many different animals, including sponges, clams, worms, crustaceans, sea stars, anemones, and young fish, but trawling and dredging degraded these habitats. In addition, gear intended to catch scallops often took fish incidentally, and vice versa. To address these issues, the U.S. government banned all fishing gear except lobster traps from three large areas, totaling 6,500 square miles, in 1994. While these closed areas are not fully protected marine reserves, scientists have been able to use the closed areas to study the process of larval export at Georges Bank.

Although intended to restore cod and other groundfish, the closures dramatically affected other species as well. For example, within four years, there were 14 times more scallops in the closed areas than in surrounding waters. The scallops in closed areas grew far larger than people had thought possible. Scallops also became five times more numerous in neighboring waters.



Adult scallop abundance inside and near closed areas on Georges Bank.

Lessons Learned

- Within five years, the abundance and body size of some species, including scallops, dramatically increased in the closed areas on Georges Bank.
- Large and abundant scallops in the closed areas can produce more young than smaller scallops outside the closed areas.
- These young boost populations of scallops in the closed areas and some drift into surrounding waters.
- After the closures were established, scallop abundance rose in unprotected waters nearby.
- Using known habitats and current patterns, scientists predicted the places that young scallops, produced in the closed areas, can settle and grow inside the closed areas and in adjacent waters.
- The actual distribution of scallops in waters around the closed areas matches the scientist's predictions.

What do these changes tell us?

The scallops provide some insight into how reserves can supply young to surrounding areas. Because the scallops in the closed areas are larger and more abundant, they can produce many more young than small scallops in surrounding waters. A portion of young scallops may stay and grow up near their parents, while others are carried outside the closed areas by ocean currents. Scientists use known current patterns and locations of suitable habitat to predict where scallops will make their homes and have the most successful growth (see maps). The distribution of adult scallops matches these predictions, demonstrating the potential impact of closed areas on surrounding waters.

Potential scallop settlement on Georges Bank from larvae originating in Closed Area I.

Potential scallop settlement on Georges Bank from larvae originating in Closed Area II.
Data: C.V. Lewis (UC Berkeley)

Reference: 17.

considerations for reserve design

How Long Does It Take To See a Response?

What causes species to differ in their rates of recovery in marine reserves?

Key factors are the availability of breeding stock to initiate a recovery and certain characteristics of their life cycles, including how fast individuals grow, when and how they reproduce, and how many young each individual produces. Some animals grow quickly, mature at an early age, and produce large numbers of young. These animals, such as scallops and sea urchins, may multiply rapidly after protection, sometimes increasing significantly within a year or two. Other animals grow slowly and mature later in life. These species, such as rockfish and cod, may take years or even decades to increase noticeably in a reserve.

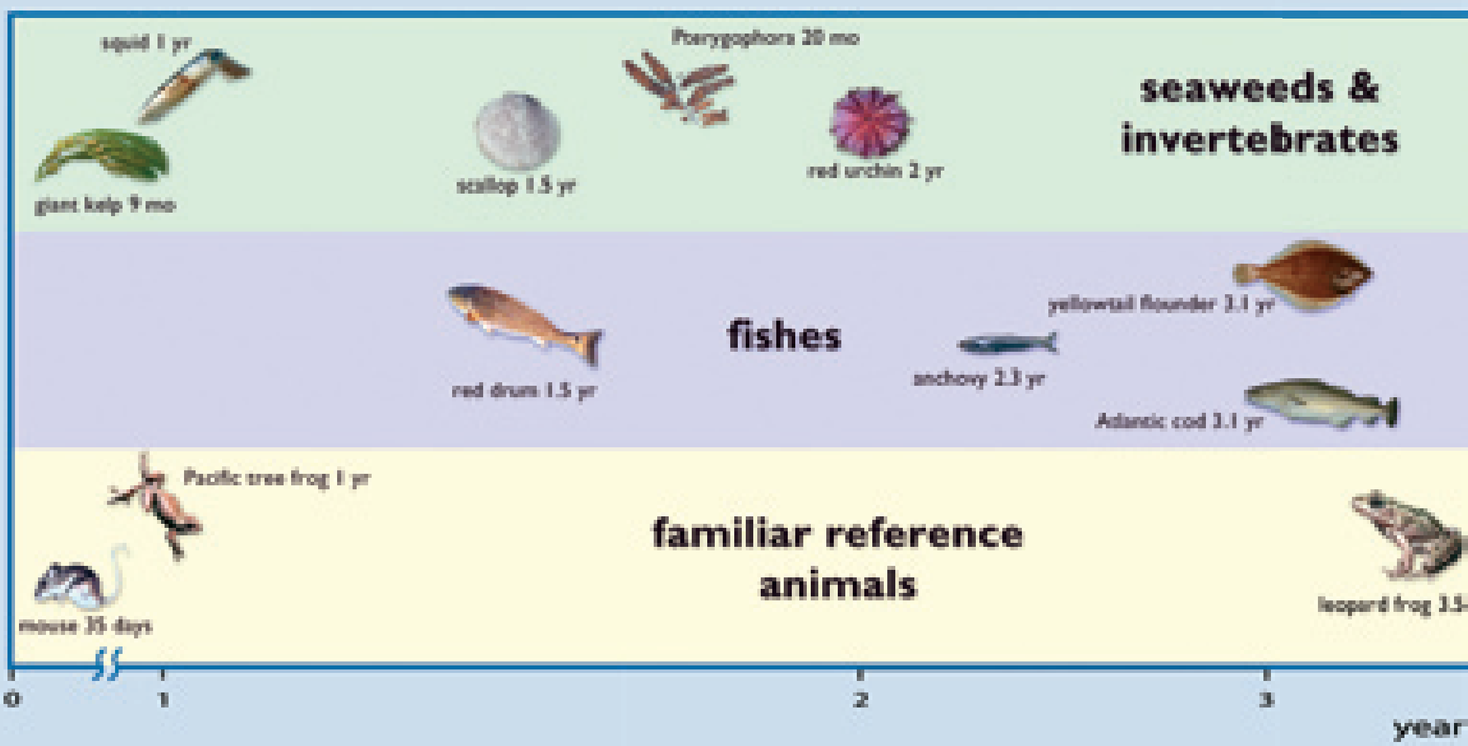
General Principles

- Fast-growing animals that mature quickly and produce many young can respond rapidly to protection within reserves.
- Slow-growing animals that mature at a relatively old age and produce few young take longer to respond.

An example comes from Georges Bank off New England, where the federal government closed three areas to most types of fishing in 1994. The scallop populations in the closed areas grew 14-fold by 1998. The rapid recovery of scallops is due to the fact that they reproduce at a young age. Cod, which develop more slowly and reproduce later in life, are beginning to recover in the closed areas, but not as quickly.

Slow-growing species are especially vulnerable to overfishing. Populations of cowcod, a large rockfish, have been severely overfished in southern California. Because it takes 10 to 15 years for cowcod to mature and begin to reproduce, these populations could take decades to recover after fishing is stopped.

Age of Maturity for Selected Species



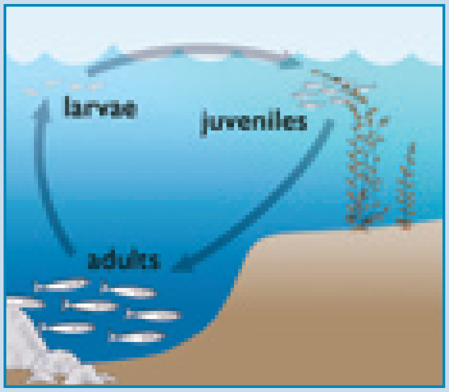
Do All Habitats Need Protection?

The marine environment is a mosaic of different habitats. Beach, mud flat, salt marsh, seagrass bed, kelp forest, and rocky shores fit together like puzzle pieces. Each habitat is home to a different and often unique community of plants and animals, all of which have their own environmental requirements. For example, clams, sand dollars, and burrowing worms thrive in sandy bottoms, whereas abalone and mussels live in rocky habitats.

An important reason to protect a variety of habitats is that different habitats often influence each other. For example, estuaries serve as nursery habitats for some fishes of the open ocean. Organic matter produced in estuaries can flow into the ocean, fertilizing coastal marine ecosystems. Fragments of kelp from rocky reefs wash up on beaches, providing food and shelter for animals that live there. Some habitats, such as estuaries and mangroves, trap sediments moving down rivers, preventing these sediments from entering the ocean. Without these habitats, sediments could accumulate in the coastal waters, smothering life on coral and rocky reefs.

Another reason to protect a variety of habitats is that most marine animals use more than one habitat during their lives. As animals grow, they may require different kinds of food and shelter, and animals meet these changing needs by moving between different habitats. Each habitat used by an animal or plant is important for its survival. An organism may not be able to complete its life cycle if any one of these habitats is degraded. For example, as adults, many fish live in deep reefs offshore, while their larvae drift in the open waters on the surface of the ocean. The young fish move into shallow coastal waters as they grow and subsequently to deep waters, where they remain as adults.

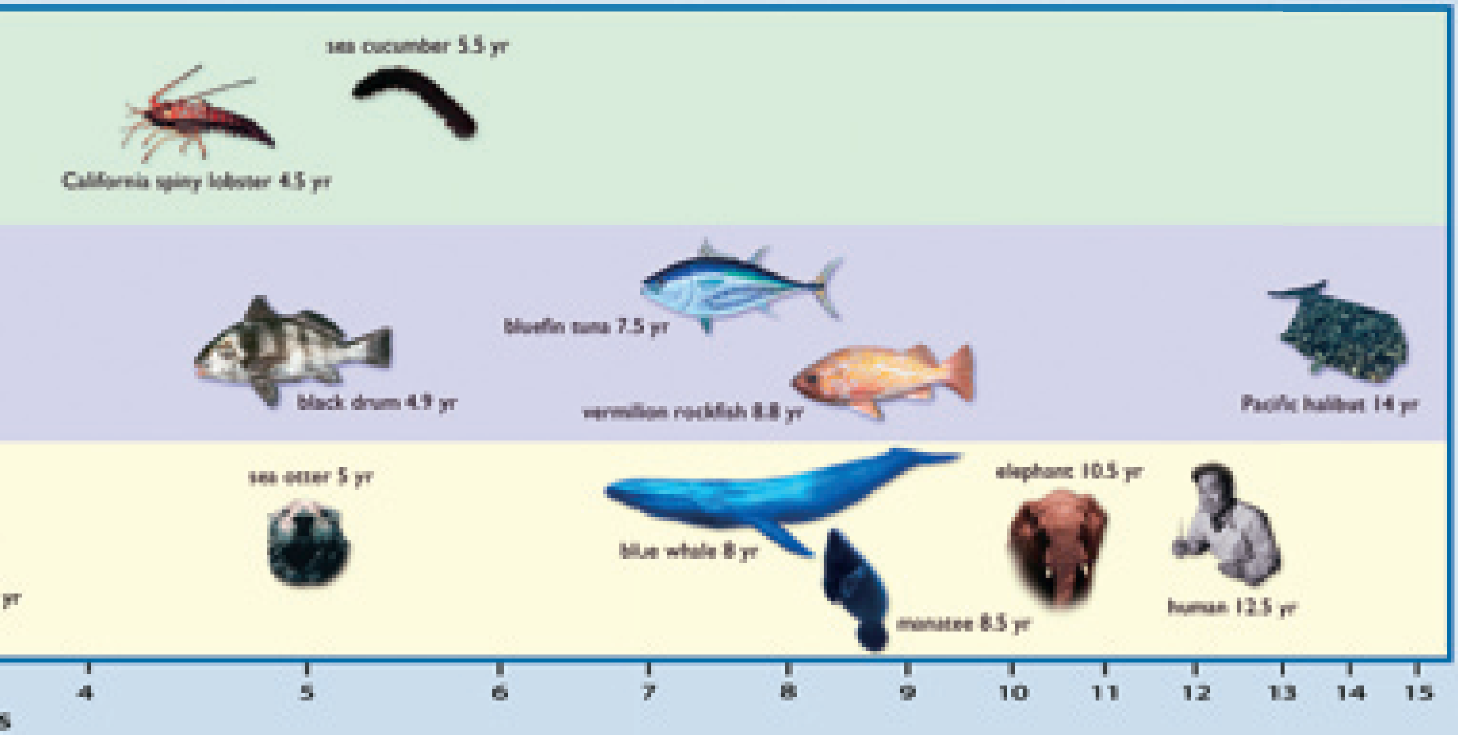
Since the ocean contains so many different kinds of animals and plants, all habitats play an important role. In order to support a variety of ocean life, it is essential that at least some of each habitat is preserved in a natural state. Marine reserves that include several adjacent habitats allow animals to move between habitats while remaining in protected areas.



Marine animals often use a variety of different habitats during their life cycles. For example, some adult fish live on deep reefs offshore while their larvae drift above in the open ocean. The young fish eventually settle in shallow kelp forests and later move into deeper waters to complete their life cycle.

General Principles

- Each habitat supports a unique community of plants and animals.
- Many animals use more than one habitat during their lives, and if any one of these habitats is degraded, these animals may not be able to complete their life cycles.
- Marine reserves that include several different types of habitats can be an effective way of protecting entire ecosystems.



How Do Ocean Processes Influence Reserve Design?

Ocean processes strongly affect where animals and plants live in the ocean. These processes include movement of water and changes in water properties, such as temperature and salinity. Knowledge of local ocean processes can help determine where marine reserves should be located.

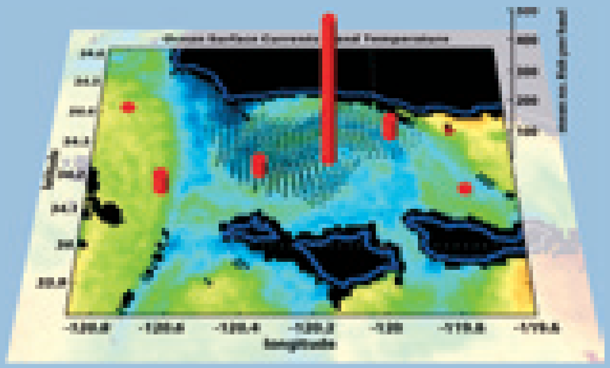
Flowing water commonly transports the larvae or propagules of marine animals and plants. This transport affects their geographic distributions in the ocean. In some regions, currents travel predominantly in one direction for great distances. For example, the California Current flows southward along the west coast of North America, while the Gulf Stream flows to the north and east along the Atlantic coast. Winds and coastal landforms can affect currents on a smaller scale, causing the water to change direction and speed.

General Principles

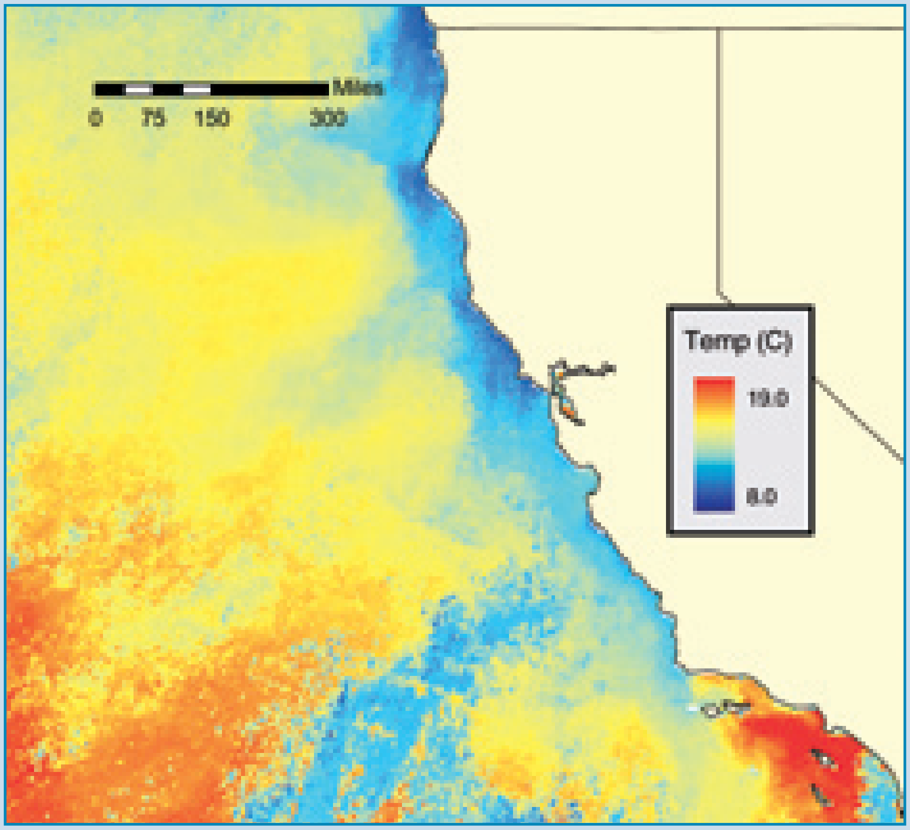
- Currents carry larvae and nutrients, providing connections between different places in the oceans.
- Ocean water properties, such as temperature, can determine the types of animals and plants are found in a particular area.

Currents can carry larvae from place to place or concentrate them at specific locations. For example, in the summer of 1998, many young rockfish were found in the center of the Santa Barbara Channel off southern California. Circular water flow occurring in the channel at that time appears to have retained the young fish in this spot. As they grew bigger, some of the young fish settled in nearby habitats. At other times, currents transport the young rockfish out of the Channel.

Data: M. Nishimoto & L. Washburn (UCSB)



The red bars indicate the numbers of young rockfish in the Santa Barbara Channel at one time during the summer of 1998. The black arrows indicate the predominant currents at the same time. When circular currents form, they may retain young rockfish.



Sea surface temperature for the California coast.

Water temperature also affects the distributions of plants and animals in the ocean. Water temperature is influenced by latitude and by major currents. Ocean temperatures within one region can be very different (sometimes 5-10°C) if the region is influenced by two (or more) major currents. The distributions of animals and plants in regions like this are strongly influenced by these changes in water temperature. For example, off the coast of Point Conception in southern California the cool waters of the southward-flowing California Current collide with the warm waters of a northward-flowing current. As a result, subtropical fish rarely occur north of Point Conception, while rockfish live primarily in the cooler waters to the north.

What Size & How Many Reserves Are Needed?

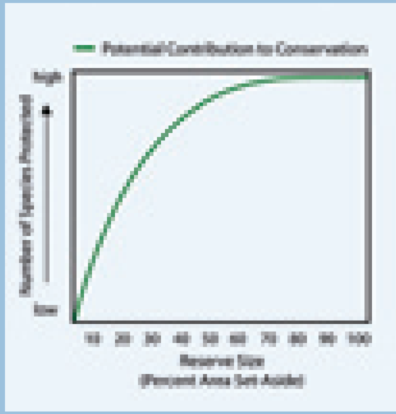
Reserve size affects the level of protection for ecosystems. Decisions about the size and number of marine reserves for a given place often depend on local environmental, socioeconomic, and regulatory factors. However, several general ecological concepts based on scientific studies can help guide these decisions on reserve size and location.

Even small marine reserves can have positive effects on the abundance, size, diversity, and biomass of animals and plants within their boundaries. However, large reserves include more and larger habitats, more species, and a greater number of individuals of each species. Thus, large reserves protect more of the local ecosystem. In addition, larger populations are less likely to be wiped out by catastrophic events such as big storms and oil spills.

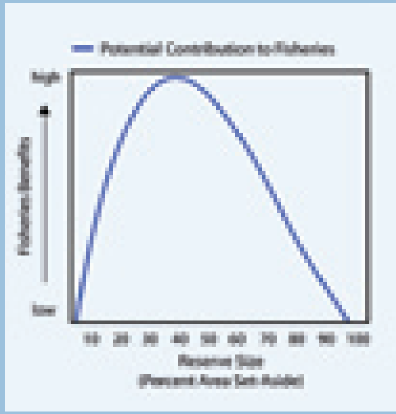
To receive full protection from fishing, a particular animal or plant must be able to complete all vulnerable stages of its life cycle inside a reserve. A large reserve or several reserves, located in critical habitats, may be necessary to protect populations of animals that move long distances. A few species complete their life cycles in very small areas (less than 1 square mile) and smaller reserves can protect such species. In many cases, however, scientists do not know how far species actually move during their lives. One strategy to protect these species is to set aside a portion of all habitats that are necessary for the species to complete its life cycle. As the reserve size increases, the number of different kinds of species protected also increases (top graph, right). Large reserves that encompass and protect many different kinds of habitats are most effective for conservation, but large reserves also may concentrate fishing into small areas.

General Principles

- Small reserves can have positive effects within their boundaries. However, when a reserve is small, the overall benefits are small since few species are protected.
- If a reserve is very large, it will likely satisfy conservation goals, but fishing effort may be crowded into small spaces.
- Reserve areas of moderate size can protect and restore important habitats, plants, and animals while leaving substantial areas of the ocean open to fishing.



As reserve size increases, more species (or populations) will be protected.



As reserve size increases, the potential fisheries benefit from spillover and larval production will increase. After a certain point, the reserve becomes so large that spillover and export no longer offset the losses to fisheries due to the reduction in fishing grounds.

The criteria for choosing reserve size to maximize catch in surrounding waters are different from those used to design a reserve for conservation. Small reserves generally have little positive effect on surrounding fisheries, because the number of animals that eventually swim or drift out of the reserve becomes diluted in the large area around the reserve. If a reserve is large enough and includes the necessary habitats to support various species, it can become a "source" of these species for surrounding waters. However, if reserves are extremely large, little area will be left open to fishing. Therefore, to be an effective tool for fisheries management, reserves must be small enough that surrounding waters can still support commercial and recreational fishing, but large enough to become a source of fish and invertebrates (bottom graph, right).

Although priorities for fisheries and conservation are different, recommended reserve sizes are often similar. Existing models of marine reserves for fisheries management suggest that the highest sustained catch and the lowest risk of population collapse occur when reserves include approximately 20 to 60 percent of the total population of a target species. One way to attain this goal for many species is to set aside the equivalent percent of all habitats. The range of sizes reflects variability among species and differences in the success of management strategies outside reserve boundaries. Importantly, the greatest increase in protection for conservation purposes occurs over a similar range of reserve sizes. Small reserves protect few species, while moderate to large reserves are likely to conserve the majority of species in a particular area. A network of several reserves of different sizes, strategically located in critical habitats, may provide the best combination of conservation and fishery benefits.

References: 6, 7, 9, 21.

General Principles

- A "network" includes a series of marine reserves connected by larval dispersal or juvenile and adult migration.
- To be an effective network, reserves must be located in critical and productive habitats, such as breeding grounds, and spaced appropriately to assure larval transport between them.
- Although mathematical models and our knowledge of life history and ecology of marine species suggest that networking is likely to be an effective strategy, few reserves actually have been established as networks.

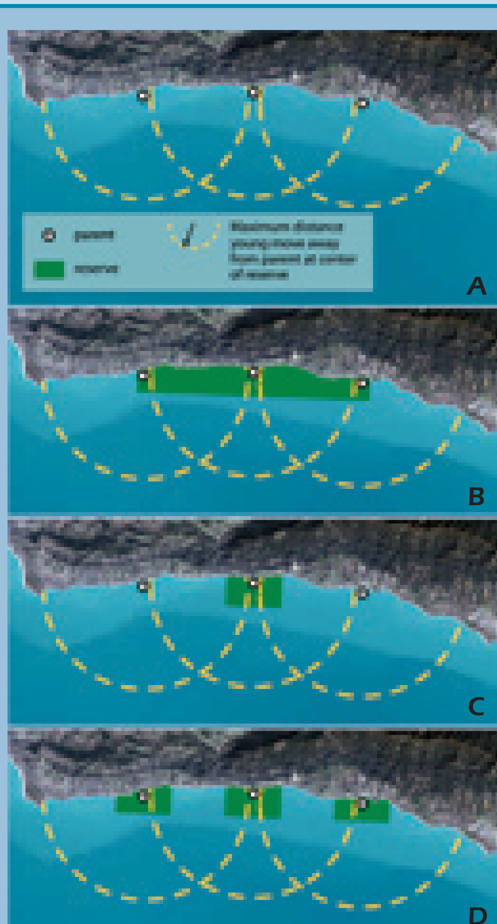
Why Use Networks of Several Reserves?

By themselves, small reserves do not tend to support fish and invertebrate populations that are large enough to sustain themselves. To ensure that young are available to replenish and sustain populations within reserves, the area protected within reserves must be fairly large. However, in some regions, economic constraints may make it impractical to create a single large reserve that can support viable populations. Establishing networks of several smaller reserves can help reduce economic impacts without compromising conservation and fisheries benefits.

A network includes several reserves of different sizes, located in critical habitats, and interconnected by movement of animals and plant propagules. A network can contain critical components of a particular habitat type, or portions of different kinds of important habitats, depending on the goals for the network. To be an effective network, animals and plant propagules must be able to travel beyond the boundaries of a single reserve into other reserves. To facilitate this movement, a network should be designed within a naturally defined ecosystem, such as a bay, gulf, sound, or biogeographic region.

By using different sizes and spacing of reserves, a network can protect species with different characteristics. For example, a network of reserves may include feeding habitats in open waters and breeding and nursery grounds in shallow bays. If marine reserves protect these critical habitats, the resident animals are likely to grow larger and have greater reproductive success.

This diagram shows the relationship between reserve design and movement of plants and animals dispersed in the water.



(A) Currents often carry young animals and plant propagules away from their birthplace. The yellow dashed lines indicate the spread of young from their birthplace.

(B) Young produced in a large reserve are likely to stay in the reserve, which contributes to conservation. However, large reserves reduce the area open to local commercial and recreational fishing.

(C) A small reserve may protect animals while they are in the reserve, but most young may settle and grow in surrounding waters. If reserves are too small, few populations in the reserves will be able to sustain themselves, and the reserves are unlikely to contribute many young to adjacent fishing grounds.

(D) An alternative is to establish a network of reserves that are connected to each other through movement of animals and plant propagules. Some animals and plants will be protected in reserves and others will move into surrounding waters.

Because of the many different patterns of movement and habitat use among species, models suggest that one of the most effective strategies for protecting many species is to establish a network of multiple reserves of different sizes that are strategically placed in critical habitats.

References: 21, 22, 23.

Scientific Criteria for Reserve Design

Once a group decides that marine reserves might be part of a solution, what is the next step? How might they begin to put lines on a map?

If the objectives of marine reserves are to restore and protect biodiversity and to enhance sustainable fisheries, it is possible to use scientific criteria to evaluate different areas and to generate possible reserve scenarios. The following chart lists and defines important criteria, and explains how and why they should be considered in reserve design. Ecosystem protection will be diminished if any one of these criteria is excluded from the design of marine reserves.

	Scientific Criteria	Definition	Application
✔	Biogeographic representation	The inclusion of different regions characterized by particular sets of habitats, environmental conditions, and species	Protecting all biogeographic regions can help protect the biological communities associated with each region.
✔	Habitat representation	The inclusion of different types of habitats (e.g., estuary, rocky shore, kelp forest, sandy bottom)	Protecting a variety of different habitat types can help protect the various plants and animals in those habitats, and allow them to complete their life cycles.
✔	Vulnerable habitats	Rare or threatened habitats susceptible to stresses	Marine reserves offer additional protection to vulnerable habitats.
✔	Vulnerable life stages	Important life stages, such as breeding, juvenile, or migration periods	Protecting habitats where these vulnerable stages live can help boost abundance, size, and population growth rates.
✔	Species or populations of special concern	Species that are of economic or recreational value, are globally rare, or live in small geographic ranges	Protecting habitats where these species live can help boost abundance, size, and population growth rates.
✔	Reserve size	The area covered by a single reserve or a network of reserves	The choice of reserve size depends on the objectives for reserves. Larger reserves produce proportionately greater effects. A network of several smaller reserves may be a good compromise.
✔	Ecosystem linkages	The exchange of nutrients, plants, and animals that connects many ecosystems	Identifying important linkages among ecosystems can help locate potential reserve sites.
✔	Reserve networks	A system of reserves in critical habitats that are linked by movement of animals and plant propagules	A network of marine reserves protects critical habitats that are used by plants and animals during different stages of their life cycles.
✔	Ecosystem services	Beneficial services that people use directly, such as removal of pollutants from the water and climate control	Reserves should include critical habitats that sustain ecological services.
✔	Human threats	Human actions that endanger an ecosystem and cannot be prevented or reversed by establishing a reserve (e.g., pollution and habitat loss)	Sites affected by human threats, such as pollution and coastal development, are not likely to be effective marine reserves. Other types of management may be necessary to control these threats.
✔	Natural catastrophes	Events such as large storms, harmful algal blooms, disease epidemics, and climate changes	Sites subjected to frequent catastrophes are unlikely to be effective marine reserves. Establishing multiple reserves in different locations can reduce the overall risk from natural catastrophes.
✔	Social and economic criteria	Social and economic values expressed by community members affected by ocean management	Social and economic criteria should be incorporated into reserve design in order to maximize social and economic benefits, and minimize costs.

References: 6, 7, 21, 23.

where should reserves be located?

Science Can Provide Options

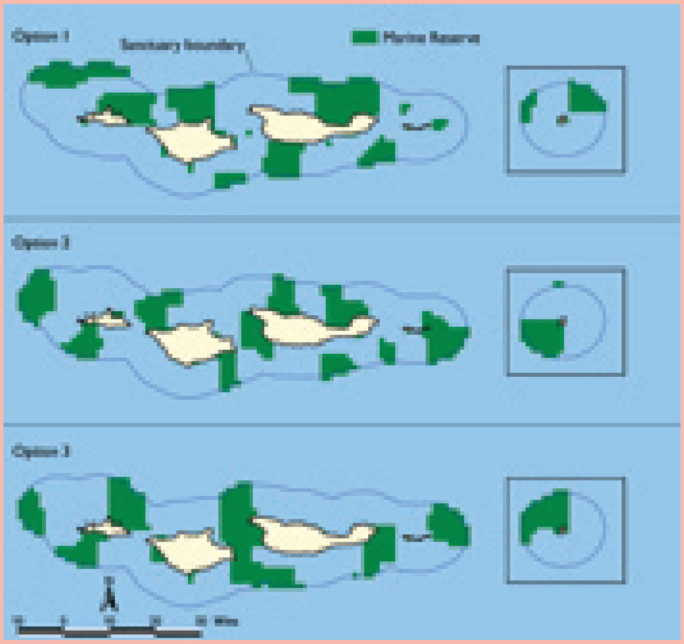
The reserve planning process often involves collaboration among many groups, including resource managers, government agencies, natural and social scientists, commercial and recreational fishermen, environmentalists, and other community members. Various scientific tools can provide options for the design of reserves or reserve networks, but decision-makers ultimately must weigh tradeoffs among short- and long-term goals, costs, and benefits.

Science can provide options through the use of models that analyze data and assist in the design of marine reserves. One such computer model, known as SITES or MARXAN, has been used to design reserve options in California's Channel Islands, the Florida Keys, and the Great Barrier Reef. This tool can identify many possible arrangements of reserve sites that satisfy particular management objectives. Maps of possible reserve sites produced by the program can help resource managers and stakeholders review many different options. This approach uses scientific criteria, but provides flexibility for reserve design.

General Principles

- Reserve design can be based upon ecological, economic, and personal knowledge.
- Useful ecological criteria have been identified (see checklist on previous page) to guide reserve design.
- Models are available to help resource managers identify various options.
- There are often many options for reserve design that meet a particular set of goals.

In the Channel Islands of southern California, for example, a group of federal and state agencies, fishermen, conservationists, and other members of the community initiated a process to design a network of marine reserves in 1999. The group selected a panel of marine scientists to gather and evaluate biological information from this region. These scientists used the SITES model to generate hundreds of options for marine reserves. The three maps on this page are among the many options produced using SITES for a potential marine reserve network covering 30 percent of the Channel Islands National Marine Sanctuary. These options are based on the goals established by the community, and the options satisfy the ecological criteria for reserve design, including different biogeographic regions, habitats, and vulnerable species.



Three of the hundreds of options for marine reserves in the Channel Islands National Marine Sanctuary, developed using the SITES computer model.

References: 22, 23, 24, 25, 26, 27.

Human Values and Community Involvement Are Important

The social and natural science of marine reserves indicates that a great deal of flexibility often exists in reserve design. In many cases, this flexibility makes it possible to accommodate the behaviors, livelihoods, and lives of many ocean users.

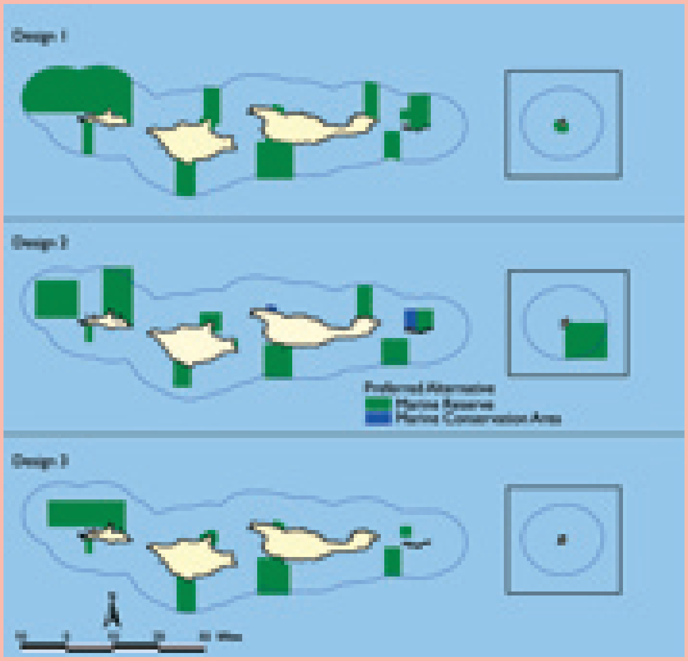
Full community involvement is one of the most important aspects of successful reserve design. Science can help us learn what reserves do, but communities must work together to decide how to apply this knowledge. A variety of questions must be considered before reserve design can satisfy the goals of diverse communities.

- **How will marine reserves affect commercial and recreational activities?**
- **How will current management regulations affect reserve design?**
- **What other management strategies will be needed to complement marine reserves?**
- **Who has the authority to establish and enforce marine reserves?**
- **How will the reserves be enforced?**
- **How will an agency or community secure adequate funding for establishment, maintenance, monitoring, and evaluation of reserves?**
- **What kinds of monitoring will take place in the reserve?**

The breadth of knowledge and values in each community can help to answer some of these questions. Personal knowledge can fill some of the gaps in scientific data. Economic modeling, based on data from landing records and logbooks, can be used to evaluate the potential short- and long-term economic impacts of reserves. Societal values can influence the design of reserves so that our traditional relationships with the ocean are protected and sustained.

Consider an example of how these questions were integrated into the design of marine reserves. In the Channel Islands of southern California, a group of regional community representatives developed various designs to protect marine ecosystems and address fisheries concerns. The representatives used the options developed by the SITES computer model (previous page) and additional scientific recommendations, as well as economic data and personal knowledge, to develop reserve designs.

Some of the designs (e.g., Designs 1 and 2) meet most of the ecological criteria, while accommodating different interests in the community. However, some designs (e.g., Design 3) do not satisfy all of the ecological criteria because of the way that economic and social factors were incorporated. Design 3 does not include habitat protection in some areas that are popular for recreational fishing, and this limits the effectiveness of the reserve network. Eventually, decision-makers must evaluate potential short- and long-term ecological and economic costs and benefits of reserves, and make the necessary choices given the trade-offs among these factors.

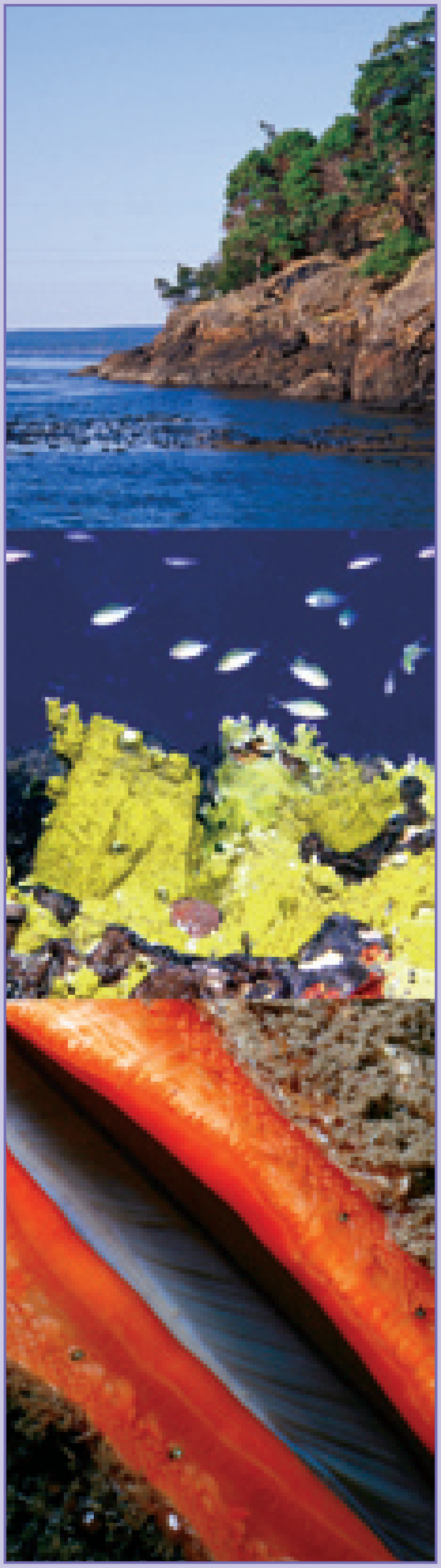


Three of nearly 40 designs for marine reserves in the Channel Islands National Marine Sanctuary. The community worked together to develop these designs using the ecological and economic data, as well as personal knowledge.

how do marine reserves fit into the big picture?

Marine reserves work on many different levels of biological organization, affecting individual animals and plants, populations, communities, and ecosystems.The benefits of marine reserves can include:

- **protection of habitat**
- **conservation of plants and animals that live in protected habitats**
- **recovery of depleted populations of fished species that live in reserves**
- **movement of animals from reserves to surrounding fished waters**
- **insurance against environmental or management uncertainty**
- **provision of ecosystem services**
- **protection of places to provide baseline information**
- **provision of sites for enjoyment and inspiration**



Marine reserves produce this unique combination of benefits because they limit where fishing, drilling for oil or gas, and other extractive activities can occur, rather than how much or when those activities occur. Moreover, they prohibit other activities such as dumping, which can pollute or destroy habitat. By eliminating extractive and other destructive activities in particular locations, reserves can protect significant portions of entire ecosystems at once. Traditional approaches tend to focus on single species independent of other elements of the ecosystem. The most effective protection for even a single species requires an ecosystem approach, because every species interacts with numerous other species and the environment.

Reserves can protect habitat and produce dramatic increases in populations living inside their borders, offering insurance against local extinctions and declines. Marine reserves also may affect areas beyond their borders by supplying larvae, juveniles, and adults to adjacent waters.

Research demonstrates that marine reserves can be a useful management and conservation tool, if they are properly designed and enforced. However, other types of management are still critical. Traditional practices such as fishing quotas, seasons, and gear restrictions are important to achieve sustainable fisheries in surrounding waters. Scientists are developing fisheries management models that incorporate both marine reserves and more traditional methods of regulating fishing effort.

Marine reserves cannot address all that ails the oceans. Problems such as pollution, invasive species, disease epidemics, and climate change affect whole regions and require complementary solutions. However, by protecting critical habitats, reserves can contribute to the protection and restoration of healthy marine ecosystems.

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For more information:
Web site: www.piscoweb.org
E-mail: pisco@piscoweb.org

PISCO
University of California, Santa Barbara
Marine Science Institute
Santa Barbara, CA 93106-6150
Tel (805) 893-5175
Fax (805) 893-8062

PISCO
University of California, Santa Cruz
Long Marine Laboratory
100 Shaffer Road
Santa Cruz, CA 95060
Tel (831) 459-5022
Fax (831) 459-3383

PISCO
Stanford University
Hopkins Marine Station
Oceanview Boulevard
Pacific Grove, CA 93950

PISCO
Oregon State University
Department of Zoology
3029 Cordley Hall
Corvallis, OR 97331
Tel (541) 737-9173
Fax (541) 737-3360

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