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Managing Marine Resources Sustainably

by Susan J. Roberts and Kenneth Brink

Increasing demand for ocean resources due to population growth and economic expansion has raised concern about the sustainability of the ocean resources and amenities that contribute to the well-being of people around the globe. Highly productive fisheries have collapsed, marine and coastal habitats have been lost or degraded, and carbon dioxide from fossil fuels is changing the climate and some of the basic properties of the marine environment. These stresses increase the urgency of developing sustainable practices for activities in the ocean. Of the ocean's renewable resources, fish are probably the most pressing concern to people around the world. The sustainability of the ocean's fisheries is essential for the well-being of people in both developing and industrialized nations, through markets that range from local to global in scale. Seafood is the major source of protein for more than 1 billion people internationally, while about 44 million depend on fishing or fish farming for their livelihood. Because seafood provides an immediate connection between the ocean and people, we discuss fish production in terms of managing the wild harvest and developing sustainable aquaculture practices.

Many human activities affect, or potentially affect, the health and productivity of the ocean. A sampling of important subjects include:

- Sea level rise and the loss of estuarine habitats
- Endocrine disrupters that affect reproductive capacity and immune responses of marine life
- Pollutants such as oil, heavy metals, and other toxic chemicals
- Floating debris, which concentrates where ocean currents converge

Each of these issues could be the sole topic of an article on sustainability for the ocean. To provide some focus among the major challenges facing sustainability, this article examines sustainable approaches for management of marine fisheries and includes a brief description of the intersection of one other environmental stressor, nutrient pollution, to illustrate the interplay of various human activities on the health and productivity of the ocean.

Fisheries Statistics

Wild capture fisheries and aquaculture globally produce more than 141 million tons of fish (both finfish and shellfish) per year (see Figure 1). The ocean produces almost 90 percent of the world's wild capture fish—about 82 million tons in 2006, of which 49 million tons were destined for human consumption while the remaining 33 million tons were turned into fishmeal and fish oil for use in animal feeds. Although the yield from capture fisheries has stagnated over the past few decades, the increasing demand for seafood has stimulated the growth of aquaculture, which is approaching one-half of the fish (both freshwater and marine) harvested for human consumption.[1,2]

Common to most definitions of sustainability is the concept of using renewable resources without jeopardizing their availability for use by future generations. Most sectors of society agree that sustainability should be the goal for management, but this common ground has not provided much traction for reaching consensus in fisheries management. In this article, we focus on the challenges in implementing sustainable management in fisheries.

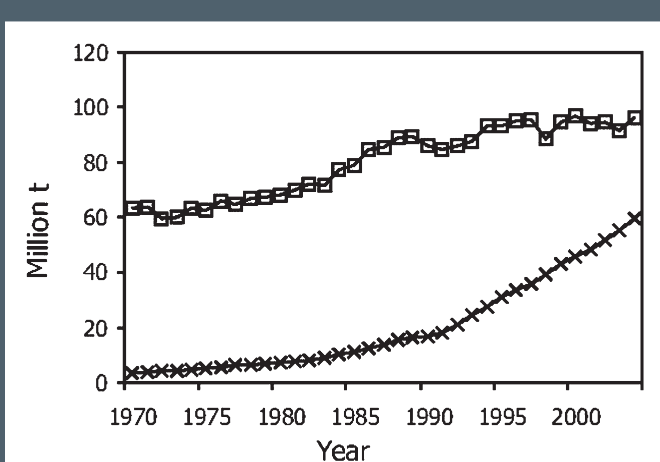
Concept of Sustainable Fisheries

Sustainability means different things to different people, and notably has been a point of contention in fisheries management. The 1992 U.N. Convention on Biological Diversity defined sustainable use as "the use of components of biological diversity in a way and at a rate that does not lead to the long-term decline of biological diversity, thereby maintaining its potential to meet the needs and aspirations of present and future generations."[4] This definition emphasizes conservation of biological diversity and considers the effects of harvest and other human activities on the whole marine ecosystem. From the perspective of the fishing industry, sustainability may be more narrowly defined as the level of fish harvest that is high enough to support the current fishery but low enough to avoid the collapse of the stock. As described below, federal U.S. fisheries policy initially codified the latter approach, such that annual catch targets were set to maximize the harvest of each managed species without a specific requirement to address potential effects on other components of the ecosystem.

With the passage of the Fisheries Conservation and Management Act in 1976, the United States adopted a fisheries policy based on the concept of optimal yield defined as the amount of fish which

> … (A) will provide the greatest overall benefit to the Nation, particularly with respect to food production and recreational opportunities, and taking

Figure 1. World fisheries production from capture fisheries (open squares) and aquaculture (crosses). These figures represent the global totals, including China. The Chinese contribution is often not included in global assessments because the production from China is not well documented.



(From K. M. Brander, "GLOBAL Fish Production and Climate Change," PNAS 104, no. 50 (2007): 19709–19714.)

Did You Know?[3]

- The United States is the third largest consumer of seafood in the world.
- Americans ate an average of 16.5 pounds of fish and shellfish per person in 2006.
- Our commercial marine fishing industry contributed $35.1 billion to the 2006 U.S. Gross National Product.
- Americans spent $46.6 billion in seafood restaurants in 2006, a $2.1 billion increase over 2005. They also purchased $22.7 billion worth of seafood for home consumption.
- The United States imports more than 75 percent of the seafood Americans eat, at least 40 percent of which is farmed overseas.

A lost fishing net that washed ashore on the island of Hawaii. Nets and other types of marine debris damage coral reefs and cause harm to marine life such as the endangered Hawaiian monk seal through entanglement.

> into account the protection of marine ecosystems; (B) is prescribed as such on the basis of the maximum sustainable yield from the fishery, as reduced by any relevant economic, social, or ecological factor; and (C) in the case of an overfished fishery, provides for rebuilding to a level consistent with producing the maximum sustainable yield in such fishery.[5]

The key concept referenced in (B) is maximum sustainable yield (MSY), the theoretical number of fish that can be caught in a year without reducing the capacity of the population to replenish, as determined by the number and size of the fish that remain. In simplest terms, the goal is to maintain the fishery at a level where the total mortality (number of fish lost to natural causes plus the number taken by the fishery) is not greater than the number of young fish that survive and grow to replace them. Most fish stocks produce many more young than required to maintain the population. In a stable, unfished system, only a small fraction of these young will "recruit" into the adult population in an average year. Reduction of the size of the adult population by fishing leaves more room for the next generation of fish. Hence a larger number of young may survive to adulthood, at least partially compensating for some of the fishery removals.

Fisheries Management

In practice, it has proven difficult to manage fisheries near MSY, in part due to ineffective measures to control fishing, but also due to the difficulty of establishing conservative target catch levels to compensate for the uncertainty inherent in the scientific assessments of fish populations. When a fish stock and the fishery are healthy, managers have more leeway in setting catch limits, because the consequences of setting the target too high or too low are likely to be less severe. If a stock becomes overfished, the target catch limit becomes more contentious because of the impact on the fishery and the increased risk of collapse of the fish stock. As a result, the fishing industry may press for a higher catch level despite the increased risk of depleting the stock and jeopardizing future catches. The pressure to err on the side of overestimating the stock size to maintain the fishery has, in some cases, outweighed arguments to reduce catch limits to lower the risk of overfishing and to allow the stock to rebuild.

In addition to estimates of the current size of the fish stocks, scientists also need to understand the potential productivity of the fish stock in the absence of fishing. Since many commercial fish stocks have been harvested for over a century, often accompanied by many other changes in the ecosystem, it can be challenging to determine how large the population would be if there were no fishery. Yet, this information is central to setting realistic goals for rebuilding depleted stocks. A 2005 study[6] led by Dr. Andrew Rosenberg of the University of New Hampshire estimated the catch and abundance of cod off the coast of Nova Scotia in 1852 based on daily fishery logs. Rosenberg and his colleagues found that even with limited technology, schooners fishing in 1852 caught far more fish than the mechanized Canadian fleet does now. In the 1850s, the total cod biomass was over 1.2 million metric tons, or 24 times the 50,000 metric tons estimated for today's cod stock on the Scotian Shelf. Restoring cod to their previous abundance could increase both the yield and the efficiency of that fishery.

So why haven't cod stocks been restored? There is a human element that can contribute to the slow rate of recovery. Since our frame of reference is mostly based on personal experience, we may not perceive changes in the ecosystem that take place over a long period of time. In the case of fisheries, a fisherman may not perceive a stock as low in abundance if it has been low throughout his lifetime. Also, there may not be much incentive for fishermen to accept lower catch limits to allow the stock to recover because the immediate value of staying in business may outweigh the potential benefits of a more abundant fish stock at some point in the future.

With cod, although the human element has contributed to the decline and continuing low population, other circumstances conspire to keep this iconic fish from returning to its former abundance. Indeed, stocks of haddock—a groundfish species similar to cod that became depleted about the same time and place as the cod stocks in the New England fishery—have shown signs of a robust recovery. Understanding why cod stocks have remained low requires delving more deeply into the nature of marine ecosystems.

Marine Ecosystem Structure

Ecologists often characterize ecosystems by the structure of the food web. Food webs describe the relationships between and among plants and animals in the context of their trophic level. The flow of energy through an ecosystem starts at the bottom of the food web with primary producers (organisms that use energy to create organic matter), and a minor fraction of the original energy is transferred through each successive level of consumer. In terrestrial ecosystems, a large-standing crop of plants (the primary producers) forms the base of the food web. Herbivores graze on plants, carnivores consume the herbivores, and some species consume other carnivores. Biomass decreases with each step in this trophic pyramid, such that the abundant plant life at the bottom supports a relatively small population of carnivores at the top. By contrast, ocean food webs are based predominantly on short-lived, microscopic phytoplankton. Phytoplankton have short life spans (measured in days) compared to land plants (measured in years), such that the standing stock of plant biomass in the ocean is a thousand times less than on land, even though the global productivity of the ocean is roughly equivalent to that on land. Because the abundance of phytoplankton can change rapidly in response to a host of environmental variables such as nutrients, temperature, and sunlight, marine ecosystems tend to be more variable both temporally and spatially. In addition, marine food webs are remarkably complex, with many species feeding at different trophic levels, and numerous interdependencies of species within and even across ecosystems.

Recent studies have shown that the global ocean's primary productivity responds to climate shifts, with a net decrease in phytoplankton productivity observed during the recent warming period.[7] At a regional scale, there are several examples of dramatic changes in marine ecosystems in response to climate variability. For example, the El Niño phenomenon causes widespread declines in fish populations and other species when a pool of warm ocean water lowers the nutrient content of upwelled water along the coast of Peru. Understanding all of the linkages between species and their environment would require a tremendous amount of research and monitoring to develop models with greater predictive capacity.

In addition to climate, fish populations respond to a variety of environmental conditions that, by influencing abundance, affect our ability to manage fisheries sustainably. Many human activities have the potential to reduce the productivity of fish and shellfish stocks through, for example, habitat modification or the release of pollutants. Of the pollutants, nutrient overenrichment is a problem that appears to be affecting more and more bodies of water around the world and has the potential to affect fishery yields (see the Sidebar on Eutrophication and Nutrient Overenrichment).

Claire Fackler, CINMS, Courtesy of National Oceanic and Atmospheric Administration, Department of Commerce

Giant kelp in the Channel Islands National Marine Sanctuary (CINMS) in California. The kelp forest ecosystem supports a high level of marine biodiversity.

Eutrophication and Nutrient Overenrichment

Eutrophication has been defined as the process by which a water body becomes enriched with nutrients that stimulate algal growth, producing higher concentrations of organic material.[8] As the organic material sinks, it decays, which consumes oxygen such that subsurface waters may become hypoxic (depleted of dissolved oxygen) or anoxic (effectively devoid of dissolved oxygen). Eutrophication and oxygen depletion can occur due to either natural or anthropogenic inputs of nutrients. In some cases, such as off the coast of Peru or in the Arabian Sea, natural processes enrich surface waters with nutrients that, with the broader scale circulation patterns, create areas of high near-surface productivity and hypoxic deeper waters.[9] The enrichment of the surface waters supports the Peruvian fisheries, which are among the world's most productive, despite the perennial hypoxia over the continental slope and occasional hypoxia over the shelf.

There are many situations, however, where eutrophication is caused by anthropogenic nutrient inputs. Eutrophication is often caused by fertilizer runoff, but nutrients from many other anthropogenic sources can also contribute to the development of hypoxia or anoxia in estuarine or coastal waters. For example, atmospheric deposition of fossil fuel combustion products or stream transport of untreated farm animal wastes can also be locally important sources of excess nutrients.[10] One of the most intensely studied cases of eutrophication occurs in the Gulf of Mexico off the coast of Louisiana. The Mississippi River system drains much of America's prime farmland, carrying with it the excess nutrients from fertilizers applied to ensure high crop yields. The river carries these nutrients to the Gulf of Mexico, triggering large blooms of phytoplankton. In the summer, the coastal waters become stratified with little mixing of the warm, fresher surface waters with the cooler waters below. As the bloom sinks to the bottom, the decay of the organic materials consumes oxygen, and the deeper water becomes hypoxic. In an average year, hypoxia spreads over 12,900 square kilometers of the Louisiana-Texas continental shelf; this area is popularly referred to as the "dead zone" (Figure 2).[11] A large portion of this shelf area becomes anoxic within about 10 meters of the bottom.[12]

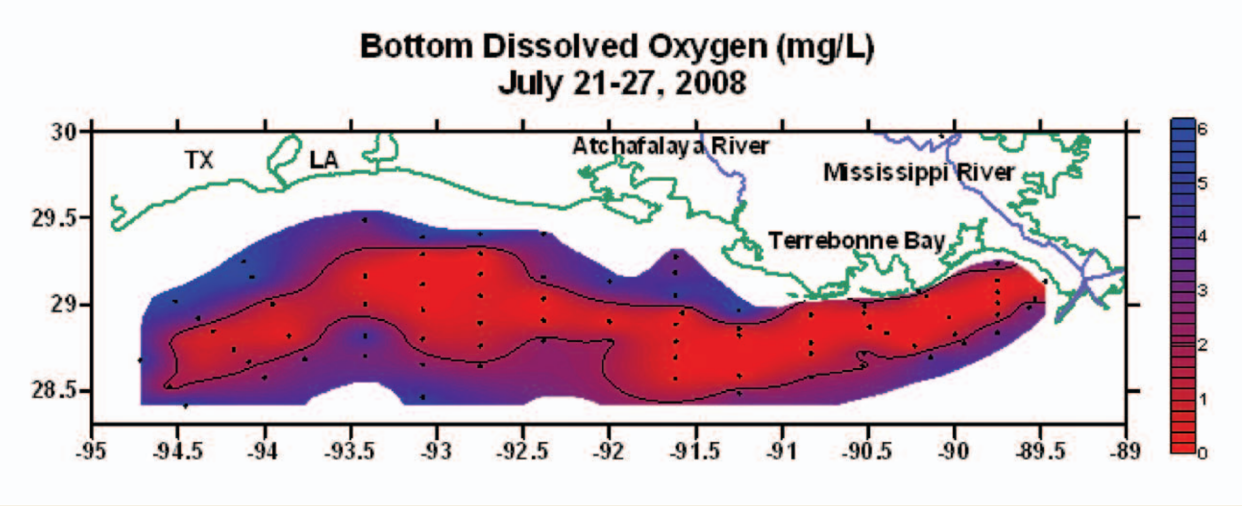
Anthropogenic eutrophication occurs globally[13] and has been documented especially often in estuaries and coastal waters near developed nations (Figure 3). Although some of this geographical pattern may reflect the frequency with which these areas are sampled and monitored, these nations are also among the world's largest consumers of synthetic fertilizers. In addition, the incidence of eutrophication has clearly grown over the last five decades. For example, surveys of the Mississippi outflow have shown increased hypoxia since the 1970s,[11] and hypoxia in the Danube River Black Sea outflow was never documented before 1973.[14] This growth mirrors the continued increase in global nitrate fertilizer production.[10] The problem has expanded to the extent that anthropogenic hypoxia is arguably the most acute of ocean pollution problems.

Nevertheless, the impact on fisheries of eutrophication and hypoxia is surprisingly ambiguous. In the Gulf of Mexico, catches of commercial fisheries have not decreased over the past 20 years despite the large area affected by hypoxia.[12] However, there are indications that the catch of brown shrimp is related to the size of the hypoxic zone.[11] In other locations, such as the Baltic Sea or Chesapeake Bay, direct evidence exists for mortality due to anoxia, as well as for other adverse effects on populations.[15] Indisputably, hypoxia and anoxia change the benthic habitat for many species, with some winners, some losers, and others that either tolerate hypoxia or are able to escape to waters with higher dissolved oxygen.

In addition to hypoxia, there are other potential problems caused by eutrophication. One particularly notable example is the connection between nutrients and toxic algal blooms (a subclass of harmful algal blooms, which are also known as "red tides").[16] In some situations, there is a clear linkage between toxic bloom occurrence and excess nutrients. In other settings, the connection is not clear but appears to depend upon the particular algal species and the overall oceanographic context. Toxins produced by these algal species can cause fish kills and can also affect human health when seafood (especially shellfish) becomes contaminated. In 2005, an intense bloom of an algal species that produces a potent neurotoxin closed shellfish beds in New England for a month during the peak harvesting season.

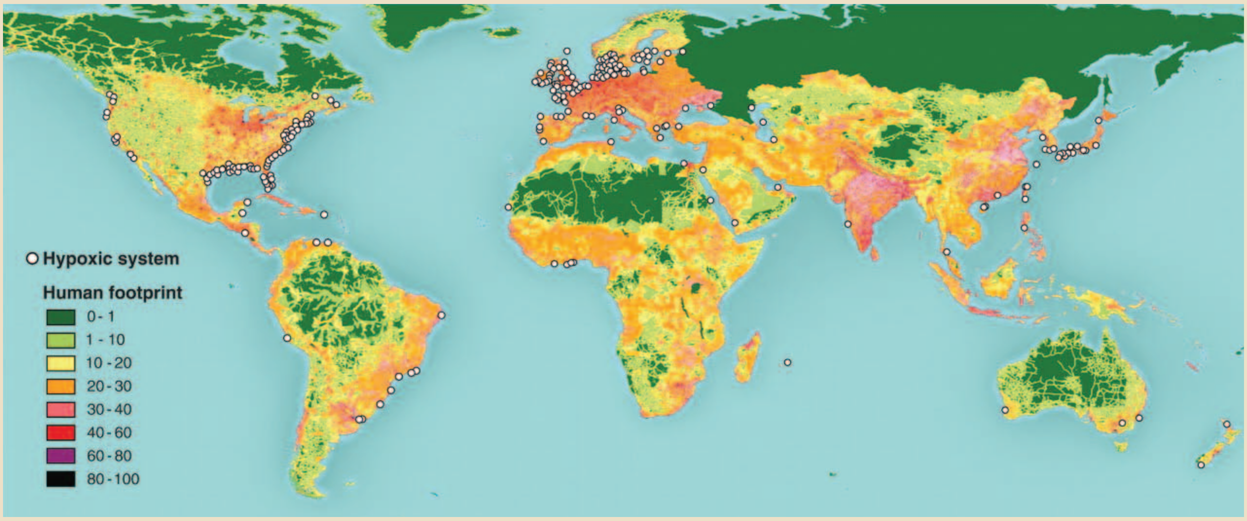
Although detrimental impacts of anoxia on various fish species have been observed, it has been difficult to quantify the net effect of anoxia in many circumstances because of the many other environmental influences on fish stock productivity. In this sense, eutrophication is typical of many of the other human impacts on fisheries: Although a logical linkage can be proposed, demonstrating the linkage and quantitatively assessing the impact can be extremely difficult. The complexity of the natural environment precludes controlled experiments, and so environmental scientists must grapple with results that are frequently inconclusive.

Figure 2. Map illustrates the area of hypoxic bottom water that developed on the Louisiana shelf in 2008. Hypoxic waters (oxygen levels less than 2mg/Liter) are indicated in red.



Nancy Rabalais, Louisiana Universities Marine Consortium, map by B. Babin. National Oceanic and Atmospheric Administration.

Figure 3. Distribution of sites that reported hypoxic events overlaid on a map that indicates the extent of human modification of the landscape.[13]



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As a result of ecosystem and environmental complexity, it is challenging to predict how an ecosystem will respond to the removal of a major fraction of a fish stock, such as the cod stocks in the northwest Atlantic. In most marine ecosystems, many species are targeted by major fisheries and there are other environmental changes that shift the balance in the marine food web. For cod, the slow rate of recovery of many of the stocks from Newfoundland to the Gulf of Maine could reflect ecosystem complexity, perhaps through a change in abundance of prey species, competition with other species, environmental changes in cod's preferred spawning or juvenile habitat, or some other aspect of the cod's life history.

Ecosystem-Based Management Approaches

Because of the collapse of several highly valuable fisheries and increasing signs of stress on marine ecosystems, there has been a groundswell of interest in new approaches to make management more effective both from the human and the ecosystem perspective. The shift toward a more comprehensive view of managing human uses of marine ecosystems has been termed *ecosystem-based management*. Ecosystem-based management recognizes the complex interactions among fished species, their predators and prey, and other sources of environmental variability. Recent studies[17–20] have concluded that an ecosystem-based approach would improve the prospects for the long-term sustainability of marine fisheries. In this approach, the many aspects of human interactions with the oceans—fishing, shipping, water quality, extraction and transport of oil and gas, and invasive species, among others—are taken into consideration in setting management goals. For fisheries, the first step has been to build upon what has been learned from single-species management and incorporate what is currently known about other influences on stock abundance and fisheries interactions into management decisions. In the 2006 reauthorization of the Magnuson-Stevens Fisheries Conservation and Management Act, Congress encouraged managers to try more ecosystem-based approaches in the development of fishery management plans, beginning with "a study on the state of the science for advancing the concepts and integration of ecosystem considerations in regional fishery management."[21] In addition, the Secretary of Commerce was authorized to support the development and design of regional pilot programs by the regional fisheries management councils.

Many different strategies have been proposed to make fisheries more sustainable. A few of these approaches, which could be pursued in concert, are described here: (i) adopting more conservative catch limits, (ii) changing the economic incentives of the fishing industry, and (iii) enhancing the demand for sustainable products. For the first category, moving away from using maximum sustainable yield as a benchmark for management has been advocated as a way to address uncertainty in stock assessments, reduce risk of overfishing, and reduce the impact of the fisheries on other components of marine ecosystems. The concept of "pretty good yield" was first proposed by Alec MacCall of the National Marine Fisheries Service and recently explored for its potential application in various management situations by Ray Hilborn.[19] Pretty good yield (PGY), defined as within 80 percent of the optimum yield, places greater emphasis on the robustness of the fish population than on maximizing the productivity of the fishery. PGY covers a broad range of harvest options that vary with the current abundance of the fish stock and with the life history characteristics of the target species. For many species, PGY may be achieved even at low levels of abundance (20–25 percent of the unfished biomass), but PGY can also be achieved at relatively high levels of abundance (around 50 percent), which suggests that other conservation goals can be met while still allowing a reasonable harvest rate for the fishing industry.

For the second category, the concept of dedicated access privileges or catch shares has been proposed as a way to align the economic interests of the fishing industry with broader marine conservation goals. This approach has been adopted for managing some fisheries in the United States such as the halibut fishery in Alaska. In this system, the predetermined annual harvests are allocated to designated individuals or communities. These individuals or communities have an exclusive right to their share of each year's harvest, thus removing the incentive to compete with

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Halibut fished off of the Alaska coast being sold in Seward, Alaska.

other fishermen. In some versions of this approach, the catch share is transferable, such that the owners may sell the allocation if they decide to leave the fishery. Under this system, owners of a dedicated share of the catch have a long-term economic interest in the health of the fishery to maintain the value of their share. A National Research Council report,[22] for example, describes the strengths and limitations of dedicated access privileges and concludes that a well designed program can avoid some of the potential drawbacks of this management approach and can help industry personnel better align harvesting and processing capabilities to the resource available, slow the "race for fish," provide consumers with a better product, and reduce wasteful and dangerous fishing practices.

A third mechanism for encouraging more sustainable fishing practices is through the development of consumer-driven markets. This has taken many forms, including high profile boycotts (led by conservation groups or consumer education programs) of fish from depleted fisheries such as swordfish and Chilean sea bass. Another approach, taken by the Marine Stewardship Council (MSC), is to develop standards for sustainable and well-managed fisheries and then certify fisheries that meet these standards. Products from certified fisheries may then be sold with the MSC label. Fisheries that apply for MSC certification are evaluated by independent, accredited certifiers that assess the fishery's adherence to MSC standards. Fisheries are reassessed for compliance every five years to retain the MSC certification. The certification program started small, with few certified fisheries and not many distributors. In 10 years of MSC operations, however, 42 fisheries have been certified and several major distributors including Whole Foods and Wal-Mart have made commitments to carry MSC-certified seafood. In 2009, MSC certified seafood was estimated to be worth over $1.5 billion—an indication that certification programs have broad appeal and considerable consumer power.

Susan Roberts

Shrimp in culture at the Thad Cochran Marine Aquaculture Center, a facility of the Gulf Coast Research Laboratory, University of Southern Mississippi. This land-based, closed aquaculture system offers an alternative to the placement of shrimp farms in valuable coastal habitats.

Marine Aquaculture

The wild capture fisheries are only one part of the seafood industry. The largest growth in seafood production since 1990 has been in aquaculture, which currently accounts for about one-third of the world's total fish and shellfish harvest. Aquaculture is expected to increase in importance as the demand for seafood increases. Along with population growth, demand for fish has been driven by a 66-percent increase in per capita consumption since the 1960s.

Although aquaculture at a small scale has been practiced for centuries, only recently has the demand increased to create an industry on a scale with agriculture (Figure 1). Like agriculture, aquaculture stands to benefit from selective breeding to produce faster growing, more domesticated stocks. Farmed salmon across the world are based on Atlantic salmon stocks that have been bred for just these characteristics.

Salmon, and many other popular fishes, are carnivores both in the wild and in culture. Currently, the feed used on salmon farms is partially composed of fish meal and fish oil from wild stocks. As a consequence, aquaculture hasn't reduced reliance on wild fisheries; instead of salmon, forage fish such as anchovies and menhaden are targeted for their value in producing the fish meal and fish oil used in animal feeds. In the future, research on nutritional requirements may yield aquaculture feeds with less reliance on fish meal and oil, thus allowing less impact on wild fisheries.

There are several challenges in addition to the composition of fish feed that must be addressed to increase the sustainability of aquaculture. For example, aquaculture facilities can threaten natural habitats. In some countries, shrimp farms have replaced the natural mangrove forests. Although a commercial success, the loss of the forests has meant the loss of important nursery areas for native species and, in some cases, the loss of a natural buffer that protects the coastline during severe storms.

In aquaculture, there is also the option of farming herbivores instead of carnivores. This typically means culturing filter-feeding shellfish such as mussels, clams, and oysters. These spe-

Fishermen sorting freshly caught fish wearing rain gear and gloves.

cies do not require fish feeds—they are mostly herbivores that consume phytoplankton in the water and their culture can be beneficial in areas prone to phytoplankton blooms and eutrophication.[23] However, some of the other concerns about aquaculture also apply to the culture of these mollusks including the effects of aquaculture operations on marine habitats and the resident species.

The Ocean is Finite

We count on the ocean for many reasons: as a food source, for oxygen production, and as a transportation pathway, to name a few. At the same time that we look to the ocean for practical needs, we treat it as the ultimate "downstream" where excess nutrients or other human byproducts accumulate. Human impacts are changing the ocean with regard to all of these aspects, even shipping, where a northwest passage through the Arctic has recently been realized. We now recognize that the ocean is finite, both in terms of what we can extract, and in terms of what it can absorb from our culture. Effects are not spread evenly, and so some portions of the ocean remain fairly pristine, while others are quite severely impacted. Human impacts often originate on land, as happens with nutrient overenrichment, chemical contaminants, and floating debris.

As we look forward over a century, it is clear that human impacts will continue, but that the nature and form of those impacts will surely change. For example, many large fisheries are embracing sustainable practices to ensure longer term profits and to satisfy more discerning consumers. Clearly, there are governance actions that can be addressed profitably now, regardless of the exact changes to come. New approaches are being developed to help balance the uses of coastal and marine environments, including nonconsumptive ecosystem services such as erosion control, biological carbon sequestration, recreation, and tourism. Continued investments in research and strategic, long-term planning can help to ensure that future generations will have an opportunity to experience and enjoy the ocean and its many resources.

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Acknowledgments: The authors wish to recognize the many experts who contributed their time, knowledge, and energy to the studies cited below, including several National Research Council committees. Insights from all of these studies form an important foundation for this article, although the opinions expressed within are strictly those of the authors. In addition, K. Brink wishes to acknowledge support from the National Science Foundation, Physical oceanography, grant OCE 0647050.

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