ISSUE 20

Does Commercial Fishing Have a Future?

YES: Carl Safina, from "A Future for U.S. Fisheries," *Issues in Science and Technology* (Summer 2009)

NO: Boris Worm et al., from "Impacts of Biodiversity Loss on Ocean Ecosystem Services," *Science* (November 3, 2006)

ISSUE SUMMARY

YES: Carl Safina argues that despite an abundance of bad news about the state of the oceans and commercial fisheries, there are some signs that conservation and even restoration of fish stocks to a sustainable state are possible.

NO: Boris Worm and colleagues argue that human activities, including overfishing, so threaten marine biodiversity that before the mid-twenty-first century, populations of all those ocean fish currently sought will be so reduced that commercial fishing will have ended.

Carl Safina called attention to the poor state of the world's fisheries in "Where Have All the Fishes Gone?" *Issues in Science and Technology* (Spring 1994) and "The World's Imperiled Fish," *Scientific American* (November 1995). Expanding population, improved fishing technology, and growing demand had combined to drive down fish stocks around the world. Fishers going further from shore and deploying larger nets kept the catch growing, but the UN's Food and Agriculture Organization had noted that the fisheries' situation was already "globally non-sustainable, and major ecological and economic damage [was] already visible."

The UN declared 1998 as the International Year of the Ocean. Kieran Mulvaney, "A Sea of Troubles," *EMagazine* (January/February 1998), reported, "According to the United Nations Food and Agriculture Organization (FAO), an estimated 70 percent of global fish stocks are 'over-exploited', 'fully exploited', 'depleted' or recovering from prior over-exploitation. By 1992, FAO had recorded 16 major fish species whose global catch had declined by more than 50 percent over the previous three decades—and in half of these, the collapse had begun after 1974." Ocean fishing did not seem sustainable.

Daniel Pauly and Reg Watson, "Counting the Last Fish," *Scientific American* (July 2003), note that desirable fish, such as tuna and cod, tend to be top predators. When the numbers of these fish decline due to overfishing, fishers shift their attention to fish lower on the food chain and consumers see a change in what is available at the market. The cod are smaller, and monkfish and other once less-desirable fish join them on the crushed ice at the market. This change is an indicator of trouble in the marine ecosystem.

Responses to the situation have included government buyouts of fishing fleets and closures of fisheries such as the Canadian cod fishery. But the situation has not improved. David Helvarg, in "The Last Fish," *Earth Island Journal* (Spring 2003), concludes that about half of America's commercial seafood species are now overfished. Globally, the figure is still over 70 percent, and the North Atlantic contains only a third as much biomass of commercially valuable fish as it did in the 1950s. Helvarg recommends more buying out of excess fishing capacity; limiting the number of people allowed to enter the fishing industry; creating marine reserves; and perhaps most importantly, taking fisheries management out of the hands of people with a vested interest in the status quo.

In June 2000, the independent Pew Oceans Commission undertook the first national review of ocean policies in more than 30 years. Its report, "America's Living Oceans: Charting a Course for Sea Change," (Pew Oceans Commission, 2003) (www.pewoceans.org/), noted that many commercially fished species are in decline (North Atlantic cod, haddock, and yellowtail flounder reached historic lows in 1989). The reasons include intense fishing pressure to feed demand for seafood, as well as pollution, coastal development, fishing practices such as bottom dragging that destroy habitat, and fragmented ocean policy that makes it difficult to prevent or control the damage. The answers, the commission suggests, must include such things as the no-fishing zones known as marine protected areas, which have been shown to restore habitat and fish populations, with clear benefits for commercial fishing. See also Julia Whitty, "The Fate of the Ocean," *Mother Jones* (March/April 2006); Michelle Allsopp et al., *Oceans in Peril: Protecting Marine Biodiversity* (Worldwatch Institute, 2007); and Fen Montaigne, "The Global Fish Crisis," a special report in *National Geographic* (April 2007). There is also a pressing need to rein in illegal fishing; see Stefan Flothmann et al., "Closing Loopholes: Getting Illegal Fishing under Control," *Science* (June 4, 2010).

In the following selections, Carl Safina argues that despite an abundance of bad news about the state of the oceans and commercial fisheries, there are some signs that conservation and even restoration of fish stocks to a sustainable state are possible. Marine ecologist Boris Worm and colleagues argue that human activities, including overfishing, so threaten marine biodiversity that before the mid-twenty-first century, populations of all the ocean fish currently sought will be so reduced that commercial fishing will have ended.

YES

Carl Safina

A Future for U.S. Fisheries

For the fishing industry in the United States, and for the fishery resources on which the industry depends, there is good news and bad news. Bad news still predominates, as many commercial fishers and their communities have suffered severe financial distress and many fish stocks have declined considerably in numbers. Poor management by the National Marine Fisheries Service (NMFS), which regulates the fishing industry, and some poor choices by many fishers have contributed to the problems. But there are some bright spots, small and scattered, that suggest that improvements are possible.

Starting with the bad news, the federal government's fisheries management remains primitive, simplistic, and, in important cases, ineffectual, despite a fund of knowledge and conceptual tools that could be applied. In many regions—New England and the Pacific Northwest, among others—failed management costs more than the receipts from fisheries. This does not suggest that management should be given up as a lost cause, leaving the industry in a free-for-all, although this strategy might, in fact, be cheaper and not much less effective.

As a key problem, most management efforts today are based primarily on catch quotas that regulate how much fishers can harvest of a particular species in some set period, perhaps a season or a year. The problem is that quotas are set according to estimates of how much of the resource can be taken out of the ocean, rather than on how much should be left in. This may sound like two sides of the same coin, but in practice the emphasis on extraction creates a continual bias on the part of fisheries agencies and unrealistic short-term expectations among fishers. For example, a basic tenet of these approaches is that a virgin fish population should be reduced by about two-thirds to make it more "productive." But this notion is belied in the real world, where it has been proven that larger breeding populations are more productive.

The failure of this approach is readily apparent. The Sustainable Fisheries Act of 1996, reaffirmed by Congress in 2006, states that fish populations may not be fished down below about one-third of their estimated virgin biomass. It also states that in cases where fish stocks already have been pushed below that level, they must be restored (in most cases) to that level within a decade. On paper, this act looked good. (Full disclosure: I drafted the quantitative overfishing and recovery goals and triggers mandated by the act.) Unfortunately, the NMFS wrote implementing regulations interpreting the mandates as meaning

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that overfishing could continue for some time before rebuilding was required. This too-liberal interpretation blurred the concept and delayed benefits. In its worst cases, it acknowledged that fish populations must be rebuilt in a decade but said that overfishing could continue in the meantime.

Clearly, the nation needs to take a different approach, based solidly on science. As a foundation, regulatory and management agencies must move from basing their actions on "how much can we take?" to concentrating on "how much must we leave?" The goal must be keeping target fish populations and associated living communities functioning, with all components being highly productive and resilient.

The nation must confront another reality as well. So many fisheries are so depleted that the only way to restore them will be to change the basic posture of regulations and management programs to one of recovery. Most fish populations could recover within a decade, even with some commercial fishing. But continuing to bump along at today's depleted levels robs fishing families and communities of income and risks resource collapse.

Ingredients for Success

Moving to a new era of fisheries management will require revising some conventional tools that are functioning below par and adopting an array of new "smart tools." Regulations that set time frames for overfishing and recovery can play a valuable role, if properly interpreted. For example, traditional catch quotas must be based firmly on scientific knowledge about fish stocks, and they must be enforced with an eye toward protecting the resource. Newer tools, adapted to specific environments and needs, would include:

Tradable Catch Shares

In this approach, now being used in some regions in varying degrees, fishery managers allot to fishers specific shares of the total allowable catch and give them the flexibility and the accountability for reaching their shares. Thus, fishers do not own the fish; rather, they own a percentage of the total allowed catch, which may fluctuate from year to year if management agencies adjust it up or down.

In expanding the use of such programs, managers must establish the shares based on the advice of independent scientists who are insulated from industry lobbying. Managers also should allot shares only to working fishers, not to corporations or processors. Of course, finding equitable ways of determining which fishers get catch shares will be critical. Methods of allocating shares may vary from location to location, but the key is ensuring an open process that accounts for fishers' legitimate interests and maintains conservation incentives. In many cases, fewer fishers will be eligible to keep fishing. But those not selected would likely have been forced out of business anyway by the combination of pressure from more successful fishers and reduced fish stocks.

By significantly reducing competition that breeds a race for fish, this approach offers several benefits. For one, it makes for safer fishing. Fishers who own shares know that they have the whole season to fill their quota regardless of what other boats are catching, so they are less likely to feel forced to head out in dangerous weather. In addition, owning a share helps ensure (other factors permitting) that a fisher can earn a decent living, so local, state, or regional politicians will feel less pressure to protect their fishing constituents and push for higher catch quotas. At the same time, marginal operators granted shares would no longer feel trapped, because they would have something to sell if they wished to exit the fishery. By promoting longer-term thinking among fishers and politicians alike, catch-share programs help foster a sense of future investment in which quota holders will benefit from high or recovered fish populations.

The impact of tradable catch shares can be seen in experiences in several regions. In Alaska, where fisheries managers once kept a tight cap on the halibut catch, the fishing season shrank to two days annually because there were so many competing boats. After managers introduced tradable catch shares, the number of boats fell precipitously and the season effectively expanded to whenever the fishers wanted to work toward filling their shares. Safety improved markedly, and the halibut population remained robust. In New England, where the industry resisted tradable shares, the story ended differently. Managers allotted individual fishers a shrinking number of days at sea, which progressively crippled their economic viability, gave them no option to exit the fishery short of foreclosure, and kept fishing pressure so high that the fish stocks never recovered.

Area-Based Fisheries

Although this concept may be relatively new in Western fisheries management, it has underpinned the management of fishing in Pacific islands for millennia. In practice, this approach is most applicable where fish populations spawn in localized areas and do not migrate far from their spawning area. For example, consider the case of clams, which spawn in limited areas and never move far away. In many regions, clamming is regulated on a township-by-township basis. Thus, conserving clams off one port will benefit that port, even if (especially if) the next port eliminates its own clam beds. This model holds promise for greater use with various fish species as well. In New England waters, cod once spawned in many local populations, many of which are now extinct. Overall regional quotas and regional mobility of boats contributed to their extinction. Had managers established local area-based restrictions, these populations might well have been saved, to the benefit of local communities.

In implementing area-based fisheries, managers will need to move deliberately, being mindful of what is scientifically supported and careful not to unduly raise people's expectations. If managers move too hastily, the restrictions may meet a lot of social skepticism and may not work as well as advertised, setting back not only the health of the fish stocks but also the credibility of the managers and scientists who support such actions.

Closed Areas

In recent years, fisheries managers have decided that some stocks are so threatened that the only choice is to close all or part of their habitat to fishing. Such

efforts are to be applauded, although they have been too few and too limited in scale to achieve major success. Still, the lessons are instructive, as closures have been found to result in increases in fish populations, in the size of individual fish, and in greater diversity of species.

On Georges Bank in the north Atlantic, for example, success has been mixed, but tantalizing. Managers closed some of the grounds in an effort to protect northern cod, in particular, whose stocks had become severely depleted. So far, cod stocks have not rebounded, for a suite of reasons. But populations of several other important species, notably haddock and sea scallops, have mushroomed. These recovered populations have yielded significant financial benefits to the region, although in the case of sea scallops, fishing interests successfully lobbied to be allowed back into the closed areas, hampering full recovery of the resource.

Mixed Zoning

In many resource-based industries, even competing interests often agree on one thing: They do not want an area closed to them. Yet regarding fishing, conservationists too often have insisted that protected areas be closed to all extraction, and their single-minded pursuit of all-or-nothing solutions has made it easy for commercial interests to unite in demanding that the answer be nothing. A more nuanced approach is needed.

A comprehensive zoning program should designate a mix of areas, including areas that are entirely open to any kind of fishing at any time, areas that are closed to fishers using mobile gear, areas that are closed to fishers using gear that drags along the seafloor, areas that are closed in some seasons, and areas that are fully protected no-take zones. Such integrated zoning would better protect sensitive seafloor habitats and aquatic nursery areas from the kinds of activities that hurt those areas, while allowing harmless activities to proceed. For instance, tuna fishing could be banned in tuna breeding or nursery areas, yet allowed in ocean canyons, even those with deep coral and other important sedentary bottom communities. This type of zoning would also be most likely to gain the support of competing interests, as each party would get something it wants.

Reduction of Incidental Catch

Almost all methods of commercial fishing catch undersized or unmarketable individuals of the target species. Few of these can be returned alive. Fortunately, a number of simple changes in fishing methods and gear, such as the use of nets with larger mesh size, have been developed that can reduce incidental kill by more than 90%, and the government should adopt regulations that require use of these cleaner techniques. In some cases, however, it may be appropriate to require fishers to keep all fish caught—no matter their size, appearance, or even species—in order to reduce the waste that otherwise would result.

Commercial fishers also often catch creatures other than fish, with fatal results. For some creatures, such as sea turtles, capture may endanger their species' very survival. Here, too, advances in fishing technology are helping, but regulators must pay increased attention to finding ways to reduce this problem.

Protection Based on Size

Managers may be able to protect some fish stocks by setting regulations based on graduated fish sizes. This approach, taken almost by default, has led to a spectacular recovery of striped bass along the Atlantic coast. At one time, this population had become deeply depleted, and reproduction rates had fallen precipitously. But one year, environmental conditions arose that favored the survival of eggs and larvae and led to a slight bump in the number of young fish. After much rancor and debate, federal fisheries managers forced states to cooperate in shepherding this class of juveniles to adulthood. They did this primarily by placing a continually increasing limit on the minimum size of fish that fishers could keep. Over the course of more than a decade, the limits protected the fish as they grew and, ultimately, began reproducing. The limits also protected fish hatched in subsequent years, and they, too, grew into adulthood. This simple approach—protecting fish until they have had a chance to reproduce—did more to recover a highly valued, highly sought species than all of the complex calculations, models, and confused politics of previous management efforts.

Subsidy Reform

The federal government provides various segments of the fishing industry with major subsidies that have resulted in a number of adverse consequences. Improperly designed and sized subsidies have propped up bloated and overcapitalized fisheries that have systematically removed too many fish from the seas. Of course, some subsidies will remain necessary. But in most cases, subsidy amounts should be reduced. Also, many subsidies should be redirected to support efforts to develop cleaner technologies and to ease the social pain that fishers and their communities might face in adopting the improved technologies.

Ecologically Integrated Management

Perhaps the worst mistake of traditional fisheries management is that it consider each species in isolation. For example, simply focusing on how much herring fishers can take from the ocean without crashing herring stocks does not address the question of how much herring must be left to avoid crashing the tuna, striped bass, and humpback whales that feed on herring. Management regulations must be revised to reflect such broader food-web considerations.

Sustainable Aquaculture

During the past quarter-century, many nations have turned increasingly to aquaculture to supplement or even replace conventional commercial fishing. Although not at the head of this effort, the United States offers various forms

of assistance and incentives to aid the development of the industry. But fish farming is not a panacea. Some operations raise unsustainable monocultures of fish, shrimp, and other aquatic species. Some destroy natural habitats such as marshes that are vital to wild fish. Some transfer pathogens to wild populations. Some pollute natural waters with food, feces, or pesticides necessary to control disease in overcrowded ponds and pens.

As the nation expands fish farming, doing it right should trump doing it fast. Generally, aquaculture will be most successful if it concentrates on raising smaller species and those lower on the food chain. Fish are not cabbages; they do not grow on sunlight. They have to be fed something, and what most fish eat is other fish. Just as the nation's ranchers raise cows and not lions, fish farmers should raise species such as clams, oysters, herring, tilapia, and other vegetarian fish, but not tuna. Farming large carnivores would take more food out of the ocean to feed them than the farming operation would produce. The result would be a loss of food for people, a loss of fish to other fisheries, and a loss to the ocean. Done poorly, aquaculture is as much of a ticking time bomb as were overcapitalized fisheries.

Working Together

Given the magnitude of the problems facing the nation's commercial fishers and fisheries, the various stakeholders must draw together. Although some recent experiences may suggest otherwise, fishers and scientists need each other in order to succeed. Fishers might lack the training to understand the scientific techniques, especially data analysis, that underpin improved management tools, and scientists might lack the experience required to understand the valid concerns and observations of fishers. But without more trust and understanding, adversarial postures that undermine wise management will continue to waste precious time as resources continue to deteriorate and communities and economies suffer. This need not be the case.

Similarly, fishers, fishery managers, and scientists should work together to better inform the public about the conditions and needs of the nation's fishing industry and fish stocks. Consider the example of marine zoning. The less people understand about fishing, the more they insist that closed, no-take marine reserves are the answer. Similarly, the less people understand about conservation, the more they insist that traditional methods of fisheries management, which typically ignore the need for reserves, are adequate tools for protecting fish stocks. As in many other areas, knowledge breeds understanding—and very often solutions.

Boris Worm et al. → **NO**

Impacts of Biodiversity Loss on Ocean Ecosystem Services

What is the role of biodiversity in maintaining the ecosystem services on which a growing human population depends? Recent surveys of the terrestrial literature suggest that local species richness may enhance ecosystem productivity and stability. However, the importance of biodiversity changes at the landscape level is less clear, and the lessons from local experiments and theory do not seem to easily extend to long-term, large-scale management decisions. These issues are particularly enigmatic for the world's oceans, which are geographically large and taxonomically complex, making the scaling up from local to global scales potentially more difficult. Marine ecosystems provide a wide variety of goods and services, including vital food resources for millions of people. A large and increasing proportion of our population lives close to the coast; thus, the loss of services such as flood control and waste detoxification can have disastrous consequences. Changes in marine biodiversity are directly caused by exploitation, pollution, and habitat destruction, or indirectly through climate change and related perturbations of ocean biogeochemistry. Although marine extinctions are only slowly uncovered at the global scale, regional ecosystems such as estuaries, coral reefs, and coastal and oceanic fish communities are rapidly losing populations, species, or entire functional groups. Although it is clear that particular species provide critical services to society, the role of biodiversity per se remains untested at the ecosystem level. We analyzed the effects of changes in marine biodiversity on fundamental ecosystem services by combining available data from sources ranging from small-scale experiments to global fisheries.

Experiments

We first used meta-analysis of published data to examine the effects of variation in marine diversity (genetic or species richness) on primary and secondary productivity, resource use, nutrient cycling, and ecosystem stability in 32 controlled experiments. Such effects have been contentiously debated, particularly in the marine realm, where high diversity and connectivity may blur any deterministic effect of local biodiversity on ecosystem functioning. Yet when the available experimental data are combined, they reveal a strikingly general picture. Increased diversity of both primary producers and consumers enhanced all

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examined ecosystem processes. Observed effect sizes corresponded to a 78–80% enhancement of primary and secondary production in diverse mixtures relative to monocultures and a 20–36% enhancement of resource use efficiency.

Experiments that manipulated species diversity or genetic diversity both found that diversity enhanced ecosystem stability, here defined as the ability to withstand recurrent perturbations. This effect was linked to either increased resistance to disturbance or enhanced recovery afterward. A number of experiments on diet mixing further demonstrated the importance of diverse food sources for secondary production and the channeling of that energy to higher levels in the food web. Different diet items were required to optimize different life-history processes (growth, survival, and fecundity), leading to maximum total production in the mixed diet. In summary, experimental results indicate robust positive linkages between biodiversity, productivity, and stability across trophic levels in marine ecosystems. Identified mechanisms from the original studies include complementary resource use, positive interactions, and increased selection of highly performing species at high diversity.

Coastal Ecosystems

To test whether experimental results scale up in both space and time, we compiled long-term trends in regional biodiversity and services from a detailed database of 12 coastal and estuarine ecosystems and other sources. We examined trends in 30 to 80 (average, 48) economically and ecologically important species per ecosystem. Records over the past millennium revealed a rapid decline of native species diversity since the onset of industrialization. As predicted by experiments, systems with higher regional species richness appeared more stable, showing lower rates of collapse and extinction of commercially important fish and invertebrate taxa over time. Overall, historical trends led to the present depletion (here defined as >50% decline over baseline abundance), collapse (>90% decline), or extinction (100% decline) of 91, 38, or 7% of species, on average. Only 14% recovered from collapse; these species were mostly protected birds and mammals.

These regional biodiversity losses impaired at least three critical ecosystem services: number of viable (noncollapsed) fisheries (−33%); provision of nursery habitats such as oyster reefs, seagrass beds, and wetlands (−69%); and filtering and detoxification services provided by suspension feeders, submerged vegetation, and wetlands (−63%). Loss of filtering services probably contributed to declining water quality and the increasing occurrence of harmful algal blooms, fish kills, shellfish and beach closures, and oxygen depletion. Increasing coastal flooding events are linked to sea level rise but were probably accelerated by historical losses of floodplains and erosion control provided by coastal wetlands, reefs, and submerged vegetation. An increased number of species invasions over time also coincided with the loss of native biodiversity; again, this is consistent with experimental results. Invasions did not compensate for the loss of native biodiversity and services, because they comprised other species groups, mostly microbial, plankton, and small invertebrate taxa. Although causal relationships are difficult to infer, these data suggest that substantial loss of biodiversity is closely associated with regional loss of ecosystem services and increasing risks for coastal inhabitants. Experimentally derived predictions that more species-rich systems should be more stable in delivering services are also supported at the regional scale.

Large Marine Ecosystems

At the largest scales, we analyzed relationships between biodiversity and ecosystem services using the global catch database from the United Nations Food and Agriculture Organization (FAO) and other sources. We extracted all data on fish and invertebrate catches from 1950 to 2003 within all 64 large marine ecosystems (LMEs) worldwide. LMEs are large (>150,000 km^2) ocean regions reaching from estuaries and coastal areas to the seaward boundaries of continental shelves and the outer margins of the major current systems. They are characterized by distinct bathymetry, hydrography, productivity, and food webs. Collectively, these areas produced 83% of global fisheries yields over the past 50 years. Fish diversity data for each LME were derived independently from a comprehensive fish taxonomic database.

Globally, the rate of fisheries collapses, defined here as catches dropping below 10% of the recorded maximum, has been accelerating over time, with 29% of currently fished species considered collapsed in 2003. This accelerating trend is best described by a power relation ($y = 0.0168x^{1.8992}$, $r = 0.96$, $P < 0.0001$), which predicts the percentage of currently collapsed taxa as a function of years elapsed since 1950. Cumulative collapses (including recovered species) amounted to 65% of recorded taxa. The data further revealed that despite large increases in global fishing effort, cumulative yields across all species and LMEs had declined by 13% (or 10.6 million metric tons) since passing a maximum in 1994.

Consistent with the results from estuaries and coastal seas, we observed that these collapses of LME fisheries occurred at a higher rate in species-poor ecosystems, as compared with species-rich ones. Fish diversity varied widely across LMEs, ranging from ~20 to 4000 species, and influenced fishery-related services in several ways. First, the proportion of collapsed fisheries decayed exponentially with increasing species richness. Furthermore, the average catches of noncollapsed fisheries were higher in species-rich systems. Diversity also seemed to increase robustness to overexploitation. Rates of recovery, here defined as any post-collapse increase above the 10% threshold, were positively correlated with fish diversity. This positive relationship between diversity and recovery became stronger with time after a collapse (5 years, $r = 0.10$; 10 years, $r = 0.39$; 15 years, $r = 0.48$). Higher taxonomic units (genus and family) produced very similar relationships as species richness . . . typically, relationships became stronger with increased taxonomic aggregation. This may suggest that taxonomically related species play complementary functional roles in supporting fisheries productivity and recovery.

A mechanism that may explain enhanced recovery at high diversity is that fishers can switch more readily among target species, potentially providing overfished taxa with a chance to recover. Indeed, the number of fished taxa

was a log-linear function of species richness. Fished taxa richness was negatively related to the variation in catch from year to year and positively correlated with the total production of catch per year. This increased stability and productivity are likely due to the portfolio effect, whereby a more diverse array of species provides a larger number of ecological functions and economic opportunities, leading to a more stable trajectory and better performance over time. This portfolio effect has independently been confirmed by economic studies of multispecies harvesting relationships in marine ecosystems. Linear (or log-linear) relationships indicate steady increases in services up to the highest levels of biodiversity. This means that proportional species losses are predicted to have similar effects at low and high levels of native biodiversity.

Marine Reserves and Fishery Closures

A pressing question for management is whether the loss of services can be reversed, once it has occurred. To address this question, we analyzed available data from 44 fully protected marine reserves and four large-scale fisheries closures. Reserves and closures have been used to reverse the decline of marine biodiversity on local and regional scales. As such, they can be viewed as replicated large-scale experiments. We used meta-analytic techniques to test for consistent trends in biodiversity and services across all studies.

We found that reserves and fisheries closures showed increased species diversity of target and nontarget species, averaging a 23% increase in species richness. These increases in biodiversity were associated with large increases in fisheries productivity, as seen in the fourfold average increase in catch per unit of effort in fished areas around the reserves. The difference in total catches was less pronounced, probably because of restrictions on fishing effort around many reserves. Resistance and recovery after natural disturbances from storms and thermal stress tended to increase in reserves, though not significantly in most cases. Community variability, as measured by the coefficient of variation in aggregate fish biomass, was reduced by 21% on average. Finally, tourism revenue measured as the relative increase in dive trips within 138 Caribbean protected areas strongly increased after they were established. For several variables, statistical significance depended on how studies were weighted. This is probably the result of large variation in sample sizes among studies. Despite the inherent variability, these results suggest that at this point it is still possible to recover lost biodiversity, at least on local to regional scales; and that such recovery is generally accompanied by increased productivity and decreased variability, which translates into extractive (fish catches around reserves) and nonextractive (tourism within reserves) revenue.

Conclusions

Positive relationships between diversity and ecosystem functions and services were found using experimental and correlative approaches along trajectories of diversity loss and recovery. Our data highlight the societal consequences of an ongoing erosion of diversity that appears to be accelerating on a global scale. This trend is of serious concern because it projects the global collapse of all taxa currently fished by the mid–21st century (based on the extrapolation of regression . . . to 100% in the year 2048). Our findings further suggest that the elimination of locally adapted populations and species not only impairs the ability of marine ecosystems to feed a growing human population but also sabotages their stability and recovery potential in a rapidly changing marine environment.

We recognize limitations in each of our data sources, particularly the inherent problem of inferring causality from correlation in the larger-scale studies. The strength of these results rests on the consistent agreement of theory, experiments, and observations across widely different scales and ecosystems. Our analysis may provide a wider context for the interpretation of local biodiversity experiments that produced diverging and controversial outcomes. It suggests that very general patterns emerge on progressively larger scales. High-diversity systems consistently provided more services with less variability, which has economic and policy implications. First, there is no dichotomy between biodiversity conservation and long-term economic development; they must be viewed as interdependent societal goals. Second, there was no evidence for redundancy at high levels of diversity; the improvement of services was continuous on a log-linear scale. Third, the buffering impact of species diversity on the resistance and recovery of ecosystem services generates insurance value that must be incorporated into future economic valuations and management decisions. By restoring marine biodiversity through sustainable fisheries management, pollution control, maintenance of essential habitats, and the creation of marine reserves, we can invest in the productivity and reliability of the goods and services that the ocean provides to humanity. Our analyses suggest that business as usual would foreshadow serious threats to global food security, coastal water quality, and ecosystem stability, affecting current and future generations.

POSTSCRIPT

Does Commercial Fishing Have a Future?

Worm et al. are by no means alone in warning of disaster for commercial fisheries. Karin E. Limburg and John R. Waldman, "Dramatic Declines in North Atlantic Diadromous Fishes," *Bioscience* (December 2009), report that for 24 fish species studied, "populations have declined dramatically from original baselines." Oran R. Young, "Taking Stock: Management Pitfalls in Fisheries Science," *Environment* (April 2003), notes that despite putting great effort into assessing fish stocks and managing fisheries for sustainable yield, marine fish stocks have continued to decline. This is partly the "result of the inability of managers to resist pressures from interest groups to set total allowable catches too high, even in the face of warnings from scientists about the dangers of triggering stock depletions. The problem also arises, however, from repeated failures on the part of analysts and policy makers to anticipate the collapse of major stocks or to grasp either the current condition or the reproductive dynamics of important stocks." He cautions against putting "blind faith in the validity of scientific assessments" and suggests more use of the precautionary principle despite the risk that this would set allowed catch levels lower than many people would like. Lynda D. Rodwell and Callum M. Roberts, "Fishing and the Impact of Marine Reserves in a Variable Environment," *Canadian Journal of Fisheries and Aquatic Sciences* (November 2004), find that in variable marine environments, reserves can increase catches, reduce variability of catches, and make planning more efficient. Christian Mullon, Pierre Freon, and Philippe Cury, "The Dynamics of Collapse in World Fisheries," *Fish and Fisheries* (June 2005), find that current trends are likely to cause a "global collapse of many more fisheries" than hitherto. However, it is worth noting that Martin D. Smith, Junjie Zhang, and Felicia C. Coleman, "Effectiveness of Marine Reserves for Large-Scale Fisheries Management," *Canadian Journal of Fisheries and Aquatic Sciences* (January 2006), find that the effect of at least some marine reserves is not beneficial. Results may vary according to size of reserve and the fish species of interest; see Robert E. Blyth-Skyrme, et al., "Conservation Benefits of Temperate Marine Protected Areas: Variation Among Fish Species," *Conservation Biology* (June 2006). Christopher Pala, "Our Imperiled Oceans: Victory at Sea," *Smithsonian Magazine* (September 2008), describes the world's largest marine reserve surrounding the Phoenix Islands in the South Pacific.

In September 2004, the U.S. Commission on Ocean Policy issued its report, "An Ocean Blueprint for the 21st Century" (www.oceancommission.gov/documents/full_color_rpt/welcome.html), calling for improved management systems "to handle mounting pollution and declining fish populations and coral reefs, and promise new industries such as aquaculture." In many ways it agreed with the Pew report. Carl Safina and Sarah Chasis, "Saving the Oceans," *Issues in Science and Technology* (Fall 2004), discuss the two reports and say that it is time for Congress to craft a new approach to ocean policy, including fisheries protection, and put scientists in charge of policy. James N. Sanchirico and Susan S. Hanna, "Sink or Swim Time for U.S. Fishery Policy," *Issues in Science and Technology* (Fall 2004), add that an ecosystem approach is essential. According to Rainer Froese and Alexander Proelß, "Rebuilding Fish Stocks No Later Than 2015: Will Europe Meet the Deadline?" *Fish and Fisheries* (June 2010), "Maintaining or restoring fish stocks at levels that are capable of producing maximum sustainable yield is a legal obligation under the United Nations Convention on the Law of the Sea (UNCLOS) and has been given the deadline of no later than 2015 in the *Johannesburg Plan of Implementation* of 2002. . . . But even if fishing were halted in 2010, 22% of the stocks are so depleted that they cannot be rebuilt by 2015. If current trends continue, Europe will miss the 2015 deadline by more than 30 years." They note that just passing laws is not enough.

Marine reserves are gaining favor as part of the solution. So is aquaculture, with researchers struggling to save the bluefin tuna by domesticating it; see Richard Ellis, "The Bluefin in Peril," *Scientific American* (March 2008), and Robert F. Service, "Persevering Researchers Make a Splash With Farm-Bred Tuna," *Science* (June 5, 2009). Conflict does, however, remain over whether such measures are necessary; see C. Pala, "Conservationists and Fishers Face Off Over Hawaii's Marine Riches," *Science* (July 20, 2007).

When the report by Worm was reprinted in Taking Sides series in 2006, critics were vocal. After some debate, according to Eric Stokstad, "Détente in the Fisheries War," *Science* (April 10, 2009), Worm and one major critic, Ray Hilborn, of the University of Washington in Seattle, teamed up with other researchers and graduate students to study larger data sets in search of a better vision of the future. One recent report from Worm's group, Camilo Mora et al., "Management Effectiveness of the World's Marine Fisheries," *Public Library of Science Biology* (June 2009) (www.plosbiology.org/article/info%3Adoi%2F10.1371%2Fjournal.pbio.1000131), finds that demand for seafood is rising far beyond what can be met sustainably and only a handful of countries have "a robust scientific basis for management recommendations." Boris Worm et al., "Rebuilding Global Fisheries," *Science* (July 31, 2009), examine efforts to restore damaged marine ecosystems and fisheries and find that although there is some success, "63% of assessed fish stocks worldwide still require rebuilding, and even lower exploitation rates are needed to reverse the collapse of vulnerable species." Global fisheries remain in danger.