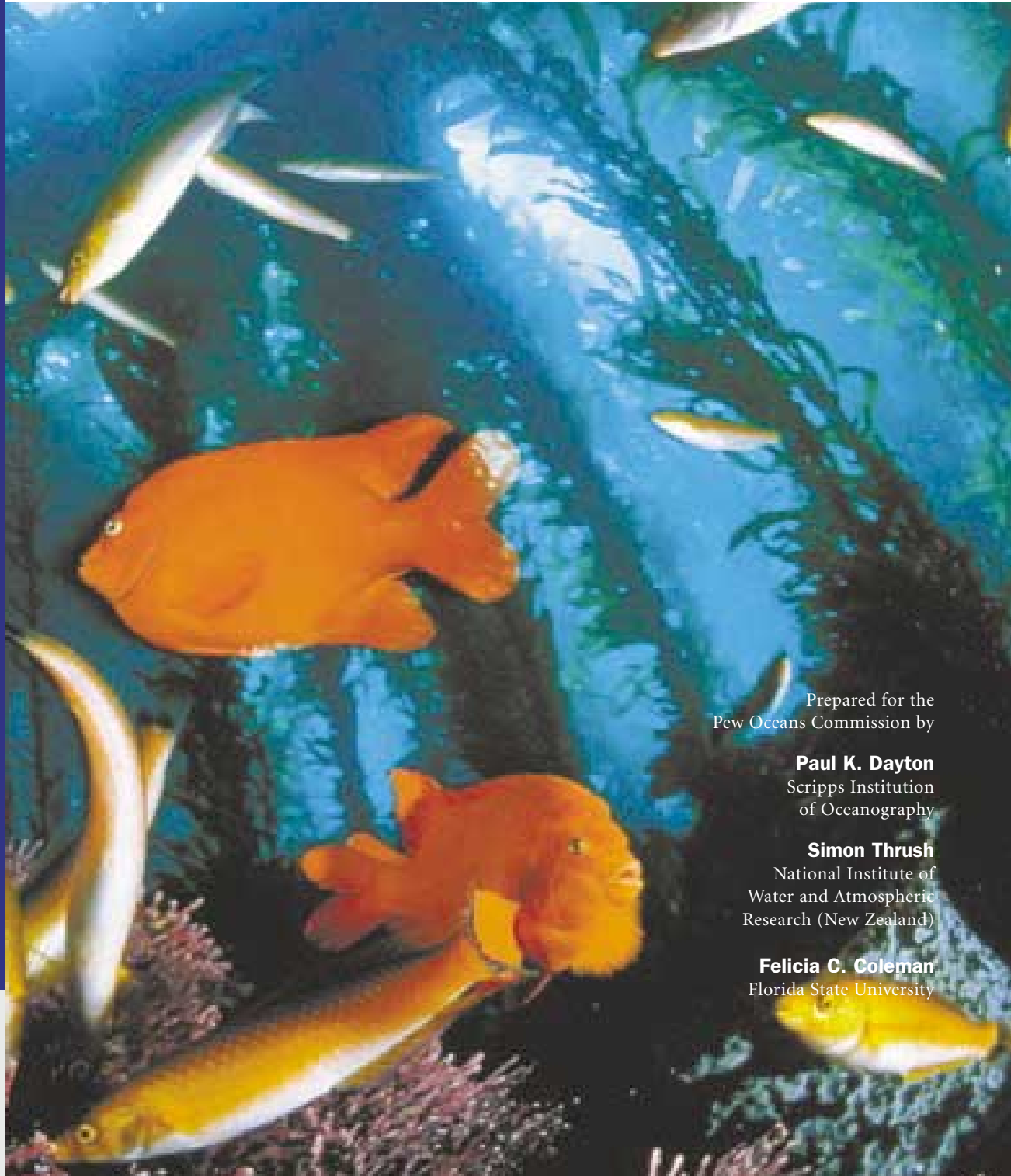# Ecological Effects of Fishing

IN MARINE ECOSYSTEMS OF THE UNITED STATES

Prepared for the
Pew Oceans Commission by

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Contents

Commercial fishermen landed
about 9.1 billion pounds of
fish from waters in the United
States in 2000. In addition,
recreational fishermen took an
estimated 429.4 million fish and
kept or released dead an
estimated 184.5 million fish
weighing 254.2 million pounds.
Source: NMFS, 2002.*

*Does not include bycatch and discards

Abstract

Are the oceans in crisis because of fishing? Perhaps they are not. Data from the last decade of United Nations' reports suggests that global fishing yields have kept pace with increasing fishing effort. However, this simple correlation tells little of the story. Indeed, the reality of declining yields has been obscured by chronic misreporting of catches, by technological advances in gear that increase the capacity to locate and capture fish, and by shifts among industrial fishing fleets toward lower trophic-level species as the top-level predators disappear from marine ecosystems.

Do these global realities transfer to the United States? Yes. They may not transfer at the same scale, but with the addition of recreational impacts of fishing, the elements are consistent. In the 2001 report to Congress on the status of U.S. stocks, the National Marine Fisheries Service (NMFS) found that approximately one-third of the stocks for which the status was known were either overfished or experiencing overfishing. Though increasing application of conservative single-species management techniques has begun to improve conservation in recent years, it remains that current levels of fishing result in significant ecological and economic consequences. The combined effects of overfishing, bycatch, habitat degradation, and fishing-induced food web changes alter the composition of ecological communities and the structure, function, productivity, and resilience of marine ecosystems. A discussion of these ecological consequences serves as the basis for this report.

Understanding the ecological consequences of exploitation is a necessary component of ecosystem-based management, an approach called for by the NMFS Ecosystem Principles Advisory Panel in a report to Congress in 1999. It requires (1) knowledge of the total fishing mortality on targeted and incidentally caught species, including mortality resulting from regulatory discards and bycatch; (2) investigations of the links between species (e.g., predators and prey, competitors) and the habitat within which they reside; and (3) recognition of the trade-offs to biodiversity and population structure within ecosystems that result from high levels of extraction. Current fisheries practice effectively ignores these essential requirements.

Based on our review of the ecological effects of fishing, we recommend that ecosystem-based management incorporate broad monitoring programs that directly involve fishers; ecosystem models that describe the trophic interactions and evaluate the ecosystem effects of fishing; and field-scale adaptive management experiments that evaluate the benefits and pitfalls of particular policy measures. In adopting this approach, it is incumbent upon the citizens of the United States to recognize their position as the resource owners, and to properly hold the U.S. government responsible for management that ensures that benefits are sustained through time. It is also imperative that the regulatory milieu be restructured to include marine zoning designed to reduce management

error and cost, and provide sites for evaluating the effects of fishing. The regulatory milieu should also provide substantive support for law enforcement by developing enforceable regulations, require the use of vessel monitoring systems, and require permitting and licensing for all fisheries.

If we are serious about saving our fisheries and protecting the sea's biodiversity, then we need to make swift—and perhaps painful—decisions without the luxury of perfect knowledge, while still grappling for a more thorough understanding of the ecological mechanisms driving population dynamics, structuring communities, and affecting biodiversity. We must also hold the managers responsible when there is inaction. Otherwise, sustained fisheries production is unlikely.

Glossary

Bycatch is the incidental catching, discarding, or damaging of living marine resources when fishing for targeted species. Three categories of bycatch are:

- Economic discards—species with little or no current economic value, such as certain sponges, corals, skates, or targeted species in poor condition;

- Regulatory discards—individuals of commercially valuable species discarded for not meeting regulatory requirements because they are a prohibited species, an illegal size, or the quota for the species has already been filled and the fishery is closed;

- Collateral mortality—individual species killed through encounters with active or discarded fishing gear (Alverson, 1998).

Depensation is a reduction in per capita productivity of a fish population.

Ecosystem overfishing Fishing-induced ecosystem impacts, including reductions in species diversity and changes in community composition; large variations in abundance, biomass, and production in some of the species; declines in mean trophic levels within ecological systems; and significant habitat modifications or destruction. Catch levels considered sustainable under traditional single-species management may adversely affect other living marine resources, creating ecosystem overfishing.

Eutrophication is an excess supply of organic matter to an ecosystem—often because of excess nutrient loading.

A **fishery** is a targeted effort to catch a species of fish, as well as the infrastructure to support that effort.

Fishing down the food web refers to systematic removal of the largest and usually most valuable fish species in a system (explicitly top-level predators). As a result, smaller, less-valuable species (typically prey or forage species) are caught.

Fishing mortality is the level of mortality in an exploited population that is attributed to fishing activity or catch.

Ghost fishing is the mortality of fish caused by lost or discarded fishing gear.

Growth overfishing occurs when the fishing pressure concentrates on smaller fish, which limits their ability to reach their maximum biomass. The loss in biomass due to total fishing mortality exceeds the gain in biomass due to growth, resulting in a decline in the total yield.

Maximum Sustainable Yield (MSY) is the largest average catch that can be captured from a population under existing environmental conditions on a sustainable basis.*

Overfishing is a level or rate of fishing mortality that reduces the long-term capacity of a population (that is, an identifiable separate group within a species) to produce MSY on a continuing basis.

Recruitment overfishing occurs when the rate of removal of the parental stock is so high that it reduces the number of fish reaching a catchable size. It is characterized by a greatly reduced spawning stock, a decreasing proportion of older fish in the catch, and generally very low recruitment (that is, the survival and growth of young individuals) year after year.

Resilience is a measure of the ability of systems to absorb changes and persist. It determines the persistence of relationships within a system. Thus, resilience is a property of a system, and persistence (or the probability of extinction) is the result of resilience (Holling, 1973; NMFS, 2001).

Year-class is a "generation" of fish. Fish of a given species spawned or hatched in a given year. For example, a three-year-old fish caught in 2002 would be a member of the 1999 year-class.

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*The pitfalls of using this concept as a reference point for managing fisheries are many, including the fact that the maximum sustainable yield cannot be determined without first exceeding it (overfishing), and that it has been used as a target point rather than a limit. In addition, what might be deemed a sustainable yield for a single species lacks consideration for the complex relationships existing between the exploited species and its competitors, prey, and predators. Arguments for both its burial (Larkin, 1977) and its reformation (Mangel, 2002) point to its shortcomings.

I. Introduction

Gray's Reef Marine Sanctuary

Marine ecosystems are enormously variable and complex. They are subject to dramatic environmental events that can be episodic, like volcanic eruptions or meteor impacts. On the other hand, change can occur over far greater time and spatial scales, such as the advance and retreat of glaciers during the ice ages. Marine ecosystems maintain a high degree of biodiversity and resilience, rebounding from disturbances to accumulate natural capital—biomass or nutrients—and support sustained biogeochemical cycles (Holling, 1996; Pauly et al., 1998; NRC, 1999). When loss of biodiversity precipitates decreased functional diversity, the inherent unpredictability of the system increases, resilience declines, and overall biological productivity is reduced (Folke et al., 1996). Given human dependence on natural systems to support biological production from whence economic benefits are derived, it behooves us to understand how our activities affect ecosystem structure and function.

Using the crudest preindustrial fishing technologies, the human population has derived food from ocean waters, damaged marine habitats, and overfished marine organisms for millennia (Jackson et al., 2001). In the last hundred years, the percentage of marine waters fished, the sheer volume of marine biomass removed from the sea, and the pervasiveness of habitat-altering fishing techniques has cumulatively eroded marine ecosystems' capacity to withstand either human-induced or natural disturbances. Compounding the problem, but only touched upon here, are the influences of pollution, climate change, and invasive species (covered in the Pew Oceans Commission reports by Boesch et al., 2001 and Carlton, 2001).

This report provides an overview of the ecological effects—both direct and indirect—of current fishing practices. Among the consequences are changes in the structure of marine habitats that ultimately influence the diversity, biomass, and productivity of the associated biota (Jennings and Kaiser, 1998); removal of predators, which disrupts and truncates trophic relationships (Pauly et al., 1998); and endangerment of marine mammals, sea turtles, some seabirds, and even some fish (NRC, 1998). Fishing can change the composition of ecological communities, which can lead to changes in the relationships among species in marine food webs. These changes can alter the structure, function, productivity, and resilience of marine ecosystems (Figure One).

The repeated patterns of overfishing, bycatch mortality, and habitat damage are so transparent that additional science adds only incrementally to further documentation of immediate effect. Although it is always possible to find exceptions to these patterns, the weight of evidence overwhelmingly indicates that the unintended consequences of fishing on marine ecosystems are severe, dramatic, and in some cases irreversible.

The role of science should be to address these broader ecosystem effects and the interaction of fishing with other stressors in order to advance ocean management.

We address the policy implications of conventional management approaches and suggest options for reducing adverse ecological consequences to ensure the future values of marine ecosystems. There are management success stories, but they appear to be the exception rather than the rule. What is required is that we come to terms with the natural limits on exploitation.

We need to manage fisheries by redefining the objectives, overhauling the methods, and embracing the inherent uncertainty and unpredictability in marine ecosystems. This is accomplished by developing a flexible decision-making framework that rapidly incorporates new knowledge and provides some level of insurance for unpredictable and uncontrollable events. The sustainability we seek to support human needs requires resilient ecosystems, which in turn depend on a high degree of functional diversity (Folke et al., 1996).

Figure One

Ecosystem Overfishing

Fishing directly affects the abundance of marine fish populations as well as the age of maturity, size structure, sex ratio, and genetic makeup of those populations (harvest mortality). Fishing affects marine biodiversity and ecosystems indirectly through bycatch, habitat degradation, and through biological interactions (incidental mortality). Through these unintended ecological consequences, fishing can contribute to altered ecosystem structure and function. As commercially valuable populations of fish decline, people begin fishing down the food web, which results in a decline in the mean trophic level of the world catch.
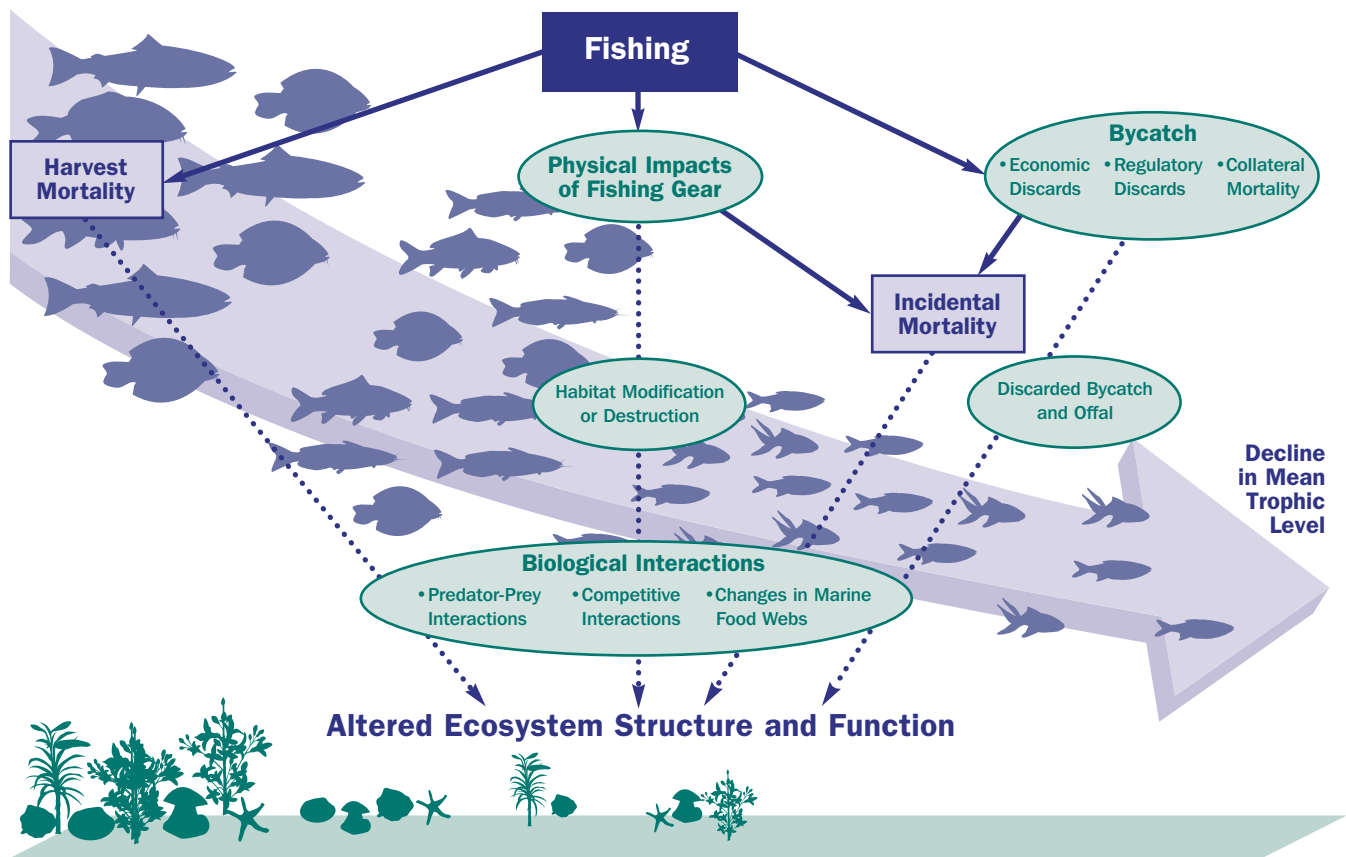
Source: Adapted from Pauly et al., 1998; Goñi, 2000.

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II. **General Effects** of Fishing

Fishing, even when not extreme, presents a very predictable suite of consequences for the targeted populations, including reduced numbers and size of individuals, lowered age of maturity, and truncated age structure. This is as true for recreational fishing as it is for commercial fishing. It is also accompanied by a less frequently predicted consequence to the ecosystems in which the exploited populations are embedded. We offer here descriptions of these fishing effects, and a discourse on the ability of marine systems to recover from them.

Extent of Fishing Effects on Target Species

Worldwide, some 25 to 30 percent of all exploited populations experience some degree of overfishing, and another 40 percent is heavily to fully exploited (NRC, 1999). Experience suggests that those populations classified as fully exploited nearly always proceed to an overfished status (Ludwig et al., 1993). Indeed, between 1980 and 1990, the number of overexploited populations increased 2.5 times (Alverson and Larkin, 1994). This is truly an unfortunate pattern because overfishing is not a necessary consequence of exploiting fish populations (Rosenberg et al., 1993).

Despite increasing levels of fishing effort, the global yield of fish—measured in weight—remained relatively constant for decades, according to reports from the Food and Agriculture Organization of the United Nations (FAO). Unfortunately, this led to shortsighted complacency among governments about the state of world fisheries. The more pessimistic view held that technological advances in gear that enhanced the capacity to locate and capture fish were keeping step to offset declines in targeted species, while the exploitation of less favored species subsidized the continued exploitation of the more valued ones.

However, reports of sustained yield proved inaccurate. Watson and Pauly (2001) revealed that decades of misreported catches obscured declining yields. In the face of increasing fishing effort, this signaled an important milestone in which the world fisheries started a decline (Figure Two).

Fisheries in the United States fare little better. The most recent report on the status of U.S. stocks reveals that of the 304 managed stocks that have been fully assessed (only 32 percent of the 959 managed stocks), just under a third are either overfished, experiencing overfishing, or both—93 out of 304 (NMFS, 2002; Figure Three on page 5). Sixty-five stocks are experiencing overfishing. Eighty-one stocks are overfished and three more stocks are approaching an overfished condition. Of the overfished stocks, 53 are still experiencing

Declines in Global Fishery Catches

Decades of inflated catch data have masked serious declines in global yield.

A.

Legend:
- Corrected
- Uncorrected
- Corrected, No Anchoveta

El Niño Events

El Niño Events

Global Catch (x 10⁶ tonnes): 90, 85, 80, 75, 70, 65, 60, 55, 50, 45, 0

1970, 1975, 1980, 1985, 1990, 1995, 2000

B.

Legend:
- Overall Marine
- EEZ Corrected
- EEZ Uncorrected

Constant Catch Mandated

Chinese Catch (x 10⁶ tonnes): 18, 16, 14, 12, 10, 8, 6, 4, 2, 0

1970, 1975, 1980, 1985, 1990, 1995, 2000
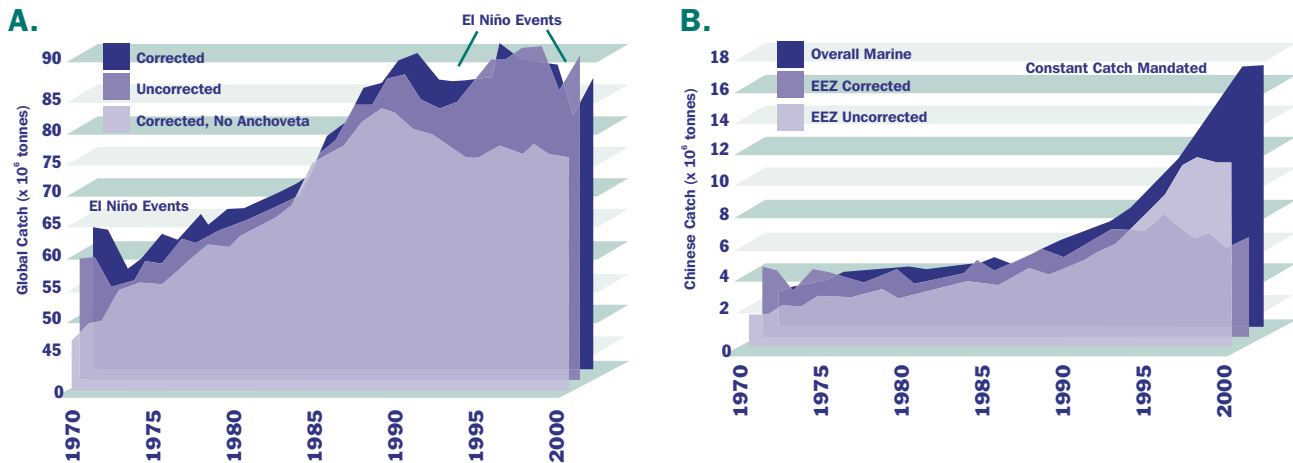
"Time series of global and Chinese marine fisheries catches…. **A.** Global reported catch, with and without the highly variable Peruvian anchoveta. Uncorrected figures are from FAO; corrected values were obtained by replacing FAO figures by estimates from **B.** The response to the 1982–83 El Niño/Southern Oscillation (ENSO) is not visible as anchoveta biomass levels, and hence catches were still very low from the effect of the previous ENSO in 1972. **B.** Reported Chinese catches (from China's exclusive economic zone (EEZ) and distant water fisheries) increased exponentially from the mid-1980s to 1998, when the 'zero-growth policy' was introduced. The corrected values for the Chinese EEZ were estimated from the general linear model [of fisheries catches]." (Watson and Pauly, 2001)

Source: Watson and Pauly, 2001.

overfishing (65.4 percent of 81 overfished stocks), frustrating efforts to rebuild those depleted stocks. Roughly 31 percent of these overfished stocks—such as queen conch in the Caribbean; red drum, red grouper, and red snapper in the Gulf of Mexico; black sea bass in the Mid-Atlantic; and white hake and summer flounder in the Northeast—are considered major stocks. Major stocks each produce more than 200,000 pound landings per year.* In an interesting move, NMFS added to its status report a new "N/A" category that includes 57 natural and hatchery salmon stocks from the Pacific Northwest. All of these stocks are listed as known stocks. Yet, none—including 20 stocks that appear on the Endangered Species List and 8 stocks considered overfished in 2000 and unchanged in 2001—is included in the overfished category.

The federal government manages some 650 additional stocks for which the status is either unknown or undefined. Many of these stocks are considered minor because annual landings per stock are less than 200,000 pounds, making their commercial value relatively low (though they may be important in an ecosystem context—a more relevant measure to ensure conservation). The fact that relatively few (28 percent) of the minor stocks that have been assessed are considered overfished should not lull us into a state of complacency. The truth is that we know pitiably little about the status of nearly 81 per-
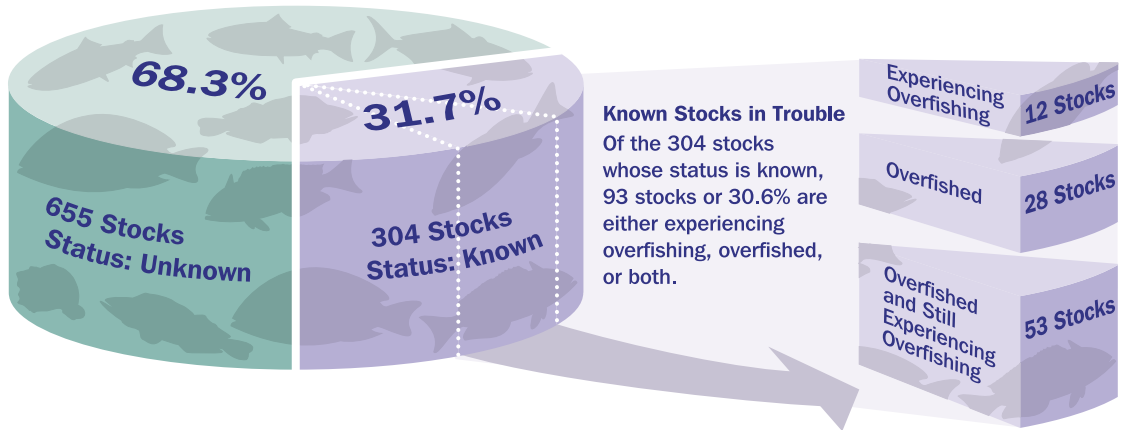
*In 2001, 295 major stocks produced the majority of landings, totaling more than 8 billion pounds, compared to 9 million pounds from 664 minor stocks.
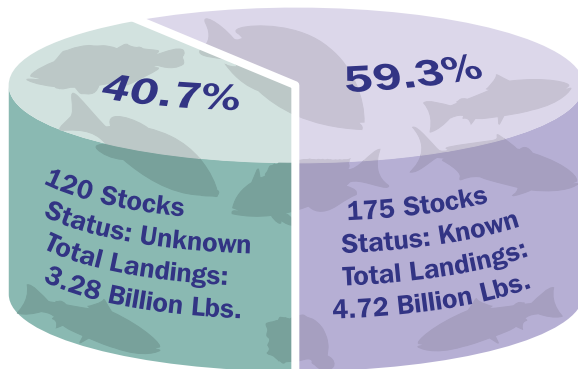
Status of Marine Fish Stocks

The U.S. Department of Commerce listed 959 stocks in its 2001 Annual Report to Congress on the Status of U.S. Fisheries. The data in the pie charts below are drawn from information in the annual report.

A. Status for 959 Stocks in 2001

68.3%

655 Stocks
Status: Unknown

31.7%

304 Stocks
Status: Known

Known Stocks in Trouble
Of the 304 stocks whose status is known, 93 stocks or 30.6% are either experiencing overfishing, overfished, or both.

Experiencing Overfishing — 12 Stocks

Overfished — 28 Stocks

Overfished and Still Experiencing Overfishing — 53 Stocks

B. Status for 295 Major Stocks* in 2001

40.7%

120 Stocks
Status: Unknown
Total Landings:
3.28 Billion Lbs.

59.3%

175 Stocks
Status: Known
Total Landings:
4.72 Billion Lbs.

C. Status for 664 Minor Stocks in 2001

80.6%

535 Stocks
Status: Unknown
Total Landings:
7.29 Million Lbs.

19.4%

129 Stocks
Status: Known
Total Landings:
1.71 Million Lbs.
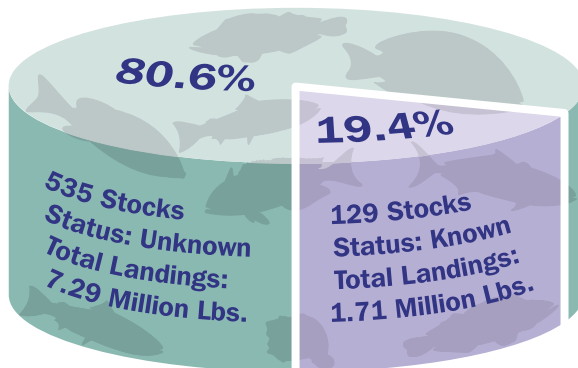
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*Major stocks are those with landings of at least 200,000 pounds. In 2001, 295 major stocks produced the majority of landings, totaling more than 8 billion pounds, compared with 9 million pounds from 664 minor stocks.

cent of these minor stocks, even though they are fished or perhaps overfished, and we still cannot determine the status of 40.7 percent of the major stocks that produce the vast majority of annual landings (Figure Three).

Absence of information should not be construed as absence of a problem. In some cases, these stocks may even be overfished. History reveals that minor stocks have a way of becoming major ones as other species decline. In addition, many of these minor stocks, including some species of snappers and groupers, have life history characteristics and behaviors that are quite similar to those of closely related overfished stocks. Thus, we can forecast their likely vulnerability to overfishing.

As the status of unknown stocks becomes known, undoubtedly some will require management to end or prevent overfishing (NMFS, 1999). In some regions of the country and for some important fisheries, this may mean developing management plans directed primarily at reducing fishing mortality effected by the recreational fishing sector. Although the recreational sector appears to contribute minimally to the total annual U.S. fishery landings—usually considered to be about 2 percent when landings from Alaska pollock and menhaden are considered— quite a different picture emerges if one considers those populations experiencing both recreational and commercial fishing pressures. In these cases, the recreational fishery can emerge as a very important source of mortality for a number of species, with pressure predominantly exerted on top-level predators rather than forage species in

marine ecosystems. In the Gulf of Mexico, for instance, recreational catches exceed commercial catches for many of the principal species landed in that region (Figure Four).

Figure Four

Recreational Fishing

Allocation of total catch (by weight) of the principal finfish species contained in the management plan for the Gulf of Mexico, as defined in the NMFS Report to Congress on the 2001 Status of Fisheries. Note: We used the landings data for the year 2000 to create this graph because the 2001 landings data on recreational fisheries were not available on the NMFS website at the time of this writing. The NMFS website notes that the catch weights for the recreational fishing component are likely underestimated.

Recreational Fishing
Commercial Fishing
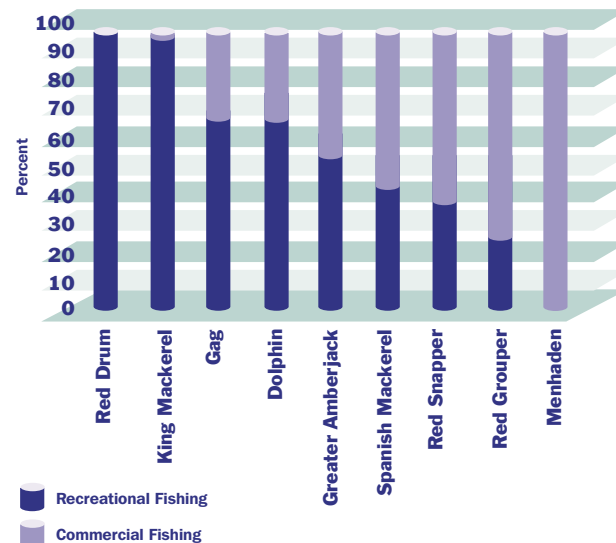
Source: NMFS, 2002.

Is it Climate or Fishing?

What puts populations at greater risk? Is it natural environmental change or human-induced effects? This is the subject of fierce debate in nearly every major fishery decline. Certainly, ocean climate shifts are associated with collapses (Francis, 1986; McGowan et al., 1998; Anderson and Piatt, 1999). Situations in which excessive fishing is the principal cause of collapse are also certain (Richards and Rago, 1999; Fogarty and Murawski, 1998). However, severe

population and fishery declines often involve some combination of environmental and fishing effects (NRC, 1999). While it is academically interesting, the continued debate over which is more important only delays implementation of precautionary policy that acknowledges the inherent variation and unpredictability in marine ecosystems.

Ecological Consequences of Fishing

By its very nature, fishing can significantly reduce the biomass of a fish species relative to its unfished condition. Therefore, the most significant ramification may be decreased prey availability for predators in the ecosystem. To some extent, fishing concentrated in space and time may exacerbate the large-scale reduction in overall biomass, increasing the likelihood of localized prey depletion (NMFS, 2000; DeMaster et al., 2001). Fishing may therefore appropriate fish or other types of biological production, forcing dietary shifts among predators from preferred to marginal prey of lower energetic or nutritional value. Also, if fishing pressure is sufficiently intense on alternative populations that it compromises a predator's ability to make adequate dietary shifts, the result may be reduced foraging opportunities and reduced growth, reproduction, and survival, as seen in both Humboldt and African penguins (Crawford and Jahncke, 1999; Tasker et al., 2000) and suggested for Steller sea lions (NMFS, 2000).

Fishing may indirectly affect trophic links

by removing species that initiate schooling behavior in their prey, making that prey unavailable to other predators. For instance, seabirds that are less well adapted to diving depend on subsurface predators such as tuna, billfish, and dolphins to make dense prey aggregations available to them at the ocean surface (Ballance et al., 1997; Ribic et al., 1997). They may lose feeding opportunities when fishing removes these predators (Ballance, personal communication). The opposite side of this particular coin is that removal of one predator may create additional feeding opportunities for others, encouraging their population growth (Tasker et al., 2000). Regardless, these are the first-line symptoms of disrupted food webs.

Acquiring information on predator-prey and competitive interactions is essential to understanding the impact of fishing on natural systems. However, getting the qualitative and quantitative measures necessary to show a relationship between these interactions and fishery production presents an enormous challenge, both logistically and conceptually. Logistically, it means a significant investment in basic ecological study and monitoring. Conceptually, it means a change in perspective from a single-species approach in which maximum sustainable yield is a goal, to acknowledging that fishery production is entirely dependent on functioning ecosystems. We are not there yet. Although we can reconstruct the cascading trophic events that led to the decline of kelp

communities (Box One on page 9), and we can trace the growth of krill populations to a decline in the whales that consume krill, there are very few other data available on trophic interactions in marine systems (Pinnegar et al., 2000). At best, we rely on inferential and corroborative evidence to make the case (Pitcher, 2001).

Fortunately, ecological models are proving useful in this regard. Kitchell and others (1999) used trophic models of the central North Pacific to demonstrate the extraordinarily diverse roles top-level predators play in organizing ecosystems. For instance, they found that fishery removals of some large predators—sharks and billfish—resulted in only modest ecosystem impacts, such as shifts in their prey. However, the removal of other top-level predators like the more heavily targeted fishery species—such as yellowfin and skipjack tuna—affected entire suites of competitor and prey species for sustained periods and constrained the species that persisted in the system.

Serial Depletion

The next set of ecological ramifications of fishing involves the shift from prized species to related, but perhaps less valuable, species as the prized ones decline in abundance. When these less valuable species then decline, fishermen move to yet another species and so on. This sequential or serial overfishing of different species is characteristic of overfished ecosystems (Murawski, 2000). It is a contributing factor in the decline of entire assemblages of

commercially valuable populations (Tyler, 1999). This is a widespread problem occurring among groundfish in the Northeast, rockfish on the Pacific coast, reef fish in the Gulf of Mexico, and contributing to severe declines in crustacean fisheries in the Gulf of Alaska (Orensanz et al., 1998; Fogarty and Murawski, 1998).

Effects on Marine Food Webs of Removing Top-Level Predators

Another ecological shift among exploited populations is the shift from higher trophic levels to lower ones. That is, subsequent to removing the top-level predators—the larger, long-lived species—to the point of fishery closure or economic extinction, we then fish for their prey. The result? A decline in the mean trophic level of the world catch—a direct consequence of how we fish, revealed through ecosystem-level analyses of fishing.

This "fishing down the food web" is a top-down ecological problem, having its greatest documented influence through the removal of predators at the peak trophic levels with concomitant changes among their competitors and prey (Pauly et al., 1998). Examples of truncated trophic webs occur worldwide. In the Gulf of Thailand, for instance, the elimination of rays and other large, bottom-dwelling fish resulted in a population explosion of squid (Pauly, 1988). In addition to trophic shifts, the changes often reveal unexpected linkages among species not normally considered to interact (Box One on page 9).

"This sequential or serial overfishing of different species is characteristic of overfished ecosystems."

Kelp Forest Ecosystems: Case Studies in Profound Ecosystem Alterations Due to Overexploitation

Large seaweeds, such as kelp, which furnish structure and food for a highly diverse and productive ecosystem, are typical of hard-bottom habitats in all cold-temperate seas. Their productivity rivals that of the most productive terrestrial systems and they are remarkably resilient to natural disturbances. Yet, kelp ecosystems are destabilized to such an extent by the removal of carnivores that they retain only remnants of their former biodiversity (Tegner and Dayton, 2000).

In the United States, kelp systems occur along the Pacific coast and in the northwest Atlantic. All have suffered severe declines because of exploitation that may have started thousands of years ago. In the North Pacific, aboriginal hunters probably caused the disappearance of the huge kelp-eating Steller's sea cow as well as population declines in sea otters, and a consequent increase in the number of sea urchins—a principal prey of the otters. Without effective control of their populations by predators, sea urchins often completely overgraze the seaweeds. The shift from a carnivore-dominated system to a sea urchin-dominated system triggered the collapse of kelp communities (Simenstad et al., 1978). Although sea otters recovered to some extent, Russian fur hunters nearly exterminated the animals through the 1800s. One hypothesis suggests that more recent sea otter

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declines result from predation by killer whales seeking alternative prey in a system depleted of their normal prey (Estes et al., 1998).

In the northwest Atlantic, large predatory fish—especially halibut, wolffish, and cod—rather than sea otters are key predators of sea urchins and crabs. Heavy fishing of these large fish, beginning 4,500 years ago and peaking in the last century, dramatically reduced their abundance, allowing sea urchin populations to explode and overgraze the kelp (Witman and Sebens, 1992; Steneck, 1997). More recently, the sea urchin population has been subjected to intense fishing, which, together with widespread diseases, has led to the collapse of the population. Left in the wake, a once productive kelp habitat is now characterized by a community of invasive species with little economic value (Harris and Tyrrell, 2001).

Effects on Marine Food Webs of Removing Lower Trophic-Level Species

Lower trophic-level species—like sardines, herring, and anchovies—typically mature rapidly, live relatively short lives, and are extremely abundant. As a result, they are among the most heavily exploited species in the world.

Single-species models, particularly those based on maximum sustainable yield, suggest that lower trophic-level species have tremendous potential for sustainable exploitation. Ecosystem models, on the other hand, present a more sobering view. First, these models suggest that heavy exploitation could effect

increased populations of their competitors, and declines in populations of their predators. Second, ecosystem models suggest that large removals of forage species could work synergistically with heavy nutrient loading to exacerbate problems of eutrophication in enclosed coastal ecosystems (Mackinson et al., 1997). Thus, intense harvesting of these species can affect ecosystems in two different directions—from intermediate levels up and from intermediate levels down.

Bottom-Up Effects

There are, in fact, few data revealing bottom-up interactions resulting from fishing species at intermediate trophic levels. Suggestive, however, are reports that intense exploitation of menhaden negatively affects their predators. Menhaden stocks support one of the largest fisheries in the southeastern United States. It also serves as an important food source for many of the top-level predators in marine food webs—such as mackerel, cod, and tuna. Population declines associated with intense fishing for menhaden* are correlated with body condition declines in striped bass, which, in the face of fewer encounters with menhaden, pursue alternate prey of lower caloric value (Mackinson et al., 1997; Uphoff, in press).

Top-Down Effects

The intense exploitation of menhaden to some extent (Gottlieb, 1998; Luo et al., 2001) and of oysters to a greater degree (Boesch et al., 2001) is linked to increased eutrophication of the

Chesapeake ecosystem through the loss from the system of these important filter feeders. Oysters present the best example. Before the mechanized harvest of oysters and the significant decline of oyster reefs in the late 19th century, oysters in the Chesapeake Bay were considered abundant enough to filter a volume of water equivalent to the volume of the bay in just three days. Their removal of phytoplankton and other fine particles from the water allowed sufficient light penetration to support extensive seagrass beds. Furthermore, oyster reefs provided habitat for a diverse range of both benthic and swimming organisms.

Oyster reefs largely disappeared by the early 20th century. This reduced oyster filtration capacity, making the ecosystem more susceptible to algal blooms associated with increased nutrient loading in the bay during the late 20th century. Indeed, it takes the present-day oyster population six months to a year to filter the same volume of water that it once could filter in a matter of days (Newell, 1988). Restoring oyster biomass to enhance biofiltration and habitat is inhibited by the scarcity of suitable hard substrates—largely removed through unsound harvesting activities—and disease mortality resulting from an introduced pathogen.

Cumulative and Synergistic Impacts

The cumulative or synergistic contributions of top-down and bottom-up effects on ecosystems can be difficult to detect (Micheli, 1999) and equally difficult to tease apart into indi-

"...large removals of forage species could work synergistically with heavy nutrient loading to exacerbate problems of eutrophication in enclosed coastal ecosystems."

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*Menhaden stocks have cycled between extreme highs (1950s) to moderate highs (1970s), and extreme lows (1960s) to moderate lows (1980s), resulting in significant fishery cutbacks. However, recent low recruitment levels do not appear to be due to overfishing. They more likely result from either habitat loss or increased predation (Vaughan et al., 2001; Vaughan et al., 2002). Therefore, reduced fishing mortality may have little to no effect on the recovery in this stock—although it would certainly leave more menhaden for predators to consume until the stock begins to rebound and fishing mortality could be increased.

vidual stresses (Boesch et al., 2001b). Although Micheli (1999) in a recent meta-analysis* of bottom-up and top-down pressures on marine food webs detected changes only across a single trophic level, she acknowledged that this was more likely because of insufficient information about the relationship than it was absence of an effect. The most important lesson derived from these models is that fishing impacts on ecosystems are diffuse, diverse, and difficult to predict.

To the list of concerns—fishing, pollution, climate change, eutrophication, and disease— we would add the effects of intensive aquaculture for consideration in the context of cumulative impacts. Although aquaculture affects a relatively small amount of acreage in the coastal habitats of the United States (Goldberg, 1997), it has resulted in significant loss of habitat in many developing nations (Naylor et al., 2000) and it is responsible for the spread of invasive species worldwide (Naylor et al., 2001). This should serve as a warning to heed as aquaculture develops in the United States.

Challenges to Recovery of Overfished Species

Fisheries scientists disagree about the ability of marine fish to resist declines in abundance in the face of intense exploitation. Although they all acknowledge the problem of growth overfishing, some have found no relevant relationship between population size and recruitment, making recruitment overfishing unlikely. This view followed from the high reproductive

potential of most exploited populations, and the classic notion that fish compensate for fishery removals with strong recruitment— that is, the per capita production of offspring could be maximized at low population densities. Indeed, many species of fish do produce huge numbers of young, from the relatively short-lived sardines, to grouper that survive for dozens of years and to the sometimes century-old rockfish. Some fish species also have remarkable compensatory growth capabilities in the face of exploitation. These characteristics led Thomas Huxley to state at the Great International Fishery Exhibition in London in 1884, "…nothing we do seriously affects the number of fish."

This misperception still haunts fishery management more than 100 years later. Fishing not only alters the abundance of stocks, but it also affects the age of maturity (McGovern et al., 1998), size structure (Hilborn and Walters, 1992), sex ratio (Coleman et al., 1996), and genetic makeup of populations (Chapman et al.,1999; Conover and Munch, 2002). The relationship between the abundance of spawners in populations and the strength of subsequent year-classes of recruits is often hard to measure empirically, but it can be both significant and positive (Brodziak et al., 2001; Myers and Barrowman, 1996). Thus, recruitment overfishing is not only possible but is largely responsible for the poor condition of stocks that have been managed without regard for maintaining the abundance of the spawning stock, as indicated in

*Summary statistical analyses across separate studies

northern cod stocks off the Atlantic coast of Canada (Myers and Barrowman, 1996; Myers et al., 1997). Further, in terms of recruit production per spawner biomass, some areas are more productive than other areas (MacKenzie et al., 2002). This important aspect of recruitment variability should be addressed in ecosystem-based management approaches.

An obvious means of improving spawner abundance is to reduce fishing mortality. However, attempts to effect meaningful reductions in fishing mortality are often compromised by stock assessments that overestimate stock size and by political interference that blocks managers from reducing catches. The result is a quota often set too high for sustainability (Walters and Maguire, 1996). Spawner abundance can be increased to some extent by instituting size limits that increase the age at which fish are caught, although this method sometimes has significant limitations (see pages 17–18).

Reduced Reproductive Potential of Populations

An important consequence of the way we fish has been a reduction in the mean fecundity across all age groups and often the disappearance of the largest, most fecund individuals. Larger fish produce far more eggs than smaller fish, demonstrating an exponential rather than linear relationship between fecundity and size. In addition, larger fish produce superior eggs (e.g., larger eggs that contain greater amounts of stored energy and growth hormones) than

National Geographic Society

Gag, *Mycteroperca microlepis*

do smaller fish. Unfortunately, models of reproductive output assume that all eggs are equal.

It is easy to see where the problem lies for a species like gag (*Mycteroperca microlepis*). Female gags may start reproducing at age 3 or 4; males at age 8. Gag live for 30 to 35 years, giving them a reproductive life span of several decades. During the time they are reproductively active, gags more than double their total length. Most of the fish caught, however, are 2 to 5 years old; fish older than 12 years of age are rarely encountered. Truncating the age structure of the population means that the largest and most fecund fish no longer exist in fished populations.

The problem of truncated age structure is exacerbated in hermaphroditic species. For instance, gag changes sex from female to male when they reach a certain age and size. Thus, larger gag in spawning aggregations would typically be males. Fishing that seasonally concentrates on spawning aggregations removes the largest fish. Over the last 20 years, the sex ratio has changed from a historic level of 5

females to 1 male to a ratio of 30 females to 1 male (Coleman et al., 1996). Stock assessments erroneously treat this declining male-to-female ratio as though it represents complete loss of the larger size classes instead of a much more significant loss of an entire sex.

Aggregating Behaviors Increase Vulnerability

Species that aggregate to spawn are often targeted by fishers who know where and when the aggregations occur (Ames, 1998; Dayton et al., 2000). Not only are individuals removed from populations, but also entire aggregations can be eliminated. A spawning aggregation, once eliminated, may never recover. Intense fishing pressure on Nassau grouper (*Epinephelus striatus*) and Goliath grouper (*Epinephelus itajara*) resulted in the rapid disappearance of many spawning aggregations. In 1990, the Gulf, Caribbean, and South Atlantic Fishery Management Councils effected complete fishery closures for these grouper species to protect the remaining populations throughout the United States (Sadovy and Eklund, 1999). The same phenomenon occurred in the population of pelagic armorhead (*Pseudoentaceros wheeleri*), which aggregates on seamounts along the ocean floor of the Hawaiian Islands (Boehlert and Mundy, 1988; Somerton and Kikkawa, 1992) and holds true for several species of abalones, especially white abalone, now perilously close to extinction in southern California (Tegner et al., 1996). When reproductive success depends on experienced fish leading novices to breeding sites, the loss of leaders results in reduced spawning success, another

complexity inadequately addressed by most management regimes (Johannes, 1981; Coleman et al., 2000).

Depensation: Are There Critical Thresholds for Population Size?

If population size falls below some critical level, per capita reproduction could decline significantly. The causes of this reduction in per capita productivity—known as depensation—are not well understood. Sedentary animals such as abalone, scallops, clams, and sea urchins need to exist in dense patches of closely packed individuals (a few meters apart) to ensure fertilization (Lillie, 1915; Stokesbury and Himmelman, 1993; Tegner et al., 1996; Stoner and Ray-Culp, 2000). These animals stop reproducing when density declines. On the other hand, reviews of heavily exploited North Atlantic and North Pacific populations by Myers and others (1995) and Liermann and Hilborn (1997) indicate that, in general, none of the population collapses could be attributed to depensation. The life histories of fish species explain this difference: the highly migratory species find mates; the less mobile species are very vulnerable to depensation.

The warm-temperate or tropical species that change sex and are fished while spawning are more likely to exhibit depensation. In addition, ecosystem relationships may play a role in depensation. Walters and Kitchell (2001) offer an example of depensation occurring because of a fishery-induced food web shift. In this case, declines in abundance of top-level predators lead to increased abundance of forage species, which are intermediate-level predators. When they are

no longer cropped by predation, the forage populations prey upon the juveniles of their predators. The result is decreased juvenile survival, which drives down top-level predator populations further. No single-species model could predict these types of consequences.

Increased Susceptibility to Environmental Variation

Fish reproduce in highly variable environments that can significantly affect reproductive success. Therefore, a population with reduced reproductive output is more susceptible to environmental vagaries than one protected by the "insurance" of large population size, longevity, and diverse age structure. In ecosystems where fishing has precipitated significant changes in the composition of marine communities, and thus the interactions of resident species, uncertainty is introduced that confounds our ability to pinpoint cause and effect. This has led many observers to consider "cascading" effects, where overexploitation increases the chances that dynamic environmental effects or ecosystem-level changes will interact with fishing to produce collapses, or prevent or prolong recovery (NRC, 1996).

Reversing Effects of Fishing: Do Populations Always Recover?

The ability and speed with which a population recovers depends largely on the life history characteristics of the species and the natural history of the community within which the species is imbedded. Myers and others (1995) found that reduced fishing mortality rates would lead to population recovery in cod, plaice, hake, and other

economically important species. Recovery appears to be the rule rather than the exception. Hutchings (2000), however, suggests that recovery depends on the individual population's resilience. Thus, some species—herring sardines, anchovies, and menhaden—that mature at relatively young ages and feed lower on the food chain, tend to respond more rapidly to reduced fishing pressure than do species that mature late and live longer. Less resilient species include warm-temperate and tropical reef fishes such as snappers and groupers in the southeastern United States (Polovina and Ralston, 1987; Musick, 1999), Pacific Coast rockfish (Leaman, 1991), and deep-sea fishes worldwide (Koslow et al., 2000). The marbled rock cod (*Notothenia rossi*) fishery of the Indian Ocean, for instance, which collapsed in the 1960s, has not recovered to fishable levels despite complete fishery closures. Similarly, the wild population of the black-lipped pearl oyster (*Pinctada margaritifera*) in the northwest Hawaiian Islands, which produced more than one hundred tons of catch in 1927, declined to fewer than ten individuals by the year 2000 (Landman et al., 2001; Birkeland, personal communication). For whatever reasons—including the possibility of depensation—this species is virtually extinct in the wild throughout the entire chain of Hawaiian Islands.

There are some success stories, however. The mid-Atlantic striped bass fishery, which declined because of recruitment overfishing in the early 1980s, recovered in less than 15 years. The recovery resulted from implementation of fishing moratoria in some states and increased size limits (effectively raising the age of first capture from 2 to 8 years) in other states (Field,

"...a population with reduced reproductive output is more susceptible to environmental vagaries than one protected by the "insurance" of large population size, longevity, and diverse age structure."

1997; Richards and Rago, 1999).*

Examples of overexploited stock populations that may be approaching recovery include Atlantic sea scallops (Murawski et al., 2000), some northeastern ground fishes (NOAA, 1999), Atlantic mackerel, and to a lesser extent, herring (Fogarty and Murawski, 1998). Scallop recovery can be credited to the establishment of large area closures. Similarly, northeastern groundfish rebuilding is due to the same area closures and to dramatic reductions in fishing mortality. Atlantic herring and mackerel recoveries appear to result from the combined effects of dramatically lower fishing pressure and reduced predation pressure resulting from depleted groundfish populations such as cod, pollock, and silver and white hake (Fogarty and Murawski, 1998). Illustrating the challenge of successful fishery restoration, most of those stocks still have a long way to go before they can be considered recovered (Figure Five).

The Possibility of Extinction

One of the growing concerns is that population collapse could threaten a species' persistence. Certainly, changes in marine communities that bring about species replacements make recovery less likely. This is a complete reversal from the once prevailing view that marine species were immune from extinction. However, the litany of species driven to that state by human activities—the Atlantic gray whale, the Caribbean monk seal, the Steller's sea cow, and the great auk—has removed our naiveté (Vermeij, 1993; Roberts and Hawkins, 1999). If we desire further evidence, we need only look at the long list of marine animals considered at risk of extinction under current

ecosystem conditions. The list includes northern right whales, the Hawaiian and Mediterranean monk seals, the Pacific leatherback turtle, several species of California abalone, and fish species such as Coelacanths, the Irish ray, the barndoor skate, bocaccio, and some 82 other marine fish species in North America (Musick et al., 2000). In addition, as Hutchings (2000) clearly points out, ignoring the potential for marine fish to go extinct is inconsistent with U.S. interests in precautionary fisheries management and the conservation of marine biodiversity.

Figure Five

The Challenge of Rebuilding Overfished Stocks
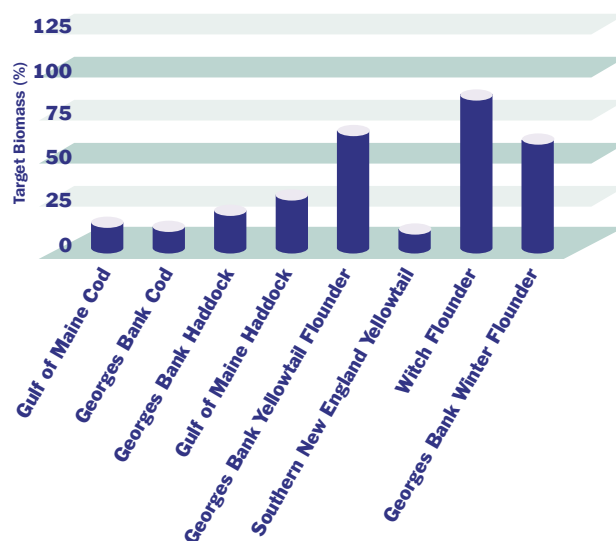
Once abundant off New England's coast, many groundfish have been depleted and have only recently begun to rebuild under aggressive conservation measures. Though their populations are on the rise, many have a long way to go before they recover. The famed Georges Bank cod population, for instance, is estimated to be less than a third of the size it was just 20 years ago. Most of the major New England groundfish stocks are currently below their target population levels, and many are far from approaching the population abundance (target biomass) that would support maximum sustainable yield.

Source: NEFSC, 2002.

Note: The eight species in this graph were selected from the NEFSC report because they are the principal FMP species listed in the NMFS 2001 Annual Report to Congress on the Status of U.S. Fisheries and the species whose status is known.

*Recovery of striped bass, however, may contribute to low recovery potential in Atlantic menhaden populations. See footnote on page 10.

III. Bycatch

"Economics and technology rather than ecological principles, have determined the way an ecosystem is exploited."
(M. Hall et al., 2000)

The significance of bycatch mortality on exploited fish populations and wild populations of otherwise unexploited species around the world varies widely. Its effect on ecological communities is proving more substantial, as evidenced in a persuasive and growing body of literature on the important ecological roles played by affected species: "the magnitude, complexity, and scope of the bycatch and unobserved fishing mortality problem will require priority attention well into the next century" (Alverson, 1998).

Bycatch monitoring should be considered an essential component of stock assessment. Although monitoring has increased in recent years, it still involves less than one-third of the fisheries in the United States (Alverson, 1998). Compiling this bycatch data is critical for two reasons. First, the inclusion of bycatch mortality data in fishing mortality analyses provides a more realistic assessment of stock health (Saila, 1983). Second, information is necessary to identify potential solutions. This is best demonstrated by efforts to reduce the incidental killing of dolphins in the eastern Pacific Ocean tuna fishery.

Causes of Bycatch and Effects on Marine Species

Bycatch fundamentally results from the limited selectivity of fishing gear (Alverson, 1998; NOAA, 1998b). It occurs in active fishing gear. It also occurs in gear that is lost at sea but continues to fish unattended. Marine species whose reproductive or foraging behaviors bring them in contact with fishers are particularly vulnerable. These include sea turtles that nest on beaches close to shrimping grounds, and seabirds, marine mammals, sharks, rays, and other species that share the same prey and feeding grounds as the targeted populations. Other species that are attracted to vessels to scavenge discards are often accidentally caught as well.

Species with low reproductive rates suffer the greatest population-level consequences of bycatch mortality. Seabirds, marine mammals, sea turtles, most sharks and rays, and some long-lived finfish all fall into this category. Colonial invertebrates, such as sponges, bryozoans, and corals, which have limited dispersal capabilities, are also affected. In most cases, the death of these important invertebrates is never recorded. For species that already have small populations or limited geographic ranges, it takes only the loss of a few breeding-age specimens or colonies to have strong nega-

tive effects on population size and stability. In many cases, the underestimation of bycatch mortality leads to overly optimistic estimates of the environmental impact of fishing as a whole (Mangel, 1993; Pitcher, 2001).

Discards of Economically Important Species

People are generally more concerned about collateral mortality caused by the bycatch of "charismatic megafauna"—marine mammals, seabirds, and sea turtles—than they are about bycatch of fish and invertebrates. Yet, billions of finfish, corals, sponges, and other habitat-forming invertebrates caught incidentally every year are damaged or discarded for a variety of reasons.

Size limits are a significant source of regulatory discards and subsequent mortality of otherwise targeted species in commercial fisheries (Chopin and Arimoto, 1995) and recreational fisheries. In the commercial Canadian Atlantic cod fishery, juvenile cod discards represent the removal of 33 percent of the young fish that would eventually have recruited into the fishery (Myers et al., 1997). In the commercial gag and red grouper fisheries, under-sized fish constitute as much as 87 percent of the total catch (Johnson et al., 1997). To a fisherman, throwing away otherwise useful fish because of regulatory requirements is perhaps the greatest tragedy of single-species management practices. Many fishermen would far rather see the use of more ecologically sound management tools.

Discarding is not always based on regulatory limitations. Indeed, high grading can represent a major source of discards in all fishery sectors that are value-based. Here, fish are caught and either discarded immediately because of nonexistent market values (commercial high grading), or they are held until they can be replaced with larger, more valued fish (commercial or recreational high grading).

Catch-and-release practices—in which fish are caught purely for sport and intended for release—are solely the province of recreational fisheries. Many fishers certainly feel justified in doing this based on their contributions to tagging programs, which presumably provide a service to managers by developing information on movement patterns, age and growth, and abundance. Tagging programs are particularly popular in high-end recreational fishing for ocean pelagics such as billfish, tuna, and mackerel, but the mortality that results from catching and "playing" these large fish for extended periods can be substantial and ecologically significant. Even relatively shallow-water species can be affected. For example, the mortality rates for some of these species ranges from 26 percent in striped bass (*Morone saxatilis*) to 45 percent for red drum (*Sciaenops ocellatus*) to as high as 56 percent for spotted sea trout (*Cynoscion nebulosus*) (Policansky, 2002).

Discards of economically important species also occur in fisheries not targeting those species. For example, discard rates of the juvenile stages of red snapper, Atlantic menhaden, and Atlantic croaker in the Gulf of

Mexico are sufficiently high enough that they have demonstrable population-level effects on those species. Gulf shrimp trawls catch some 10 million to 20 million juvenile red snapper each year (Hendrickson and Griffin, 1993)—more than 70 percent of each new year-class. This is of significant biological consequence to the currently overfished red snapper populations. It also presents an important social consequence because it pits the two most valuable fisheries in the Gulf—the red snapper fishery and the shrimp fishery—against one another (NRC, 2001). Bycatch of juvenile Atlantic croaker and Atlantic menhaden in trawl fisheries appears to reduce population growth rates, thus affecting production in these species (Quinlan, 1996; Diamond et al., 2000).

The mortality of discards in commercial and recreational fisheries depends on how the fish are captured and handled. Harsh treatment results in higher mortality. Even gear modifications intended to reduce incidental capture are not without flaws. Modifications designed to increase gear selectivity (e.g., larger net mesh, bycatch reduction devices) result in organisms escaping through gear rather than providing a means of avoiding the gear altogether. But passage through these devices can lead to delayed mortality from injury, stress-induced diseases, or increased risk of predation (Chopin and Arimoto, 1995). It is important to note that these sources of mortality go largely unnoticed, are rarely included as factors contributing to fishing mortality, and do not often appear in stock assessments.

Seabirds

Interactions between fishing vessels and seabirds occur in every ocean of the world, involving virtually all fisheries and at least 40 different species. Most of these interactions are a direct consequence of seabirds foraging in the same regions as vessels are fishing, or an indirect consequence of their attraction to the vessels to scavenge from hooks or offal.

Bycatch of albatrosses, petrels, and shearwaters in longline fisheries is one of the greatest threats to seabirds worldwide (Robertson and Gales, 1998; Tasker et al., 2000). For example, Patagonian toothfish long-liners killed around 265,000 seabirds between 1996 and 1999, resulting in unsustainable losses to breeding populations (Tasker et al., 1999). In the northwestern Hawaiian Islands, where the total breeding population of the black-footed albatross is 120,000 birds, annual fishing-relat-

"Bycatch of albatrosses, petrels, and shearwaters in longline fisheries is one of the greatest threats to seabirds worldwide."

D.H.S. Wehle

Northern Fulmar, *Fulmarus glacialis*

ed mortalities of 1,600 to 2,000 birds are significant (Cousins and Cooper, 2000). Less well understood are the threats from other U.S. longline fisheries, including the Pacific cod fishery that annually takes some 9,400 to 20,200 seabirds—primarily northern fulmars (*Fulmarus glacialis*) (Melvin and Parrish, 2001). Bycatch of the extremely endangered short-tailed albatross is also of concern in Alaska and Hawaii longline fisheries, though the Alaska industry has made significant progress in avoiding albatrosses in recent years.

Bycatch of shearwaters and auks in gill-net fisheries also threatens seabirds worldwide (Piatt et al., 1984; DeGrange et al., 1993). In the United States, attention to seabird bycatch in coastal gill-net fisheries has been minimal despite the fact that breeding colonies and gill-net fisheries occur in these areas (Melvin et al., 1999). In fact, managers have long known about problems in gill-net fisheries. Takekawa and others (1990) found significant bycatch problems for a variety of seabirds in Monterey Bay's white croaker gill-net fisheries that extended back to the late 1970s. These facts suggest that fisheries managers should investigate seabird bycatch concerns in the gill-net fisheries off New England and along the Pacific coast from California to Alaska.

Marine Mammals

Bycatch is a major factor contributing to the significant decline of many marine mammal populations (Hall, 1999). Of the 145 marine mammal populations in U.S. waters, 44 popu-

lations (30 percent) either suffer high rates of bycatch or are at risk of extinction. Thirteen of the 44 (30 percent), caught primarily in coastal gill-net fisheries and to a lesser extent in offshore drift gill-net fisheries, currently suffer bycatch mortality that exceeds sustainable levels (NOAA, 1998b). This is consistent with the fact that marine mammal bycatch is typically highest in gill-net and drift-net fisheries (Dayton et al., 1995). For example, the swordfish drift-net fishery in the Atlantic has a long-term bycatch average of at least one marine mammal per overnight set (NOAA, 1998b). Historically, bycatch in other fisheries has also been significant, including the considerable bycatch of dolphins in Pacific tuna purse seine fisheries (Goni et al., 2000). Likely most threatened are the small coastal porpoises that are especially susceptible to gill-net fisheries. The very small vaquita, or Gulf of California harbor porpoise, has suffered such high mortality rates in coastal gill nets that it is threatened with extinction (Rojas-Bracho and Taylor, 1999).

Sea Turtles

While a number of factors have contributed to the dramatic decline of sea turtle populations, fishing is the single largest factor preventing population recovery (NRC, 1990). The greatest U.S. source of sea turtle mortality stems from the shrimp trawl fisheries. Until the 1990s, these fisheries caused more sea turtle deaths than all other sources of human-induced mortality combined (NRC, 1990).

Despite the fact that the turtle excluder

Loggerhead Sea Turtle, *Caretta carretta*

devices (TEDs) in shrimp trawl nets have the potential to make major contributions to population recovery (Crowder et al., 1995) and their use is mandated in all shrimp and in some of the summer flounder trawl fisheries, these fisheries still report significantly high mortality levels of sea turtles (NOAA, 1999). This may be strictly a matter of gear design. The TED design outlined in TED regulations appears to effectively exclude the relatively small Kemp's ridley sea turtles, and the size of nesting populations of this species is increasing (NOAA, 1998b). The prescribed escape opening, however, has proven too small to allow release of the much larger adult loggerhead turtles, contributing to a substantial number of deaths in their northernmost nesting population in the North Atlantic (NMFS, 2001). Loss of this particular subpopulation would present a very serious block to recovery because it appears to supply most of the males for the entire region. In 2001, NMFS proposed increasing the size of TEDs to allow these larger turtles to escape. However, it is not clear that the proposed size increase will be sufficient to solve the problem.

Longline and gill-net fisheries also hold some responsibility, particularly recently with their geographic expansion. For example, bycatch in pelagic longline fisheries in the Pacific Ocean is a primary threat to the nearly extinct leatherback sea turtle (Spotila et al., 2000). Similarly, NMFS suspects that bycatch in the Atlantic pelagic longline fishery may be jeopardizing the continued existence of both loggerhead and leatherback sea turtles off the eastern U.S. seaboard (NMFS, 2000).

Bycatch Due to Ghost Fishing

Lost or discarded fishing gear—items ranging from lobster traps and fishing lines to gill nets many kilometers long—is another cause of significant collateral fishing mortality. Lost fishing gear often continues to capture fish for years because it does not degrade. This inadvertent killing is called ghost fishing.

The limited number of studies available on its incidence and prevalence indicates that ghost fishing can be a significant problem (Laist et al., 1999). For example, drifting fishing gear often accumulates in open ocean

Hawaiian Monk Seal, *Monachus schauinslandi*

regions of the Pacific. In these areas, ocean eddies create retention zones. Such areas in the northwestern Hawaiian Islands, for instance, accumulated enough fishing debris to result in the deaths of at least 25 endangered Hawaiian monk seals in a two-year period (MMC, 2000).

In addition to drifting gear, lost gear that settles on the seafloor is also a problem. Canadian researchers working on Georges Bank retrieved 341 nets in 252 tows dragging a grapnel anchor across the seafloor—roughly 1.4 nets per tow (Brothers, 1992). Most of the nets had been on the bottom for more than a year, and many of them were still actively catching fish and crabs. Retrieved from these nets were between 3,047 and 4,813 kgs (6,717 and 10,611 lbs) of groundfish, and between 1,460 and 2,593 kgs (3,219 and 5,717 lbs) of crabs. Since most of those caught—over 80 percent—were still alive, it suggests not only that the animals had been caught relatively recently (survival time is a few days), but also that such catches had occurred repeatedly dur-

ing the year or more these nets remained on the bottom (reviewed in Dayton et al., 1995). In a New England study, scientists found nine gill-nets spread over the seafloor in an area of 0.4 km^2 (0.15 mi^2) that continued to catch fish and crabs for over three years (Cooper et al., 1988). In Bristol Bay, the loss of 31,600 crab pots in 1990 and 1991 resulted in a loss of more than 200,000 pounds of crabs and associated bycatch (Kruse and Kimber, 1993).

Effects of Discarded Bycatch and Offal

In most fisheries, the vast majority of organic material discarded at sea is bycatch. In others, particularly those fisheries with at-sea processing of catches, an additional component is the offal of cleaned fish—the heads, tails, guts, and gonads, for which no market exists. The ecological ramifications of dumping all of this material—the bycatch and offal—overboard range from behavioral changes in resident organisms, particularly among scavenger species (Camphuysen et al., 1995), to the creation of localized hypoxic or anoxic zones on the seafloor (Dayton et al., 1995).

The most visible surface scavengers on bycatch are seabirds. Indeed, more than half of the 54 species of seabirds in the North Sea are drawn to fishing vessels for food subsidies. More typically, it is the larger, more aggressive species—such as the great black-backed gulls and herring gulls—that most successfully adopt this behavior (Camphuysen and Garthe, 2000; Tasker et al., 2000). Less visible are the numerous

> "The ecological ramifications of dumping all of this material —the bycatch and offal—overboard range from behavioral changes in resident organisms, particularly among scavenger species, to the creation of localized hypoxic or anoxic zones on the seafloor."

D.H.S. Wehle

Great Black-Backed Gull, *Larus marinus*

sharks and other fish predators that follow fishing vessels to take advantage of the thousands of dead or stunned animals thrown overboard.

Although many of the discards never reach the bottom, those that do create a food subsidy for scavengers that may differ considerably from their normal diets (Andrew and Pepperell, 1992; Britton and Morton, 1994). Such food subsidies have been credited with contributing to population increases in those scavengers availing themselves of the opportunity, but the relationship is neither clear nor predictable. To some extent, the energy subsidies that might contribute to population growth are often outweighed by the negative effects that fishing brings directly to benthic communities through habitat damage and indirectly to seabird populations through competition for the same forage species (Camphuysen and Garthe, 2000). In addition, these food subsidies can attract scavenging species from a considerable distance, forming novel communities that shift from scavenging bycatch during the highly seasonal fishing season to foraging on resident species when fishing stops.

Bycatch Trends and Magnitude in U.S. Fisheries

"For decades, bycatches were mostly ignored by scientists working on stock assessment, by fisheries managers, and by environmentalists…the emphasis on single species management models and schemes did not leave much room for consideration of bycatches."
(M. Hall et al., 2001)

There is no comprehensive estimate of the magnitude and ecological significance of bycatch in U.S. marine fisheries. Globally, it is estimated that discard-levels reached nearly 60 billion pounds every year during the 1980s and the early to mid 1990s (Alverson et al., 1994; Alverson, 1998). This is approximately 25 percent of the world's catch. If that rate occurs in U.S. fisheries, then the total landings of 9.1 billion pounds in 2000 would have been accompanied by 2.3 billion pounds of discards (with a range of 1.7 billion to 3.3 billion pounds). Because discards represent only a portion of the total bycatch, the total amount of life accidentally captured and killed in U.S. fishing operations could exceed this discard estimate.

Bycatch affects at least 149 species or species groups in 159 distinct U.S. fisheries (NOAA, 1998b), significantly altering population densities. It is most pronounced in the pelagic fisheries of the Northeast, the South Atlantic, and the Gulf of Mexico (NOAA, 1998b). Bycatch compounds the potential impacts of fishing and extends ramifications to a much wider sector of ocean life, with repercussions on ocean ecosystems through the loss of functional diversity. Without controls (or at best, with inadequate ones), bycatch has severely depleted most species of sea turtles, several species of albatross, and several skates and rays.

At least one study suggests that discard levels in the U.S. declined in the late 1990s for a variety of reasons (Alverson, 1998). New technology and management measures account for some portion

"Without controls (or at best, with inadequate ones), bycatch has severely depleted most species of sea turtles, several species of albatross, and several skates and rays."

of the apparent reduction, but the greater part more likely reflects declining populations of both targeted and nontargeted species, and increased retention of species or sizes of fish once considered unmarketable (Alverson, 1998). Credit is due those industries developing fishing techniques that reduce bycatch. The U.S. tuna purse seine industry, for example, largely reduced the bycatch of dolphins, and the North Pacific longline fleet reduced bycatch of the rare short-tailed albatross. However, the credit for "using" bycatch rather than throwing it away is largely a bookkeeping manipulation that does not provide a substantive solution to the ecological ramifications of bycatch. Similarly, a less salutary explanation for the bycatch reduction (credited to increased gear efficiency) is that trawling homogenizes the ocean floor to such an extent that it reduces species diversity and abundance, so that over time there are fewer nontarget species to catch (Veale et al., 2000).

Bycatch problems are notoriously difficult to manage, but this does not diminish the urgent need for solutions. Unfortunately, the difficulty is compounded by a management legacy of poor monitoring and inadequate regulation in the U.S. Years of neglect have cumulatively eroded populations, ecological communities, and entire ecosystems, providing mounting evidence that bycatch leads to species endangerment and increasingly significant ecological repercussions (Box Two). This fact persists even in the face of declining rates and levels of discards in some fisheries. That these declines reflect worsening ecological conditions, rather than improved management, should move us to active implementation and enforcement of more aggressive management methods.

IV. **Habitat Disturbance** and Alteration

"One of the biggest obstacles to sustainable fisheries is likely to be the 'Death by a Thousand Cuts' inflicted in fish habitats by fishing itself, and by pollution and other types of habitat disturbance over time and space scales whose significance is little understood." (Fluharty, 2000)

Habitat loss is the primary factor responsible for the rapid rate of species extinctions and the global decline in biodiversity that has been witnessed in the past one hundred years. This section addresses ecological consequences associated with the effects of fishing on marine habitats.

Significance of the Structural and Biological Features of Marine Habitats

Protecting essential habitat from human-induced impacts is a vital component of successful fisheries management. To some extent, this means protecting habitat from fishing itself.

Marine fishing practices have both temporary and long-term effects on habitat, which can lead to impacts on species diversity, population size, and the ability of a population to replenish itself. Thus, we need to appreciate the links between the various life stages of exploited species and the habitats that sustain them. The habitat features associated with the bottom, for instance—the rocks, ledges, sponge gardens, and shellfish beds—can significantly and positively influence growth and survivorship of juvenile fishes, often because of reduced risk of predation (Lindholm et al., 1999). They also serve as focal points for foraging or spawning adults (Koenig et al., 2000). Reductions in these features, whether by fishing or other means, can have devastating effects on populations, biodiversity, and ecosystem function (Sainsbury, 1988).

Seafloor Habitats

Hard bottom regions both in the coastal zone and farther offshore are composed of an array of familiar geological features, such as cliffs, cobble and boulder fields, and rock platforms. Soft sediments—which make up most of the ocean floor—range from beds of coarse gravels to fine muds. Many organisms living in both these regions provide their own architectural structure. Examples of these structures include the reefs of mussels, oysters, sponges, and corals; the kelp forests in relatively shallow areas; the clusters of single-celled foraminiferans (Levin et al., 1986); and ancient corals that tower more than 40 m (131 ft) above the floor in the deep ocean (Rogers, 1999; Druffel et al., 1995).

The architectural complexity that organisms provide supports a diverse community of associated species and enhanced ecosystem function through positive feedback loops, playing an important role in the maintenance of biodiversity and the biocomplexity of seafloor processes. Over much of the seafloor, this biogenic structure often develops from the initial settlement of larvae on small rocks and shell fragments.

The vast expanse of the deep ocean floor's soft sediment is interrupted in places by highly structured seamounts. The fauna found on these seamounts is often very different from that found on soft sediments because the presence of hard substrata projected above the seafloor and intensified currents around these projections support very long-lived, suspension-feeding corals (Koslow et al., 2001).

Apart from the diversity they bring to ocean systems, soft-sediment marine organisms are important in the biogeochemical processes that sustain the biosphere. Microbial communities in the sediments drive nutrient and carbon cycling, facilitated by the movement, burrowing, and feeding of small worms, shrimps, and other seafloor animals. These processes highlight the important links between seabed and water-column ecosystems by affecting nutrient recycling and fueling primary production. There are large spatial variations in the roles played by the benthos, which is exemplified by the processing of organic debris produced on the continental shelf. The

debris finds its way to the shelf edge, accumulating in canyons that act as sinks to the deep ocean. These detrital hotspots support extremely high densities of small crustaceans that serve as prey for both juvenile and mature fish (Vetter and Dayton, 1998).

Water Column Habitats

At first view, the open ocean seems homogeneous and perhaps exempt from the influences of fishing on habitat.* Yet many of the fish that appear on our dinner plates—tuna, mahi-mahi, opah, marlin, some sharks, and swordfish—previously resided in the open ocean. Moreover, the actual body of water, from pelagic to deep-sea realms, is anything but homogeneous. The pelagic realm is characterized by enormous physical and biological heterogeneity at all scales. Fronts between different water masses often denote boundaries between different oceanic provinces where high concentrations of phytoplankton vital to the larvae of planktonic fish occur.

The pelagic zone also constitutes a physical habitat that is important to fisheries. Unlike the seabed, however, it is not directly disturbed by fishing, although its physical features—fronts and productivity zones—can be influenced by other human-induced activities, such as eutrophication and river diversions that influence salinity and sediment regimes in coastal systems. It is most affected indirectly, when removal of pelagic organisms effects changes in areas crucial to the stability and

*Exclusive of pelagic sargassum beds, which serve as critical habitat for a suite of organisms and are themselves subject to exploitation.

resilience of ocean resources. For example, large predators in the ocean often play important roles in determining the depth distribution and aggregation of prey, thus influencing the foraging behavior and success of a suite of other predators in the system.

Natural Disturbance and Recovery

Nature is not static. Nearshore or deep-sea habitats are subjected to naturally occurring disturbances, such as the constant digging and burrowing of rays, worms, fish, and shrimps; and the less predicable storms and mudslides. While different habitats have different natural disturbance regimes, each is subject to small-scale biological disturbances that create patches on the seafloor differing markedly from one another in the types of organisms they support and the level of available resources.

What we have seen repeatedly in nature is that communities recover from most of these small-scale disturbances. In fact, the patchiness created by disturbance can be an important aspect of their resilience. They are less resilient, however, to the continuous onslaught of a wide variety of human-induced disturbances. The communities of organisms that rarely encounter natural disturbances of similar frequency or magnitude to that of human-induced disturbance are at an evolutionary loss to cope with them. This is surely the case for deep communities. With shifting fishing pressure from the relatively shallow continental shelf to greater and greater depths, these deep communities are at increasing risk.

The Role of Fishing Gear in Habitat Alteration and Disturbance

"…the great and long iron of the wondrychoun runs so heavily over the ground when fishing that it destroys the flowers of the land below the water there…."
Commons petition to the King of England, 1376 (Auster et al., 1996)

Concern about the ecological effects of bottom fishing arose in the Middle Ages and grew to global proportions after World War II, as industrialized fisheries moved across most of the world's continental shelves. The physical impact of the gear dragged over (trawls and dredges) or set upon (traps and demersal longlines) the seabed is influenced by gear mass, the point or points of contact with the seafloor, the speed with which gear is dragged, and the frequency with which these events are repeated. For example, some trawl boards or doors of otter trawls can plough furrows measuring from 0.2 to 2 meters (0.7 to 6.6 feet) wide by 30 centimeters (11.8 inches) deep (Caddy, 1973). Although there are many areas of the sea that are not worth trawling, areas deemed profitable are trawled repeatedly. A rather typical fishery in northern California, for instance, trawls across the same section of seafloor an average of 1.5 times per year, with selected areas trawled as often as 3 times per year (Friedlander et al., 1999). Similarly, U.S. trawl fisheries in Georges Bank trawl sectors of that region 3 to 4 times per year (Auster et al.,

1996). Frequency and spatial extent of impact determine the magnitude of disturbance. Thus, the better the information on these two features, the easier it will be to quantify and manage seafloor habitats at appropriate ecological scales.

### Ecological Changes Precipitated by Mobile Fishing Gear

There is no question that fishing gear towed across the seafloor can have a direct effect on the physical architecture of the habitat. Corals are toppled and sieved, as has apparently occurred in the delicate *Oculina* Banks of the South Atlantic (Koenig et al., 2000). Bedforms, which are dominated by mounds and depressions that are produced by burrowing infauna, are reduced to graded flatlands, and cobbles and boulders are displaced (Jennings and Kaiser, 1998; Freese et al., 1999).

There is also little to dispute the acute effects of trawling on resident populations. Determining the magnitude of effects is, however, a complex business. For example, repeated experimental trawling off the Grand Banks of Newfoundland significantly reduced the biomass of large bottom-dwelling species, such as snow crabs, sea urchins, and basket stars, but had little effect on smaller animals living in the sediment (Prena et al., 1999; Kenchington et al., 2001).

Studies on the North West Australian Shelf illustrate the broader concern of the long-term and pervasive effects of these impacts. Here, trawling shifted the fishery from high- to low-value species by changing the habitat from a largely suspension-feeding community composed of sponges to a simpler deposit-feeding community that did not provide suitable resources for the more valued fish species (Sainsbury, 1988). Off southern Tasmania, Koslow and others (2001) reported that fished seamounts had 83 percent less biomass than similar lightly fished or unfished sites, and many of the species collected here as well as off New Zealand (Probert et al., 1997) were new to science. Even in the eastern Bering Sea, where communities are well adapted to frequent storms, there is good evidence that trawling has reduced the abundance and diversity of bottom-dwelling species such as anemones, soft corals, sponges, and bryozoans (McConnaughey et al., 2000). Subtle changes in the physical and biogenic structure of soft-sediments can have profound effects on marine biodiversity (Thrush et al., 2001). Indeed, broadscale studies reflect both chronic and cumulative fishing effects on a variety of seafloor habitats (Thrush et al., 1998; McConnaughey et al., 2000).

Trawling disturbances can disrupt the biogeochemical pathways that support ecosystem function (Mayer et al., 1991), altering sediment particle size (Auster and Langton, 1999), suspending bottom contaminants, and increasing nutrient flux between the sediment and the water column. Shifts in sediment morphology can also alter the association of species that live in and on the sediment. Off the coast of Maine, for example, scallop dredging was implicated in
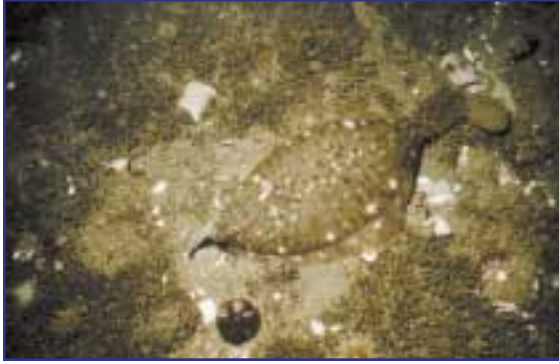
BEFORE: *Seafloor off the coast of Swans Island, Maine, before a single pass of a scallop dredge.*

PETER AUSTER, University of Connecticut (BOTH)

AFTER: *Seafloor off the coast of Swans Island, Maine, after a single pass of a scallop dredge.*

shifting sediment type from organic-silty sand to sandy gravel and shell hash, resulting in a 70 percent decline in scallops and 20 to 30 percent decline in burrowing anemones and fan worms (Langton and Robinson, 1990). There are also some indications of the broadscale ramifications of the disruption of seabed-nutrient and organic-matter processing along with potential shifts in the composition of the phytoplankton community, at least in shallow waters (Pilskaln et al., 1998; Frid et al., 2000).

Habitat Recovery

If we are to take action to reduce habitat-altering fishing practices, we must consider the intensity, frequency, and extent of habitat disturbance because each has an important implication for the feasibility of ecological recovery (Thrush et al., 1998; Zajac et al., 1998). The life-history characteristics of the organisms involved in defining ecological recovery are also critical. Recolonization rates depend specifically upon the dispersal biology of each species and the steps involved in ecological succession to the original community. Organisms capable of creating biogenic reefs over soft-sediments are likely to be particularly important because they influence sediment stability and facilitate the development of structurally complex benthic communities. While these organisms often have low recolonization potentials, recovery is still possible (Cranfield et al., 2001). In some cases, mechanically induced habitat damage may be so severe that recovery will require active restoration.

Striking a Balance between the Use of Mobile Gear and Marine Biodiversity

"The restriction of the otter trawl to certain definite banks and grounds appears the most reasonable, just, and feasible method of regulation which has presented itself to us." (Alexander et al., 1914; cited in Collie et al., 1997)

Many fishers equate trawling with tilling a field in preparation for planting. Concern over habitat change on the seafloor is not an argument against crop agriculture or an argument for a return to the era of foraging for nuts and berries. However, it is an argument for recog-

"...to reduce habitat-altering fishing practices, we must consider the intensity, frequency, and extent of habitat disturbance because each has an important implication for the feasibility of ecological recovery."

nizing the value, not only of the tilled field, but also of the undisturbed forest. In other words, it is an argument for the careful consideration of how habitat is used and modified.

Surely, concerns for the loss of biodiversity and ecosystem function are warranted. These concerns, however, can be ameliorated through comprehensive zoning. The zoning of terrestrial areas of the United States provides an example of how landscapes can be allocated for different needs, ranging from agriculture and industry to conservation and cultural sanctuaries. Levels of protection range from simple land-use restrictions of private property to full-scale protection of public lands. In the same vein, marine zoning could provide designated areas that allow fishing and other areas that provide for various levels of protection from such disturbances. Of course, since the seas and their bounty are public resources, land-use zoning is not a perfect analogy. In essence, it is a matter of scale. Farms and fishing are obviously important to society and must be maintained. To ensure the sustainability of marine habitats, marine resource managers must strike a balance on behalf of the resource, the public owning the resource, and the people who draw their living from the sea.

V. Perspectives and Recommendations for Action

The best available science reveals problems with our current management approach that require us to acknowledge uncertainty and develop management strategies that are robust to the reality of population fluctuations (Hilborn et al., 1995). It also indicates that a population's response (much less an ecosystem's response) to a particular management approach cannot always be determined until the approach is implemented (e.g., Hilborn and Ludwig, 1993; Ludwig et al., 1993). This suggests that management must be flexible and adaptive.

These attributes do not characterize existing U.S. marine fishery management. Perhaps the most disturbing realizations about the way we currently manage fisheries are (1) that much of the very expensive data collected for stock assessment is not proving very helpful in addressing ecosystem or sustainability issues; and (2) that fishing rates and total removals must be reduced. We must also acknowledge that we are as much a part of ecosystems as any of the other entities in them. Indeed, we are competing with those entities for some share of the fish. The question becomes, What trade-offs are we willing to accept to continue this pursuit?

Our choices seem to be either to continue in the traditional vein and, perhaps, if we are lucky, do incrementally better work, or over-haul our data-gathering and regulatory policies (Walters and Martell, 2002; Pitcher, 2001), and develop a fundamentally different approach that will allow us to share resources. Solving the problem may depend to some extent on redefining what we mean by "over-fishing," expanding the definition to include the level of fishing that reduces the productive capacity of fished stocks as well as the level that has detrimental effects elsewhere in the ecosystem (Murawski, 2000). Without a doubt, it requires a new institutional structure less affected by political expediency.

The cornerstones of a new approach to fishery management must include (1) a major investment and commitment to monitoring environmental conditions and fishing activity, ecosystem modeling, and field-scale adaptive-management experiments; and (2) implementation of a proactive, precautionary, and adaptive management regime founded upon ecosystem-based planning and marine zoning. The recommendations that follow address these needs.

A major challenge in developing this new approach will be creating a practical philosophy for sustainability of ecosystems that includes humans. While we leave social and economic recommendations to others (POC, 2002; Orbach, 2002), we are compelled to acknowledge that the single most important

problem of fishing—that too many fish are killed each year—is partly rooted in the social and economic dimensions of fisheries, which are inseparable from the ecological dimensions. Social and economic pressures contribute to the fact that excessive fishing effort persists in the current management arena, sometimes through manager inaction, through ineffective regulations, or through inadequate support of law enforcement.

The Proper Perspective for an Ecosystem-Based Approach to Management

The American people own the fish and other living marine resources in U.S. waters. They bestow upon some the privilege—not the right—to extract those resources for the common good and on others the privilege—not the right—to use the resources for personal satisfaction. Recognizing and asserting these truths is the first step toward implementing a new fishery management approach.

All too often, this perspective provides little guidance in U.S. fishery management. Indeed, most natural resource managers react to a laundry list of fishery problems that follow from population declines and habitat destruction in a crisis mode, rather than react in a proactive, precautionary manner. Proposed solutions that include catch reductions or that

Recommendations for Action

We recommend the United States adopt a new approach to fishery management based upon (1) a major investment and commitment to monitoring, ecosystem modeling, and field-scale adaptive-management experiments; and (2) implementation of a proactive, precautionary management regime founded upon ecosystem-based planning and marine zoning.

Adopting the Proper Perspective

- Understand that U.S. citizens own the nation's natural resources and allow the extraction of natural resources for the good of the nation.

- Recognize that the U.S. government is responsible for protecting and managing the use of natural resources to preserve the full range of benefits for current and future generations.

- Realize that there are trade-offs to biodiversity and population structure within ecosystems that result from high levels of extraction.

Increasing Scientific Capacity

- Establish broad monitoring programs that involve fishers and require quantitative information on targeted catch and all forms of bycatch.

- Develop models for each major ecosystem in the nation, describing the trophic interactions and evaluating the ecosystem effects of fishing and environmental changes.

- Create field-scale adaptive management experiments to directly evaluate the benefits and pitfalls of particular policy measures, while allowing management the flexibility to change as new information is provided.

Restructuring the Regulatory Milieu

- Implement marine zoning to help reduce management error and cost, while promoting more uniform management decisions among different jurisdictions.

- Support enforcement through the development of enforceable regulations, the required use of vessel monitoring systems on all commercial and for-hire recreational vessels, and the required use of permits and licenses for all fisheries.

- Shift the burden of proof from managers to fishers, including the burden of demonstrating the effects of fishing mortality rates on target species and bycatch; demonstrating the effects of fishing on habitat; and assuming the liability for the costs associated with fishing-induced habitat restoration.

alter traditional fishing patterns are met with resistance from consumptive users (both recreational and commercial) who perceive their use of the resource as an inalienable right and perceive that nonusers have no stake in the game. In addition, the more politically well heeled attract sufficient legislative support to compromise management decision-making, jeopardizing the integrity of natural resource protection.

We find that the focus on extractive users diverts the American public's attention from the government's responsibility to protect natural systems for its citizens. Our recommendation for fundamental changes that switch this perspective serves as a reminder that the U.S. government has sovereign jurisdiction over living marine resources. The government is to act as the protective agent for the interests of all citizens of the United States now and in the future, including (rather than focusing on) those extracting resources and those who otherwise depend upon them. Adopting the proper perspective as a guiding principle for resource management is crucial if industry and management are to be held accountable for solid and enforceable conservation and restoration.

Increasing Scientific Capacity for an Ecosystem-Based Approach to Management

The transition to ecosystem-based approaches to fishery management requires increased investment in monitoring and ecological studies of targeted and nontargeted species to better identify and address the fundamental trade-offs that result from management decisions.

Ecosystems have functional, historical, and evolutionary limits that no technological advance in the world can change. Implementing an ecosystem-based approach to management means that policymakers recognize the risk of passing these limits, the critical need to maintain diversity, and the importance of balancing system integrity against short-term profits (Holling and Meffe, 1996).

Fundamental Trade-Off of Fishing

The fundamental trade-off is between fish for human consumption and fish for the rest of the ecosystem. The more fish we take the greater the risk of unintended and undesirable dynamic changes in marine ecosystems. It seems inconceivable that we can have constant catches in highly variable environments or that we can continue to remove upwards of 40 to 60 percent of a single population or multispecies complex each year without significant ecological consequences. In fact, the long-term yield of economically valuable species depends on the very diversity their exploitation can threaten (Boehlert, 1996; Tyler, 1999). Although high catch levels are generally focused on the most productive species in an ecosystem and may be supportable by them, the less productive species taken coincidentally as part of a multispecies complex or as bycatch can experience serious population declines. Even populations that show no immediate impact from being fished may (through their loss) cause disproportionate declines in abundance of species that forage upon them, lead-

ing to trophic cascades.

Addressing these trade-offs requires ecosystem-based management, gathering information using broad monitoring programs, ecosystem model development for long-term policy comparison, and field-scale adaptive management experiments to directly evaluate the benefits and pitfalls of particular policy measures. Adaptive management experiments may provide the best information to support ecosystem-based management.

Monitoring Programs

Broader monitoring programs include both fishery-independent and fishery-dependent data-gathering systems that require direct involvement of the fishers. Fishery-independent systems should emphasize large-scale tagging programs that can provide better information on spatial stock dynamics, growth, and fishing mortality rates on both well-known and understudied species. The fishery-dependent component involving fishers must state clearly that reliable data collection is not only in the fishers' best interest, but that it is a condition of fishing. Thus, data must represent an accurate and complete qualitative and quantitative record of catch, including targeted and untargeted species.

Commercial fishers already use logbooks to report where and when they fish and how much of a targeted species they land. But they are rarely required to record their regulatory discards, and they are not required to report bycatch unless it involves endangered species.

The first step in shifting the burden of proof from resource managers to resource extractors is to engage recreational and commercial fishers more fully in the data-gathering process by requiring the collection of these data.

Ecosystem Models

Ecosystem models require information on biotic interactions and habitat dependence coupled with physical oceanographic models on broad spatial and temporal scales (Sherman, 1994). They should be required to contain parameters that allow critical evaluation of management measures. Such an integrative and adaptive approach could vastly improve the quality of long-term management. In fact, existing single-species surveys, as well as existing environmental information, could be folded into these models to great effect (Boehlert, 2002). We encourage development of these sorts of models for every major ecosystem in the country.

The success of the now 50-year-old California Cooperative Oceanic Fisheries Investigations (CalCOFI) Program serves as a case in point. Here, models integrate physical and biological oceanographic data over large spatial and temporal scales to provide a holistic view of low frequency—but biologically important—events such as El Niño/Southern Oscillation (ENSO) systems and oceanographic regime shifts. They also provide insight about ocean climate effects on the biota of the system, from larval fish abundance to marine mammals and birds. By providing better baseline data, pro-

grams like CalCOFI can help reduce uncertainty about the ecological consequences of fishing.

Restructuring the Regulatory Milieu

The existing regulatory milieu is rooted in a paradigm of exploitation and expansion. It is based on single-species, reactive management, rather than ecosystem-based, proactive, and adaptive management. Among the many problems caused by single-species, reactive management, concerns about enforcement and burdens of proof stand out. Specifically, reactive management:

- Leads to cumbersome, ineffective government regulation, which compromises enforcement and accountability; and
- Improperly places the burden of proof on the regulators to show harm in cases where information is uncertain rather than on the user industry.

The first step toward resolving these problems is to adopt a proactive, precautionary management regime founded upon ecosystem-based planning and marine zoning.

Implement Marine Zoning

Marine waters of the United States need to be comprehensively zoned in a manner that integrates land-sea interactions and ecosystem function and services operating throughout watersheds, the coastal zone, and farther offshore. Comprehensive zoning is more conceptually sound and ecologically useful than implementing piecemeal closures intended to protect special features or habitats. It allows designation of specific areas for specific activities, including those for industrial use (e.g., oil and gas development and shipping), recreation (e.g., diving, boating, and fishing), or commercial fishing. Equally important would be the designation of marine protected areas, such as national parks intended to conserve biodiversity and cultural features as well as various spatial and temporal closures to enhance fisheries.

Marine reserves represent one end of a continuum of zoning options for fisheries management (NRC, 2001) that clearly offer better protection than other types of management strategies. Reserves can serve as sites for the protection and/or restoration of habitat (NRC, 2002), biodiversity, and critical stages in the life cycles of economically important species. In addition, they could serve as experimental sites to test the effects of fishing on ecosystems. Further, they could also provide insurance against the considerable uncertainty in stock assessments. Because they are easily charted, they simplify both compliance and enforcement.

Area closures proved productive in the recovery of groundfish populations on Georges Bank (Fogarty and Murawski, 1998; Fogarty et al., 2000). They will likely have to be large in order to contribute significantly to fisheries production (Walters and Maguire, 1996; Lauck et al., 1998; Guenette et al., 2000) and should be required in areas where fishing would compromise the ecological integrity of ecosystems (Callicott and Mumford, 1997). They can be relatively small when used for protecting specific natural features, for biological conservation, or to protect cultural sites.

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However, they can serve another extremely important function in supporting stock assessments by facilitating better estimates of both natural and fishing mortality. Such improved information could reduce management error and management cost while promoting more uniform management decisions among different jurisdictional entities, and would not necessarily require permanent closure.

We recommend that all proposals to develop marine protected areas be accompanied by requirements that all commercial and for-hire recreational fishing vessels operating in the affected area be required to use a vessel monitoring system. Without this aid to enforcement, marine protected areas—and specifically, marine reserves—become "fisher attractant devices" in essence. Enforcement problems already surfacing for fishery reserves in the Gulf of Mexico suggest that little will be accomplished from the closures without adequate enforcement support. Certainly, their efficacy cannot be properly tested without compliance.

Improving Enforcement

The existing regulatory milieu confounds effective enforcement. It is cumbersome and has many regulations—even those borne of honest attempts to satisfy both consumptive and nonconsumptive users—that are unenforceable. This puts a tremendous strain on the agencies in charge of enforcement, including the U.S. Coast Guard, NOAA Fisheries, and all state natural resource management agencies. New piecemeal regulations increase the burden on these agencies, but do not always support enforcement either substantively (i.e., enforcement concerns are discounted) or financially (i.e., funds for increased personnel or infrastructure support are not provided).

While we suggest a complete review of the Magnuson-Stevens Act (Public Law 94-265) with an eye on developing the most politically, economically and practically efficient means of improving enforcement, we provide the following key recommendations:

As a condition of fishing, we recommend that all participants in U.S. fisheries be subject to permitting, both a general fishing permit as well as fishery-specific permits. All boat owners, captains, and crew should be required to obtain a license to fish. Further, we recommend that the laws be amended to require the forfeiture of fishing permits for certain violations, including habitat destruction and repeated fishery violations. The lack of permits in some fisheries does not allow for permit sanctions against those violating the law.

We recommend that fishers who destroy highly productive and structurally complex habitat such as spawning or nursery habitat (e.g., corals, seagrasses, or mangroves) be charged with habitat destruction and held liable for the costs associated with habitat restoration. The use of trawls, longlines, and other types of bottom gear was outlawed in the *Oculina* Banks of the east coast of Florida in 1984 to protect the dense thickets of the delicate deepwater Ivory Tree Coral, *Oculina varicose*. However, trawl violations continue,

"...we recommend that the laws be amended to require the forfeiture of fishing permits for certain violations, including habitat destruction and repeated fishery violations."

resulting in a near complete loss of *Oculina* coral thickets—a growth form of this species that occurs nowhere else in the world (Koenig, personal communication). Operators intercepted are typically charged with a poaching violation, when in fact the poaching results in catastrophic habitat destruction.

Shifting the Burden of Proof

If negative fishing effects on ecosystems are to be reduced, management approaches must contend with uncertainty, and effectively shift the burden of proof from the regulators to the resource exploiters to show that a fishery will not have unacceptable repercussions on either target or associated resources. The incentive to reduce uncertainty after shifting the burden of proof should be strong. Sparse data means large uncertainty (Figure Six). High uncertainty calls for a high degree of caution, which in fisheries translates into low fishing mortality rates and low catch levels. Better data strengthens the scientific basis for management, and thereby reduces uncertainty and the magnitude of precautionary buffers.

Conclusion

Collapsing fisheries, wasteful bycatch, and habitat destruction have drawn the attention of fishers, scientists, conservationists, and the public, and have led to intense scrutiny of the science of fishery management (Conover et al., 2000). The overwhelming weight of evidence from available fishing data points to the severe, dramatic, and sometimes-irreversible

consequences of fishing on marine ecosystems. Habitat lost is not easily (or inexpensively) regained. Species disappearances are irreversible. Ecosystems, even in the absence of fishing, are subject to fluxes that are unpredictable and intractable. Intense fishing only adds to that in ways that destabilize fishing

Figure Six

Current U.S. Precautionary Approach to Fishery Management

The dot in the center of the circle in graph A and B represents current estimated biomass and effort relative to MSY levels. The circle represents a contour of uncertainty about this point estimate. The precautionary buffer is the difference between the limit of fishing effort and the target fishing effort. In these graphs, the precautionary buffer required will increase with increasing uncertainty. In graph A, uncertainty is large, so the target for fishing effort must be set low. In graph B, improved information permits a smaller precautionary buffer and a higher fishing target.
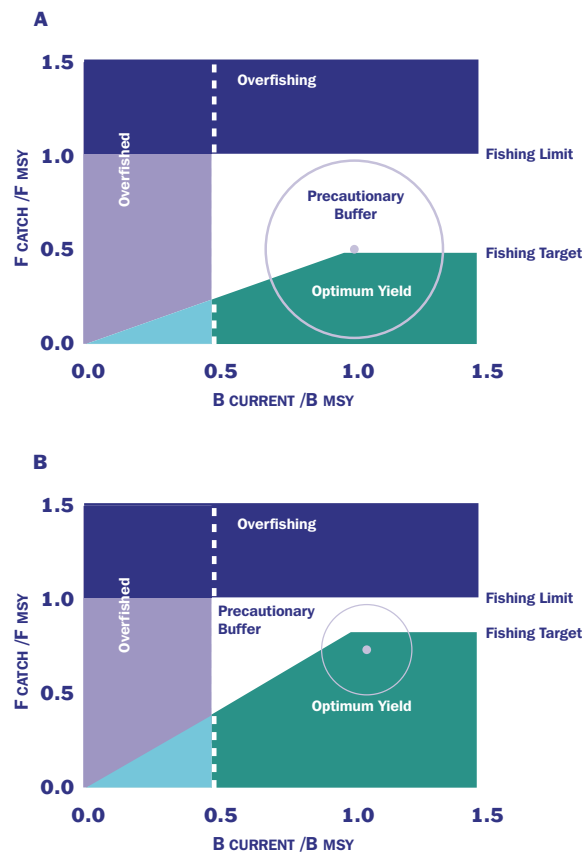
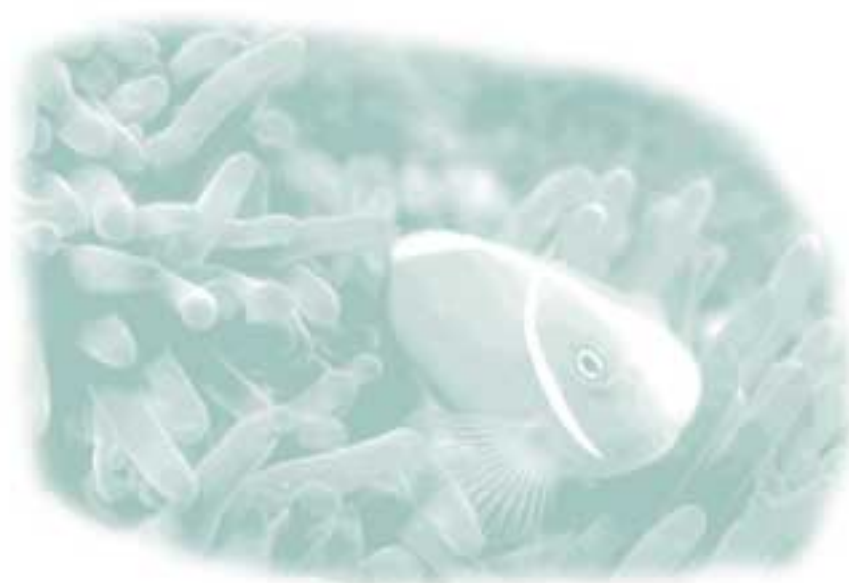
Source: Gerrodette et al., 2002.

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economies. Further, the government's obligation to protect natural resources is overlooked, ignored, or even disparaged by managers who either feel they manage solely at the behest of extractive users or who operate in that manner because of political pressure to protect industry. The result is a complete disconnect between the problem identified by science and the regulation intended to solve it.

If we are serious about saving our fisheries and protecting the sea's biodiversity, then we need to make swift, cautious, and perhaps painful decisions without the luxury of perfect knowledge (Walters and Martell, 2002). At the same time, we must continue to grapple for a more thorough understanding of the ecological mechanisms driving population dynamics, structuring communities, and affecting biodiversity (Hixon et al., 2001). We must also hold managers responsible when there is inaction. Otherwise, sustained fisheries production is unlikely.

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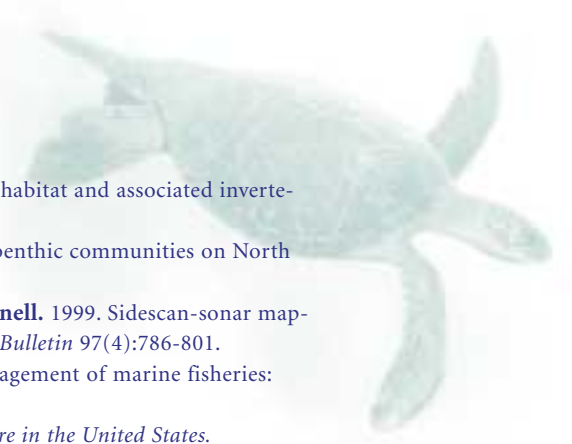
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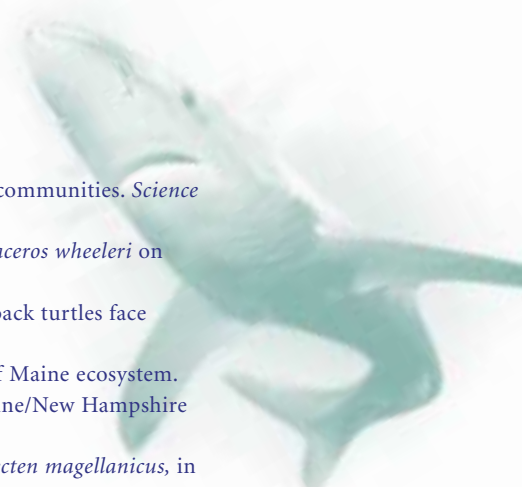
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Connecting People and Science to Sustain Marine Life

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

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