5 Extinction Risk in Marine Species

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In our imaginations, the sea is vast, limitless, and depthless. In former times, its resources seemed inexhaustible, its capacity boundless. Marine species have even been considered "extinction-proof" because they are assumed to have immense geographic ranges, huge population sizes, long-distance dispersal, and astounding fecundity. However, these assumptions are proving to be false, and the persistence of these myths leads to our denials that extinctions are occurring in the oceans on a massive scale and that humans are largely responsible.

Anthropogenic extinctions on land have been occurring for much longer than many would have thought possible. Humans equipped with technology to hunt large animals colonized the Americas some 13,000 years ago and, over a few centuries, approximately 40 genera of large mammals went extinct, including the mastodons, ground sloths, and giant peccaries (Martin 1984). Through a similar pattern of animal extinction following human expansion, 90 percent of large animals (both mammals and others) disappeared in Australia, and small mammals and birds quickly went extinct when humans colonized oceanic islands (Martin 1984). Similarly, extinctions of large vertebrates occurred in South America, the Caribbean, Madagascar, and New Zealand following the first appearance of human hunters in each region (Alroy 1999). Just as there was initial reluctance to believe that humans could cause such widespread extinction using "primitive" tools, so has there been general hesitation to accept the possibility of a widespread process of anthropogenic extinction in the sea.

The process of anthropogenic extinction in the marine realm started much later than on land; however, with ever-developing technology, decimation of species and habitat destruction are now reaching all ecosystems and areas. Many marine species may be particularly vulnerable to extinction because of a number of factors: long age at maturity, low reproductive rate, adaptation to an environment with little disturbance, and targeting by industries encouraged toward overexploitation through subsidies. Our misconceptions about the scale of our impacts derive from our limited understanding of natural processes in the ocean, our poor ability to estimate population sizes, and the single-species approach, which has generally been used in fisheries management. Some species are slipping away virtually unnoticed and with little chance for recovery. The scale and scope of such effects are vast: Myers and Worm (2003) recently showed that 90 percent of large predatory fish have disappeared from the Atlantic, Pacific, and Indian Oceans since the advent of industrial fishing.

Even in relatively well-studied areas, we can hardly begin to imagine our ignorance. Off the waters of our homes in Nova Scotia, a vast deep-sea coral forest ex-

ists in which some individual corals are likely older than 900 years. Yet we know virtually nothing about them and no effective regulations exist to prevent their destruction. Many very long lived species are extremely slow growing and can settle only upon bare rock that is free of sediment, a situation that may exist very rarely and is less likely when the bottom is mechanically disturbed (Rodgers 1999, and references therein).

The importance of anthropogenic extinctions in the sea has, to some extent, been hidden by the long timescale over which extinctions are likely to occur in the ocean, as well as by our poor monitoring. For large populations, extinctions may take hundreds of years (Tilman and Lehman 1997), so it is perhaps surprising that any marine extinctions have been observed (Carlton et al. 1999; Roberts and Hawkins 1999). However, it is the process of extinction that is important, not the recording of the last individual. Indeed, species reaching such low population levels as to be "ecologically extinct" can make huge and lasting changes to ecosystem structure if that species, or suite of species, plays an integral role in the dynamics of the system (Estes et al. 1989; Jackson 1997).

The most insidious causes of extinction are rampant yet difficult to measure. Species are driven to ecological or numerical extinction as bycatch in fisheries directed for more productive species, through habitat loss due to destructive fishing practices, through habitat degradation by land- and marine-based pollution sources, and through global changes to ecosystems caused by rapid climatic changes. Only recently are these effects coming to light, but the damage has been occurring for decades, and in some cases centuries (Jackson et al. 2001).

We believe that the scale of marine extinctions occurring now is enormous. Every marine ecologist that we have spoken to who has a deep knowledge of taxa and a sense of history has provided new insights into the current process of extinction occurring somewhere in the world. The losses are often local, but cumulatively they represent an ongoing, large-scale pattern of global extinctions. The reluctance to address

extinction in the ocean is partly based upon myth and partly lack of imagination. If a small number of hunters with stone tools could cause massive extinctions on land, what must the impact of modern fishing and habitat alteration be on the sea?

In this chapter, we address this question by identifying some of the major causes of anthropogenic extinctions in the ocean, making crude predictions about the proportions of species that will disappear and offering suggestions on how best to stave off and hopefully reverse the precipitous drops in marine populations we believe are occurring throughout the sea. The diverse systems in the sea, from productive coastal seagrass beds and mangrove swamps to the vast three-dimensional inner space of the high seas, to the cold, dark, living sediments of the deep benthos are each impacted in different ways by anthropogenic threats. We have not attempted a comprehensive discussion of all systems, but instead try to show how widespread are the threats of extinctions and to highlight, where we can, the issues of each.

Extinctions and Biodiversity in the Marine Realm

Our knowledge of the biodiversity of the sea is minimal compared with that of the land. We are a terrestrial species and are much better at counting, tracking, and even discriminating amongst terrestrial species than marine ones. It is often only in the case of the best-studied taxa, such as fishes or whales, where we would recognize an extinction if it occurred, and then only for the most highly visible or commercial species. Even for the few areas that are regularly surveyed, such as the shelf areas of the North Atlantic, near extinctions of large, distinctive, and formerly common species can occur without anyone's knowledge.

The barndoor skate (*Raja laevis*) was once abundant from Newfoundland to Cape Cod and from the shoreline to below 1,000 meters, but disappeared from most of its range without notice (Casey and Myers 1998).[1] The near extinction of this creature, which has a wingspread of more than a meter and is as distinc-

tive as the American bald eagle, was identified only through inspection of data from research trawls conducted over a 45-year period. The declines were clear and occurred early on but were not identified until recently. No directed fishery existed for the barndoor skate; decimation of this species is attributed to removal as bycatch in other fisheries. Sadly, we recently discovered in interviews with retired fishermen that the species was already extirpated in the northern part of its range (Funk Island Bank off Newfoundland) before research surveys even took place.

Unfortunately, this is not an isolated occurrence. The large and rapid decline in great shark populations in the North Atlantic (over 50 percent in the last 15 years) was noticed only recently (Baum et al. 2003) and may be an underestimate due to underreporting of catches in logbooks. Oceanic whitetip and silky sharks (*Carcharhinus longimanus, C. falciformis*), both formerly the most commonly caught shark species in the Gulf of Mexico, are now estimated to have declined by over 99 percent and 90 percent, respectively, in that area since the 1950s (Baum and Myers 2004). Due to a shifting perception of baseline abundances, the former importance of these species in this open water ecosystem had slipped from local memory.

Even in coastal areas, the disappearance of distinctive species can occur in shallow regions frequented by many sports divers without raising alarm. The sea star (*Oreaster reticulatus*), beautiful, bright orange, and once found up to 20 inches in diameter, was common throughout the Caribbean 50 years ago. Due to their popularity as curios for tourists and in the aquarium trade, populations of the sea star are extinct in the more developed regions of the Caribbean, and there is no evidence that any eliminated population of the species has reestablished (personal communication with R.E. Scheibling, Department of Biology, Dalhousie University, Halifax, Canada). If such large, distinctive creatures can slip away, raising the alarm for smaller, more cryptic species is undoubtedly more difficult.

Species with high fecundity are also vulnerable to extinction. Both the totoaba (*Totoaba macdonaldi*) and the Chinese bahaba (*Bahaba taipingensis*), members of the highly fecund Sciaenid family (drums or croakers) have been decimated to less than 1 percent of their past recorded catches within one human lifetime of science's awareness of them (Sadovy and Cheung 2003). In the case of the bahaba, dependence on estuaries for reproduction, and economies that declared them more valuable as their rarity increased, rendered them highly vulnerable to extinction. Their story was almost missed by science and has been pieced together through investigation of multiple sources of traditional ecological knowledge (Sadovy and Cheung 2003).

High biodiversity in the ocean has long been recognized in some ecosystems. For example, of the 34 animal phyla, 32 are found living on coral reefs, compared to 9 in tropical rainforests (Wilkinson 2002). However, this diversity may be even more extensive and widespread than previously imagined. The deep sea is a prime example. Because of the inherent difficulty in studying marine organisms, particularly those in the over 60 percent of the planet that is greater than 130 meters deep, the enormous biodiversity in deep-sea environments has not been hinted at until recently (Grassle and Maciolek 1992; Snelgrove 1999). This tremendous variety is often dominated by tiny invertebrates that live on and within the bottom sediment (Snelgrove 1999).

Further, the taxonomy of most marine algae and invertebrates is extremely difficult. For example, one of the most common North Atlantic polychaetes (*Capitella capitata*) was shown to be six separate species (Grassle and Grassle 1976). Increasingly, it appears that many sibling species (those that are very difficult to distinguish morphologically) exist in the oceans, many of whose identity can only be discerned with molecular techniques (Knowlton 1993; Knowlton et al. 1997). Through these methods, it was discovered that symbiotic zooxanthellae, crucial for coral, are not a single species but vary widely genetically, with little correlation to the phylogeny of their hosts (Rowan and Powers 1991). Hence, even in areas easily accessible to humans and for species of great interest, our perceptions of biodiversity may be vast underestimates.

Most marine species are thought to be very widely distributed, often over large parts of an ocean basin. However, recognizing the difficulties in distinguishing species, this concept of distribution may be false. For example, many "species" that were once thought to be widely distributed are actually genetically distinct around each island where they occur (Knowlton 1993). This has serious implications for estimation not just of biodiversity but also of current and future extinction risk. For instance, seamounts are now recognized as hotbeds of endemism and the species or populations there may be particularly sensitive to trawling (de Forges et al. 2000). Furthermore, in the sea as well as on land, the loss of populations and subpopulations might be the most important component in the decay of biodiversity (Ehrlich and Daily 1993). Compelling evidence suggests that many populations of marine species show strong local adaptations in the timing and location of spawning, the use of nursery grounds, and feeding areas.

The loss of locally adapted populations is most crucial when it is unlikely that they can be replaced. As Janzen (1986) has pointed out, if the eastern American monarch butterfly (*Danaus plexippus*), which overwinters in the Mexican highlands, were lost, the California population could not be used to reintroduce the eastern population. The monarch relies on "genetic memory" over several generations to make the migration from Mexico to Canada. Once this information is lost, it is effectively irreplaceable. Many marine species such as turtles, fishes, and whales make migrations to specific spawning, feeding, and nursery areas. Such migrations occur for marine invertebrates, such as the spiny lobster (*Panulirus* spp.), as well (Groeneveld and Branch 2002). However, the complexity, diversity, and extent of the genetic basis of that information are poorly understood for most marine species. Only for the best-known marine species, such as cod (*Gadus morhua*), do we have even some knowledge of such richness. Fishermen off the north coast of Newfoundland identify many "runs" of cod based upon timing of migration, color, shape, size, and feeding habitats. Some of these are separate populations (Ruzzante et al.

1998), and some have gone extinct even though they were formerly abundant (Ames 1997). Most likely, similar loss of populations is occurring unnoticed worldwide, particularly among reef-spawning fish. The loss of populations with a genetic memory of behaviors such as the time and location of spawning grounds, migration routes to juvenile habitats, and adult feeding migration routes, will mean a loss that cannot be recovered within ecological time. Preservation of the genetic resources of specific populations has not been a driving factor thus far in fisheries management. However, many cautious fisheries biologists consider it a crucial issue (Cury and Anneville 1998). In sum, given our vastly incomplete understanding of marine biodiversity, at both a species and a population level, the possibility is staggering that extinctions have occurred and are occurring, often without our even recognizing that species existed.

Differences between Extinction on Land and Sea

Although the biological basis of extinction risk is similar in marine and terrestrial environments, we believe that there are three important ways in which extinction is more of a problem in the sea than on land. First, the equivalents of pollinators do not appear to exist in the marine realm. This means that sessile species (i.e., with the same types of reproductive challenges as plants have on land) must rely largely on broadcast spawning or similar mechanisms for sexual reproduction, and the dispersal of clones for asexual reproduction. Hence, an Allee effect (also known as depensation or positive density-dependent mortality: a disproportionately low rate of recruitment when population density is at low levels; Begon et al. 1996; Levitan and McGovern, Chapter 4) might be important for sessile species in the ocean because for fertilization to occur, individuals will usually have to be close together. In short, populations of sessile species may have little chance to recover if driven to low levels. This effect may be acting in species such as the white abalone (*Haliotis sorenseni*), in which the re-

duction by fishing to a low density may mean extinction for the species (Davis et al. 1996). This species has not recovered for 15 years despite a ban on fishing, a pattern that has been repeated for other abalone species (Davis 1993). The Allee effect is probably less important for marine fish (Myers et al. 1995) due to their greater mobility.

A second way in which extinction in the marine realm may be more problematic than on land is in the larval behavior of some species. The larvae of some invertebrates preferentially settle where there are already live conspecific adults, making recolonization and dispersal to new areas difficult (Pennington et al. 1999; Toonen and Pawlik 1996). When such species are important to a system due to their creation of habitat (e.g., reef-building corals), colonization or reestablishment of the species will be vital to the persistence of a whole suite of organisms.

The final point to consider is that despite its physical appearance, the sea is not blue, it is red. That is, long-term environmental records for the oceans show spectra where the variance increases with longer timescales (Steele 1985). This type of frequency variation is termed "red noise." Hence, in the short term, environmental conditions in the ocean are quite stable, but at longer timescales, large shifts can occur. This can have serious implications for persistence of a species if, for instance, the conditions necessary for recruitment swing between 50 "good" years and 50 "bad" years. In contrast, in the terrestrial environment, variability tends to be more constant over temporal scale, termed "white noise."

This point on the variability of conditions becomes critical to extinction probability when anthropogenic impacts are overlaid on natural cycles we haven't identified and don't expect. Fishing regimes that appear to be sustainable for decades may cause extinctions over longer time periods. For example, coho salmon (*Oncorhynchus kisutch*) show large decadal changes in survival at sea as a result of unknown environmental factors. In the 1970s, natural survival was greater than 10 percent, whereas in recent years, it declined to less than 5 percent (Bradford et al. 2000).

During periods of good ocean survival, most coho populations could sustain a high level of fishing mortality, up to 80 percent. However, in recent years with poor ocean survival, even low levels of fishing may drive many populations to extinction.

Such long-term changes in the environment are not restricted to climatic causes. The extinction of the Atlantic eelgrass limpet (*Lottia alveus*) in the 1930s was caused by a massive disappearance of its habitat, eelgrass (*Zostera marina*), due almost certainly to a disease caused by a slime mold (Carlton et al. 1991). Such devastating epizootics that kill large proportions of populations are well known for sea urchins (Lessios 1988; Scheibling et al. 1999), and may greatly increase the chances of extinction of corals when combined with other anthropogenic sources of mortality. Similarly, the black abalone (*Haliotis cracherodii*) crashed after centuries of apparently sustainable fishing, probably because of a parasite in association with the fishing (Davis 1993).

Fishing as an Extinction Risk

Each year, industrial fishing fleets, bottom trawling, and other destructive fishing practices are spreading further into deeper and more remote locations, as well as areas that are difficult to trawl because of their bottom topography (Watling, Chapter 12). Declines in populations have occurred worldwide, even in the most remote and "pristine" parts of the ocean (Myers and Worm 2003; Pandolfi et al. 2003). The only temporary sanctuaries left are possibly the deep ocean and a few remote Pacific islands (Maragos and Gulko 2002). Fishing pressure, both direct and indirect, is a very real extinction threat for many species, since species have been driven extinct, or virtually so, while a fishing management regime was in place (e.g., Casey and Myers 1998). Moreover, even when populations barely survive, it may be difficult, or even impossible, for them to recover to their former population levels and roles in the ecosystem (Hutchings 2000; Hutchings and Reynolds 2004).

Those who doubt the damage of modern fishing

methods should examine the short, sad history of fisheries around the Antarctic. The fishery for the marbled rockcod (*Notothenia rossii*) around South Georgia Island began in the 1970 fishing season when more than half a million tons were caught. By the second year of fishing, the population had shrunk to less than 5 percent of its virgin level (Kock 1992). By the third year, the catch was about 1 percent of the initial levels, and in the fourth year, the fishery was abandoned. At the time of the most recent surveys, decades later, the stock showed no sign of recovery (Kock 1992).

In Hawaii, one of the few places where baseline areas persist, detailed scientific surveys of fished and unfished reef islands revealed that the biomass of large predatory fishes, such as sharks and jacks, on fished reefs, is only 1.5 percent of that found on unfished reefs (Friedlander and DeMartini 2002). Large predators represented 54 percent of the total fish biomass in the near-pristine reefs of the northwestern Hawaiian Islands, but less than 3 percent in the exploited reefs of the main Hawaiian Islands (Ni'ihau and those eastward) (Friedlander and DeMartini 2002). That the fisheries on the main Hawaiian Islands are largely small scale highlights the important and considerable impact such small-scale fisheries can have on ecosystems. The northwestern Hawaiian Islands may be one of the last relatively untouched reef ecosystems on the planet, yet even here, marine debris is damaging habitat, and due to previous military occupation of two atolls, toxic contaminants can be found in sediments (Maragos and Gulko 2002).

A fundamental limitation in fisheries management is our lack of knowledge. For example, although sharks are a well-known potential conservation concern, we have virtually no reliable estimates of abundance of large sharks in coastal waters or the open ocean. Nevertheless, it is possible to estimate trends using innovative methods that make minimal assumptions. Baum et al. (2003) recently examined trends in 18 species of large pelagic and shelf shark species in the northwest Atlantic caught in the US pelagic swordfish and tuna longline fleets. All but two species of sharks were found to be declining at a rapid rate (Figure 5.1;
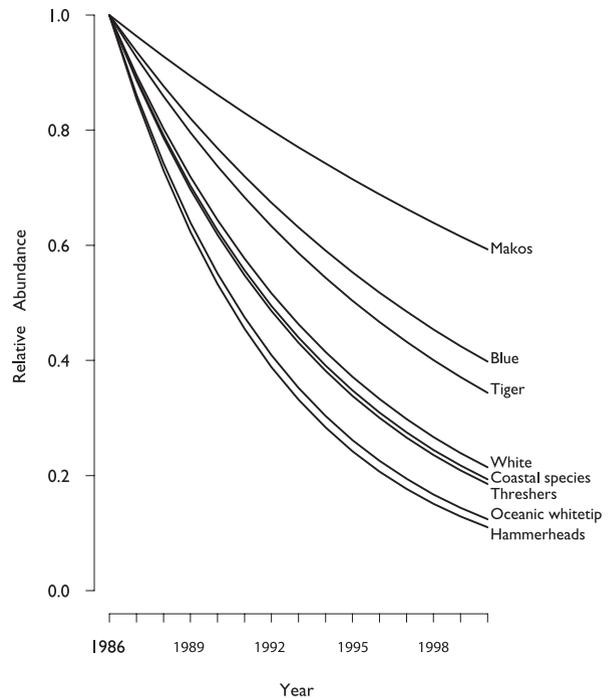

FIGURE 5.1. Estimated declines in eight shark taxa for which data were available in the western North Atlantic. The estimated declines are relative to 1986. The estimation method used produces conservative estimates, therefore the real declines are greater on average. Uncertainties in species identification cause noise in the data. However, the total declines are robust.

from Baum et al. 2003). Of particular concern were the scalloped hammerhead (*Sphyrna lewini*), great white (*Carcharodon carcharias*), and thresher sharks (*Alopias superciliosus, A. vulpinus*), which have declined by over 75 percent in the last 15 years. Clearly, these species cannot remain extant under present levels of fishing mortality: bycatch and directed fisheries for shark fins. The best data come from the North Atlantic, yet the decline of the sharks appears to be worldwide. Despite our lack of firm abundance numbers, there is more than enough information available to show how great the need is for protective policies.

The Millions of Eggs Hypothesis

Perhaps the most pernicious myth sustaining current fishing practices is the "millions of eggs" hypothesis,

which presumes that the high fecundity of many fishes and marine invertebrates protects them from extinction. This formed the basis for the idea that overexploitation of marine fish was impossible (Huxley 1884), an idea that is still remarkably common in fisheries management. However, an examination of the data shows this assumption to be incorrect. A recent meta-analysis of the maximum reproductive rate of over 300 fish populations has shown that the high fecundity of many marine fishes does not protect them (Myers et al. 1999). The most surprising result from this analysis is that, even in the absence of fishing, almost no species appear to be able to produce, on average, more than four or five replacement spawners per year. Most species are below that rate. Recovery of a stock, even under a moratorium on fishing, can be much slower than previously expected, if it is possible at all (Hutchings 2000; Hutchings and Reynolds 2004).

The biological limit to the exploitation rate of a fish stock is determined primarily by two factors: the maximum per capita reproductive rate and the age selectivity of the fishery (Mace 1994; Mace and Sissenwine 1993; Myers et al. 1994). Myers and Mertz (1998) formulated a simple model to approximate the fishing mortality required to drive a population extinct. The most critical factor is the difference between the age that fishing begins and the age at maturity. As the age of selection to the fishery decreases, the fishing mortality required to drive a population extinct drops very rapidly as well. Perhaps the most common way that fisheries collapse is that the age of selection decreases below the age of maturity. As the population of older fish is fished down, the "candle" is burned at both ends. This is the process whereby the herring stocks in the North Atlantic and North Pacific collapsed in the 1960s and 1970s and the cod stocks collapsed in the 1990s (Hourston 1980; Myers et al. 1997). Since older, larger females may produce offspring with the best ability to survive, it would be wise to protect older age classes as well (Berkeley et al. 2004a).

The important lessons to be learned from the meta-analysis (Myers et al. 1999) are that stocks are vulnerable to collapse and extinction in spite of high fecun-dity, and that protecting immature fish from fishing offers a measure of insurance that is not possible when all age classes are taken.

An Example: Haddock on the Southern Grand Bank and St. Pierre Bank

In the past, most fish populations have recovered when fishing has decreased (Myers et al. 1995). However, an example of a stock that has never recovered from overfishing is haddock on the Southern Grand Bank and St. Pierre Bank. Until it was virtually eliminated by overfishing in the 1950s (Templeman and Bishop 1979; Templeman et al. 1978), haddock (*Melanogrammus aeglefinus*), not cod, was both the most abundant groundfish and the most commercially important fish in the region (Figure 5.2). Failure to protect the few remaining fish resulted in very low spawner abundance. This, as is usual with marine fish, resulted in subsequent low recruitment (Myers and Barrowman 1996). Nevertheless, the stock began to increase in the 1980s with extraordinary recruitment, given the low spawner abundance. Again, failure to conserve the spawners, combined with fishing at very high levels, reduced these stocks to low levels. Because haddock in these regions is genetically distinct from haddock to the south (Zwanenburg et al. 1992), a recolonization would be unlikely if these stocks were driven to extinction. Finally, after many years of no directed fishery, there are some small signs of population increase, although there are still very few mature fish (DFO 2003). It may take substantially more time, if it is possible at all, for the haddock to regain their former status in the ecosystem.

Extinctions through Indirect Fishing

Our chief concern with fishing as an extinction risk is not directed fishing but the elimination of many other species that are not the primary targets. Because fishery management is typically geared to the target species, the disappearance even of large, conspicuous bycatch species can go unchecked and unnoticed (Baum and Myers 2004; Brander 1981; Casey and Myers 1998). Species, such as tuna, that support a di-
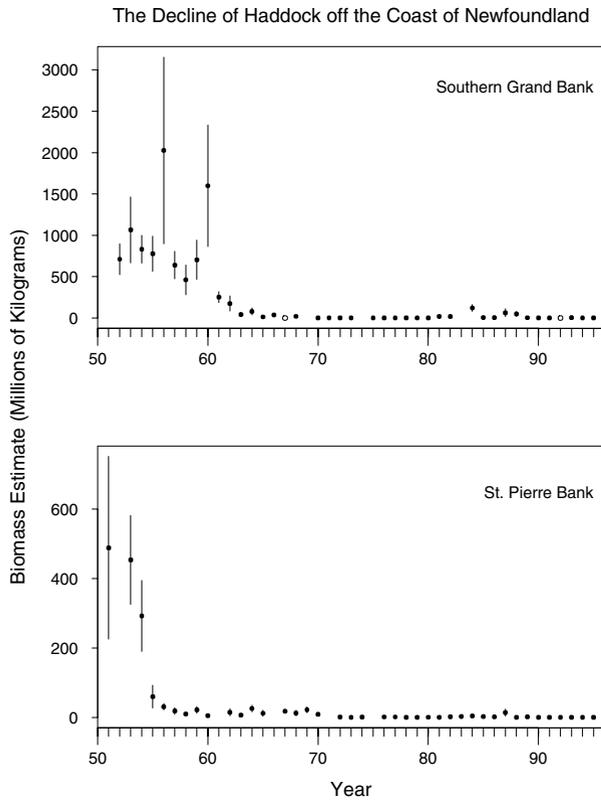
FIGURE 5.2. Estimates of biomass (± s.e.) for haddock from research surveys of the Southern Grand Bank and St. Pierre Bank for the years 1951 to 1995. Open circles indicate that no haddock were caught. These estimates are from an analysis of all research surveys conducted in the region since 1951, and represent the longest series of research surveys in the Western Atlantic. These estimates are part of the M.Sc. thesis of Jill Casey (2000).

rected fishery often have a high reproductive rate and relatively young age at maturity. However, many bycatch species, particularly elasmobranchs, have both higher catchability and more sensitive life history characteristics (older age at maturity or lower reproductive rate) that predispose them to being driven extinct (Musick 1999). Without tracking bycatch numbers, these serious declines can easily be overlooked. Fourteen species of large elasmobranchs disappeared from the Gulf of Lions (northwest Mediterranean) from trawl surveys between 1957 and 1995 (Aldebert 1997), and nine species of elasmobranchs have disap-

peared from the Bay of Biscay since 1727 (Quero 1998). Similarly, that two formerly common skate species in the Irish Sea and the northwest Atlantic had nearly reached extinction was not recognized until many years later (Brander 1981; Casey and Myers 1998). Thus it is possible to fish at the maximum sustainable yield for one population while driving another to extinction (Myers and Mertz 1998).

Other populations of large marine animals are also in grave danger due to bycatch. The leatherback turtle (*Dermochelys coriacea*), the largest turtle on the planet, is now dangerously close to extinction in the Pacific. The Mexican Pacific coast formerly hosted tens of thousands of nesting leatherbacks, perhaps 50 percent of the world's population. However, by 1985, fewer than 1,000 nesting females were estimated to persist (Sarti et al. 1996). The recent, drastic decline of this large population has been linked to the introduction of new gillnet swordfish fisheries off the Chilean coast that capture an unknown, but likely substantial, number of leatherback turtles (Eckert 1997). This is deemed to be the single largest threat facing the leatherbacks and has negated all conservation efforts at the breeding grounds since the mid-1980s (Eckert 1997). Formerly, swordfish in this area were captured using harpoons (Weidner and Serrano 1997), which results in no bycatch. Unfortunately, the situation in the Mexican Pacific is similar throughout the Pacific (Spotila et al. 2000), where effective action is slow in coming.

Fishery bycatch of seabirds, particularly in the pelagic longline fleets, has been slowly gaining attention in recent years (Tasker et al. 2000). Since many seabirds are surface foragers, recently set baitfish look like a tasty treat, but have a deadly surprise. Albatrosses, fulmars, and petrels are just some of the more than 40 species that drown in great numbers, caught on hooks or tangled in lines as the longlines sink (Morgan and Chuenpagdee 2003). Mitigating practices such as stringing up brightly colored "streamers" to discourage birds from inspecting the lines, and baiting at night when birds cannot see the sinking hooks, have the ability to reduce marine bird bycatch greatly

and actually increase the catch rates of target species due to reduced loss of bait (Morgan and Chuenpagdee 2003; Tasker et al. 2000). Since mortality in at least half of the bird species caught is high enough to cause population declines (Morgan and Chuenpagdee 2003), fishery policy should address bird bycatch as well as that of fish, marine mammals, and turtles.

Ecosystem Effects

Overfishing is a community-level problem since few fisheries operate on only one stock or species, and often remove substantial bycatch (Myers and Worm, 2004). Initially, fisheries target the largest and most valuable species, but once these are eliminated, fishing concentrates on smaller and smaller species further down the food chain (Pauly et al. 1998). Similarly, once fish are eliminated close to shore, fishing often proceeds to deeper waters. Now we have fisheries in deep slope waters, which had served as a refuge for species that were once plentiful inshore. For example, Atlantic halibut (*Hippoglossus hippoglossus*) were once abundant inshore in the North Atlantic, while now they are largely restricted to the continental slope.

Sequential removal of species after species can have profound effects on a system. Shifts in ecosystem balances can occur, which may be difficult to reverse. For instance, the depletion of a dominant predator (or the entire predator guild) can result in large biomass increases in its prey species. As one example, where Atlantic cod is a dominant predator, the collapse of cod stocks leads to large increases in benthic crustaceans (Worm and Myers 2003), and pelagic fishes (Fogarty and Murawski 1998), both a major food source of cod. The persistence of this shift could then be reinforced because large increases in pelagic fish may be correlated with low cod survival (Swain and Sinclair 2000), probably because of intense predation on cod eggs and larvae (Köster and Möllmann 2000).

Examples of such dramatic shifts in ecosystem structure and function are steadily increasing in the literature. Removal of green turtles over the last few hundred years, as a major ecological player in the Caribbean seagrass beds, has become a cautionary tale

of ecological extinction (Jackson 1997; Jackson et al. 2001). Subsequent sequential overfishing of other herbivorous species left the long-spined black sea urchin (*Diadema antillarum*) as the only major grazer remaining, until they too were decimated by an epizootic in 1983–84 (Jackson 2001). Growth of macroalgae when released from predation, and the increasing frequency of coral bleaching events, appear to be the final major contributors to the "sudden, catastrophic mortality" in the 1980s of reef corals in the western Atlantic (Jackson et al. 2001), which had been dominant for at least 500,000 years in the reef community (Pandolfi and Jackson 2001). Fundamental shifts in ecosystem functioning have also been documented in interactions of sea otters (*Enhydra lutris*), sea urchins and other herbivorous invertebrates, the kelp forests, aboriginal hunters, and killer whales (*Orcinus orca*) of the North American West Coast (Estes et al. 1989; Jackson et al. 2001; Simenstad et al. 1978).

In general, the impacts of overfishing of individual species may not be immediately recognized due to compensations in the ecosystem, but over time, the cumulative results of sequential overharvesting appear to be loss of resilience to epizootics and environmental change, and susceptibility to profound systemic change (Paine et al. 1998). It's like a global game of Pick-Up Sticks. Take one stick out, and the structure still stands. Take two, maybe there are some creaks and groans, but still the network holds. However, at some stage, one more stick is pulled and the change in structure is swift and decisive.

Illegal Fishing

Legally or illegally, fishing of endangered and/or "protected" marine species usually continues in all countries, although it is difficult to detect through official channels. For example, where we live in Eastern Canada, illegal capture from the sea is common. The illegal capture of sharks (for fins) and stocks of Atlantic sturgeon (*Acipenser oxyrhynchus*), cod, and haddock that are closed to fishing is well known to those who care to know. Similarly, incidence of dumping illegal bycatch at sea is difficult to quantify but is un-

doubtedly occurring. Onboard observer programs attempt to control this problem. However, coverage is far from complete and it is naive to expect that the behavior of all operators is unchanged with and without observers present. Strict enforcement of regulations is expensive and perhaps impossible. This state of affairs prescribes that fisheries' policies should assume that illegal practices are occurring and adjust models of population size and growth accordingly. Without this buffer, illegal capture renders even managers' more cautious plans very dangerous.

The Large Effects of Small-Scale Fishing

Thus far, we have focused largely on the effects of industrialized fishing and the global scope of its monstrous appetite. However, the cumulative effects of many individual, small-scale, inshore fishers may be profound on a system. Unfortunately, in many parts of the world, these impacts are very difficult to assess because subsistence fishing and illegal takes are not quantified or quantifiable. One example of how dramatic an effect fishing can have on the structure of the biological community comes from shallow-water reef fishes in Fiji. Jennings and Polunin (1996) compared fish species biomass with fishing effort and yield among six local fishing grounds varying in fishing effort. Continued takes of only 5 percent of fish biomass were sufficient to cause significant changes to fish community structure. Hence, even "sustainable" fishing effort can have noticeable effects. If this small, controlled amount of fishing pressure can cause significant changes, what must be the impacts of unregulated local fishing on communities?

Populations that form dense spawning or mating aggregations are particularly susceptible to loss of populations, even by artisanal fishers. Populations of Nassau grouper (*Epinephelus striatus*) migrate to specific locations to spawn and may be quickly eliminated (Sala et al. 2001), particularly because they fetch an extremely high price in Hong Kong (Safina 1997). Many groupers use this mating system (Sala et al. 2001), and this type of reproduction may be important for many other marine species, particularly fish.

Some other impacts of small-scale fishing can be even more devastating to the community. For example, some fishing practices, most often used in the tropics, such as dynamite and cyanide fishing, are not only unsustainable but can be very destructive to reefs, with recovery very difficult to achieve (Cervino et al. 2003; Riegl and Luke 1998). Sodium cyanide solution is often used to slow and stun fish to ease collection for the aquarium and live reef fish restaurant trade, a US$1.2 billion industry in 1995 (reviewed in Halim 2001). In addition to decimating some already rare species, use of cyanide damages and kills corals, anemones, and other invertebrates (Cervino et al. 2003), as well as other fish not targeted.

Dynamite fishing is even more harmful to habitats and is a particularly wasteful fishing method. Many of the fish killed are left dead on the bottom and the fish that are caught are often of poor quality due to tissue damage from the explosion. Explosives may affect fish species in different ways, virtually eliminating those most sensitive to the force of the blasts, audible to divers tens of kilometers away (personal communication with C. Harvey-Clark, University Veterinarian, Dalhousie University, Halifax, Canada). Blasted reef structures no longer provide shelter and food to other reef organisms and protection to the coastline, and they are greatly reduced in their potential to attract sustainable tourist dollars to a community (Pet-Soede et al. 1999). Reef damage due to dynamiting is difficult to quantify since monitoring is not occurring in many areas. However, where available, studies indicate heavy damage (e.g., 65 percent of studied reefs show dynamite damage in the Egyptian Red Sea) (Riegl and Luke 1998). Unfortunately, in some areas there are not the resources, and sometimes not the political will or stability, to stop these methods. For example, the use of explosives is not illegal in Burma (Myanmar) (personal communication with C. Harvey-Clark, University Veterinarian, Dalhousie University, Halifax, Canada). The combined impacts on these recently healthy ecosystems has been swift: sharks removed for the shark fin market, smaller fish removed by blasting, and coral damaged and destroyed by blasting and cyanide.

These are very complex biological and sociological issues on many levels since it is often the impoverished people of a region who engage in small-scale fishing for sustenance, the aquarium trade, curios for tourists, and traditional Asian medicines (e.g., Vincent 1997). In Indonesia, many of the fishers involved in blast fishing are tied to the lifestyle through debts, which can last for generations, owed to their middlemen, who direct catch decisions (Pet-Soede et al. 1999). In addition, it is not surprising that, increasingly, conflicts are arising between traditional artisanal fishers and the international industrialized fishing fleets that legally or illegally take fish offshore of more traditional coastal fishers.

Extinction by Loss of Habitat

Healthy marine habitats are disappearing at an alarming rate. The combined effects of destructive fishing practices such as bottom trawling, terrestrial- and marine-based pollution, development along coastlines, and global climate change are degrading the quality and changing the nature of marine habitats globally. Virtually all shelf areas have been trawled (Sainsbury 1988), at least 35 percent of all mangroves have already been removed for aquaculture or other development (Valiela et al. 2001), and natural coastal areas have been largely eliminated. The loss of marine habitat has staggering implications for extinctions, particularly due to the critical importance in the sea of biogenic habitats. Survival of healthy corals (coastal and deep sea), kelp forests, mangroves, and seagrass beds is firmly connected to the ability of vast numbers of other species to survive and reproduce.

Trawling and Loss of Habitat

Undoubtedly, any species that cannot withstand the habitat destruction of bottom trawls and dredges will go extinct over much of the world's shelf and slope regions. Use of mobile fishing gear alters seafloor habitats by reducing and destroying three-dimensional complexity (Auster et al. 1996). Bottom trawling and dredging reduce biomass, species richness, species di-

versity, and spatial rugosity of benthic sites. They also reduce or destroy structurally complex species such as corals, hydroids, bryozoans, sponges, and tube worms (Collie et al. 1997; Hall-Spencer et al. 2002). These creatures create and are themselves habitat for many other creatures, including the juvenile stages of many commercially important fish species. Other types of interactions are possible as well. For example, tilefish (*Lopholatilus chamaeleonticeps*) modify the sea bottom with burrows, which then are habitats for other species. Trawling has reduced these structures by over an order of magnitude (Barans and Stender 1993).

Trawling and dredging leave long-lasting evidence of their existence on the ocean floor (Friedlander et al. 1999) and because many organisms in the deep are very slow-growing and have late ages of maturity (Roberts 2002; Rodgers 1999), recovery from trawling and dredging may take centuries or more, if it is possible at all. Through carbon dating, deep sea coral reef structures of *Lophelia pertusa* have been estimated at 3,000 to 4,000 years old (reviewed by Mortensen et al. 1995), similar to estimates for other deep-sea coral species (Hall-Spencer et al. 2002). Species such as these of the deep slope can probably tolerate very little disturbance (Druffel et al. 1995), and those individuals that do survive will clearly take millennia to regrow.

Fishing may have additional unforeseen consequences to habitats and thus to nontarget species. In general, the effect is related to the destructive nature of the fishing practices. Such a fishery-induced cascade has been documented on intertidal flats in the Dutch Wadden Sea after three years of intensive suction dredging for cockles (*Cerastoderma edule*) and intensive capturing of the edible mussel (*Mytilus edulis*) (Piersma and Koolhaas 1997). Wherever these species were eliminated, two other species of bivalve that were thought to be competitors also declined, probably because of indirect effects of habitat alteration.

Pollution

Pollutants come in many forms, and the oceans are often the ultimate repository of these wastes. Bioaccumulation of toxic metals and human-made organ-

ics in the food web threatens, in particular, the survival of top predators. The most polluted marine mammals, mammal-eating killer whales (*Orcinus orca*) of the North American northwest coast and belugas (*Delphinapterus leucas*) of the St. Lawrence estuary, have sufficient toxic loads that their immune systems are impaired and their life spans may be shortened (Deguise et al. 1995; Ross et al. 2000).

Anthropogenic noise pollution in the marine realm due to shipping, petroleum exploration and development, and military use of low- and mid-frequency sonar have the potential to disturb, injure, or kill many marine creatures, most notably deep-diving marine mammals (Jepson et al. 2003; NOAA 2001). The impact noise has in the open and deep oceans is likely far underestimated since it is only in instances when carcasses wash up on land that humans are even aware that the deaths have occurred.

In the tropics, land-based pollution, particularly nutrient run-off from agriculture and siltation from construction, is one factor that has eliminated local populations of corals. Land-based nutrient pollution greatly reduces coral reef diversity (Edinger et al. 1998) and can make corals more susceptible to epizootics (Bruno et al. 2003). As more and more local populations disappear, extinction is the inevitable result.

The well-known loss of local populations of corals in the tropics is mirrored, but often overlooked, in the temperate regions with the loss of local populations of macroalgae due to eutrophication. As large areas of the coastal ocean are subjected to nutrient pollution, those species adapted to nutrient-poor conditions will be outcompeted (Worm et al. 2002). Over 50 percent of macroalgae have disappeared from the Black Sea (Bologa 2001), and similar losses have occurred in the Baltic Sea (Schramm and Nienhuis 1996). Furthermore, there is reason to suspect that diversity in macroalgae might be high below the levels we commonly recognize as species. Hence, the loss of biodiversity might be much greater than we suspect when local "populations" disappear. For example, along the coast of Nova Scotia, which is much less affected by eutrophication than most areas in the North Atlantic,

brown seaweeds of the genus *Fucus* have great diversity in the timing of their reproductive cycle; individual plants in the same location may vary by nine months (personal communication with A.R.O. Chapman, Department of Biology, Dalhousie University, Halifax, Canada). The genetic diversity responsible for this variation could be lost if certain populations, or other species, were favored under high nutrient conditions. Given the number of other species that depend on macroalgae for food and protection at various life stages, loss of these species spells a precarious future for others.

Climate Change and Extinctions

Other large-scale anthropogenic changes, such as increased ultraviolet radiation and global warming, may change environments more quickly than species can adapt, and if so, will result in increased extinctions. In a recent attempt to predict the potential losses, the current geographic range and "climate envelope" of 1,103 terrestrial species were compared to the regions predicted to have similar temperature, precipitation, and seasonality under different climate scenarios for 2050 (Thomas et al. 2004). Through species–area relationships, some 18 to 35 percent of terrestrial species were predicted to be "committed to extinction" due to imminent climate change. Climate change can impact the oceans as well, not just changing temperatures, and storm pattern and frequency, but by changing ocean circulation and the frequency and severity of El Niño/Southern Oscillation (ENSO) events (Buddemeier et al. 2004). Coral bleaching, the ejection by corals of their endosymbiont photosynthetic zooxanthellae (leaving the corals to appear white, as though bleached), is one of the most dramatic phenomena linked to global warming.

In the last 30 years, coral bleaching has been observed globally, and its incidence appears to be increasing (Buddemeier et al. 2004). Bleaching causes widespread coral mortality and has been shown to reduce fecundity, making recovery from bleaching episodes, particularly if frequent, very difficult (Hoegh-Guldberg 1999). Bleaching events coincide with

higher than normal sea surface temperatures; particularly severe bleaching events in 1998 appeared to be the result of extreme temperature shifts related to a strong ENSO event. While mean sea surface temperatures in tropical seas may have varied less than 2°C since the last major glaciation (Thunell et al. 1994), mean sea surface temperatures have risen 1°C in the last 100 years, and this rise is expected to continue (Hoegh-Guldberg 1999). In fact, Hoegh-Guldberg (1999) predicted that severe bleaching episodes on the order of the 1998 ENSO will be reached annually by seasonal temperature changes within the next 20 years. Other authors predict less severe scenarios, yet agree that large-scale changes in coral communities will occur due to current predictions of climate change (Hughes et al. 2003). Can corals adapt to this rapid change in temperature? Can recolonization of corals occur from areas with different temperature tolerances? These are very important questions without promising answers. Given the number of species that rely on coral reef systems, major ecosystem changes due to widespread coral decimation will have cascading effects that will inevitably result in the extinction of many species that rely on these ecosystems.

Extinction Predictions Due to Habitat Loss

Habitat loss, caused by whatever means, will eventually result in large-scale extinctions, because extinction tracks habitat loss in the sea (Carlton 1993) in the same way it does on land (Ehrlich 1995). As with tropical forests and other terrestrial biomes (Simberloff 1986; Thomas et al. 2004), it is possible to estimate roughly the long-term species loss given a known area of habitat loss. We will consider coral reefs as a marine example. Some estimates are that, due to various causes, including coastal development, marine and inland pollution, destructive fishing practices, and climate change, 27 percent of coral reefs are under high threat (including approximately 10 percent that have already been destroyed), a further 31 percent are under medium-level threat, with the remaining area deemed to be under relatively low threat (Bryant et al.

1998; Wilkinson 2002). These estimates and extrapolations are very approximate but show the order of magnitude of the problem.

The species to area relationship is a well-established hypothesis that states that the number of species is proportional to A^z, where A is area and z is an empirically determined parameter, typically with a value around 0.25 (e.g., Brooks et al. 1997; Hughes et al. 2003). Suppose we use 0.25 as an approximate value for z. This would suggest that, were we to lose the 58 percent of reefs at medium and high risk, approximately 20 percent of the coral reef–dependent species would eventually go extinct. Similar, if not greater, losses in species are to be expected in many of the shallow-water ecosystems, such as mangroves, because habitat loss is probably greater in these areas (Johannes and Hatcher 1986; Valiela et al. 2001). If we assume similar losses in other marine systems and put this in a terrestrial biodiversity perspective, this is equivalent to losing a continent.

The Role of Introduced Species

A fundamental source of biodiversity is adaptation to specialized niches. Hence, introductions of species into areas where the introduced species have few or no natural predators can lead to the decimation of local species through predation or competitive exclusion, and a worldwide process of homogenization. For example, the introduction of the seastar (*Asterias amurensis*) in southern Tasmania has been implicated in the near extinction of the spotted handfish (*Brachionichthys hirsutus*) (Anderson 1996). Although introductions of species are probably not as important in the open ocean as on land, in coastal environments they can be devastating. In some coastal regions, for example, San Francisco Bay, as many as 75 percent of the species have been introduced (Carlton and Ruiz, Chapter 8). Aquaculture can result in a more insidious form of introductions, because hatchery-adapted individuals can interbreed with wild local populations, spreading maladaptive genes (Einum and Fleming 2001).

Policy and Extinctions

Globally, most current fishery management is not only causing extinctions but is also economically unsound. On a purely economic level, virtually all analyses of fishing conclude that greater economic rent could be obtained with reduced effort (Clark 1990). However, the fishing industry is one of the most subsidized industries in the world (Garcia and Newton 1997), and therefore has very little incentive to adopt more rational policies. A common belief is that economic and biological feedbacks prevent the fishing of a species to extinction. However, economic feedbacks often do not work because of high discount rates, overcapitalization, and subsidies (Clark 1990).

Given the overwhelming importance of fisheries practices as potential extinction factors in the oceans, the single best solutions to reducing extinction in the marine realm are rational fisheries policies, which bring an ecosystem view to management. While the phrase *multispecies* or *ecosystem management* has been bandied about in management policy for some time, putting its ideals into practice has been more elusive. Preventing extinctions requires management for the most sensitive species taken and for the ecosystem effects of fishing, rather than merely the effects on the target species. We propose that several basic goals should be central to all fisheries policy: avoid habitat damage, fish selectively, and protect marine biodiversity.

Recently, a group of 70 fishers, fisheries scientists, managers, and others informed on this topic were polled regarding their perceptions of the ecological severity of various fishing practices (Morgan and Chuenpagdee 2003). Across all groups of participants, practices that caused destruction of habitat, particularly bottom trawling and dredging, were viewed to be much more severe than others, even those that may have taken more bycatch. Practices viewed most favorably were those that caused very little physical damage to habitats, such as hook and line fishing, purse seining, and midwater trawling (Morgan and Chuenpagdee 2003). These fishing practices can be

more selective and provide greater long-term sustainable yields than other fishing methods, without destructive side effects.

An example of a relatively good fishery is the largest whitefish fishery in the world, that for Alaskan walleye pollock (*Theragra chalcogramma*). This fishery has limited the use of bottom trawls in favor of midwater trawls, which reduce, although do not eliminate, negative effects on bottom-dwelling species such as Pacific halibut (*Hippoglossus stenolepis*) and king crab (*Paralithodes camtschaticus*), and which have a low rate of bycatch (Paine et al. 2003). Furthermore, the Alaskan walleye pollock has been fished in a conservative manner; the fishing mortality is usually below 20 percent. While these are steps in the right direction, the sheer magnitude of this fishery means that, although the bycatch rate is quite low, in overall numbers, bycatch is very high.

We join others in recommending a full ban on trawling and dredging in all areas that have not yet been trawled, and all areas that are likely to be sensitive to these types of gear (even if they have already been trawled); for example, seamounts and regions with corals and sponges (Halpern 2003; Pew Oceans Commission 2003). The structural damage caused to bottom habitats by mobile bottom gear may take hundreds or thousands of years to be repaired, if it is possible at all. Furthermore, from a purely economic standpoint, the importance of many of these habitats as nursery grounds for other commercial species should not be underestimated. The future of many fisheries depends on the health and persistence of these zones.

A second goal for fisheries policies should be, wherever and whenever possible, to fish selectively and to manage for the most sensitive species caught, regardless of whether this is the target species (Myers and Worm 2004). Reduction of bycatch to zero should be the overall goal when making gear choices and modifications (Halpern 2003). However, while bycatch is occurring, detecting the health of populations from fisheries statistics requires that catches be recorded at

the species level. Unfortunately, this is not the case in many regions, including nations that believe they have advanced management capabilities. For example, until recently, catches of skates were not distinguished to the species level in the catch records in North America and Europe. Because of this practice, the disappearance of large, slow-maturing species was masked by increases in other skate species (Casey and Myers 1998). This mistake has been repeated in tropical regions, often at the suggestion of fisheries consultants from northern countries paid for by foreign aid. For example, in the Caribbean countries within the Carribbean Community (CARICOM) fisheries organization, catches of groupers are not distinguished by species, even though this is usually easy to do. Thus the decline of the more vulnerable groupers cannot easily be detected from the catch records. Clearly, it is best to record catch to the species level.

Marine reserves can act to preserve a piece of the natural environment. However, most marine reserves, or marine protected areas, that exist today usually protect only very local habitats (typically of less than 10 km^2; Halpern 2003) and are too small to shelter many species. Although reserves of all sizes appear to foster population increases, large reserves more likely encompass more species, particularly rare species, at more stages in their life history, and are more likely to have substantial positive effects on ecosystem health and population recovery (Halpern 2003). We join others in encouraging the establishment of large reserves (Berkeley et al. 2004b; Jackson 1997), especially near prominent habitat features such as reefs, hotspots, or shelf breaks, where there is high oceanic diversity (Worm et al. 2003). Reserves can act as banks to ensure persistence of diversity; many have spin-off benefits as nurseries for fisheries in surrounding areas. However, reserves can be successful only if, both in legislation and in practice, destructive activities are stopped. Despite the often long process of consultation with stakeholders in establishing marine reserves, this process is important for their long-term success.

One critical issue in creating marine reserves is to ensure the overall reduction of fishing effort, not merely local fishing effort (Myers and Worm 2004). Redirection of fishing effort to other locations can be as detrimental, or more so, than the practices intended to be curtailed by a fishing closure (Baum et al. 2003).

Fisheries are not the only factors involved in marine extinctions; however, they are likely the most important and the most straightforward to alter in preventing extinctions. Nonetheless, broader threats of nutrient, toxic, and noise pollution are present and require action. In general, we need to bring into the public consciousness exactly how our land-based activities impact both ocean and atmosphere. Burning of fossil fuels and other activities hastening climate change must be greatly reduced immediately since, even now, we will be feeling the effects of current greenhouse gases for decades. Energy policies that promote and foster both conservation of energy and alternative energy production will be critical in determining our impact on the planet for the next century and beyond.

Conclusions

Humans are now causing a rapid process of marine extinctions on par with those we caused on land each time humans invaded a new terrestrial realm. Indeed, we have mounted the offensive on many fronts. We have captured and killed vast proportions of the sea's inhabitants. We are destroying the quantity and the quality of habitats through repeated physical destruction, through the slow poisoning action of pollutants, by turning up the heat, and by generating at times deadly noise. Indeed, the effects of loss of habitat on extinction may be even greater than the direct effects of fishing. Governments have and continue to subsidize these acts. One would think this onslaught were a coordinated campaign.

Ultimately, any effort to mitigate the ongoing marine extinctions requires individual action. In Nova Scotia, two fishermen have led an extensive effort for the conservation of deep sea corals off our coast. It was their knowledge and action that inspired environmental activists and university scientists to study the

problem and publicize the issues. We need now to coordinate our efforts to achieve protection and more sensible scales of use. Rational fishing practices that mitigate habitat loss, relieve pressure on target stocks, and avoid bycatch would both reduce extinctions and lead to economic benefits.

Acknowledgments

Note

1. The barndoor skate has recently increased in the southern part of its range, but not in the north.

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