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Chapter 5

Fisheries and Fisheries Science in Their Search for Sustainability

Gotthilf Hempel and Daniel Pauly

WHAT ARE FISHERIES AND FISHERIES SCIENCE ABOUT?

Fisheries is the exploitation of the living resources of the sea. In a broad sense, fisheries encompass not only the catching of finfish and invertebrates such as shrimps and squids, but also the collection of cockles and other bivalves and of seaweed, and the (largely past) hunting of marine mammals. The farming of fish and aquatic invertebrates is also often, if confusingly, considered by many to be part of fisheries, as well. Fisheries employ craft ranging from outriggers to factory trawlers and nets ranging from beach seines to open-ocean driftnets dozens of kilometers long. Fisheries products may be consumed by subsistence fishers and their families or sold on a strongly integrated global market. For millennia, fished organisms and/or their shells have been used as raw material for jewelry or other nonfood products. More importantly, one-third of the world landings are diverted from direct human consumption to feed pigs and other farmed animals, with an increasing fraction of global fish meal and oil production being used to feed salmon and other farmed fish and aquatic invertebrates, particularly shrimp.

Fisheries date back to the Stone Age, but still represent one of the key uses of the world ocean. Globally, annual marine landings peaked at about 80 million metric tons in the late 1980s (figure 5.1). About 20 to 30 million metric tons of fish caught as bycatch, and subsequently discarded, may be added to this, resulting in a global annual catch (= landings + discards) of more than 100 million tons in the waning years of the late twentieth century.

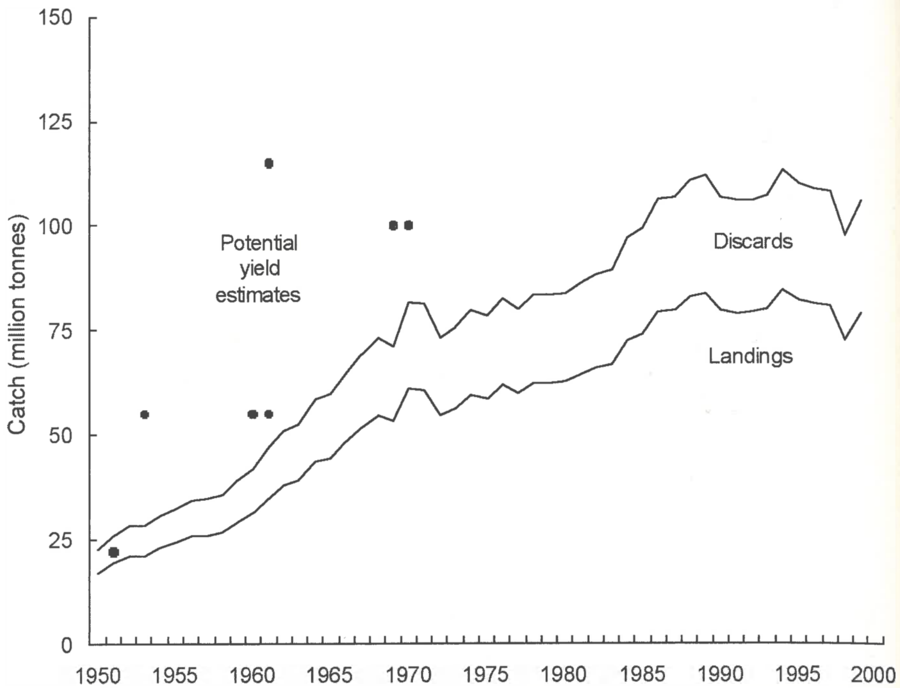

Figure 5.1. Marine fisheries statistics from 1950 to 1997, contrasting nominal landings (from www.fao.org) with an estimate of discarded bycatch for the early 1990s (from Alverson et al. 1994), scaled to the landings from other periods. Dots represent some earlier published estimates of potential yield for the global ocean. Note that nominal landings in the 1990s are probably overestimated by about 10 million tons, due to excessive reports from East Asia; also note that global catch composition is rapidly changing, with small pelagics and invertebrates increasingly replacing larger bottom fishes, whose absolute catches are declining. This results in the trends illustrated in Figure 5.3.

Marine fisheries provide about 20 percent of the world protein supply. For large parts of the world population, particularly in East and Southeast Asia, fish in the broad sense is the most important source of animal protein; 200 million heads of cattle would be required to substitute for this (Alverson et al. 1994; Hubold 1999). From the early 1950s to the late 1980s, capture fisheries landings and aquaculture production grew faster than the global human population, leading to a substantial increase in fish supply per person. This trend reversed in the 1990s, and it is only the large reported increase in global aquaculture production that has prevented a rapid decline of fish supply per person.

During the past fifty years, world fisheries have seen drastic changes due to technological developments and the emergence of the new Law of the Sea, the collapse of the Eastern Bloc distant water fisheries, and the globalization of much of the fishing industry and of the markets for marine products. All those changes had substantial effects on the living resources themselves, through various ecological and economical feedback mechanisms. Of all human impacts on marine ecosystems, fisheries are the most important, particularly in shelf seas.

Most of the world's landings are taken from about 200 fish stocks, more than half of them fully used or decreasing because of overfishing. The stocks of much sought after bottom fishes, like cod, groupers, hake, and sole, are in a particularly deplorable state. As a consequence, the fisheries have turned to species that were formerly less valuable and have expanded to deeper and more distant fishing grounds.

It was concern about the stagnation and decrease in wild-fish landings—in spite of increasing fishing effort—that more than 100 years ago gave birth to fisheries science, whose task was to provide advice for a better management of the fisheries, based on scientific insights into the dynamics of the fish stocks as parts of marine ecosystems. More ominously, other aspects of fisheries science were devoted to making fishing operations more effective, notably by improving location and catching methods.

Our chapter deals largely with the problems faced in the attempt to enhance the sustainability of fisheries and their associated ecosystems at the high level of exploitation prevailing nowadays.

ORIGINS

The hunter-gatherer ancestors of modern humans would usually stay at a given spot as long as its fauna and flora provided enough food. When the "patch" in question was too disturbed to remain productive, they then moved on. With regard to fisheries, we often still act as "patch disturbers."

The community of professional fisheries scientists that had emerged in Western Europe by the end of the nineteenth century was well aware of the impact of heavy fishing on the abundance and productivity of fish populations. The International Council for the Exploration of the Sea (ICES), founded in 1902, immediately created an Overfishing Committee and concentrated on obtaining practical results on the question of overfishing. The ICES scientists were particularly interested in the effects of fishing on the flatfishes in the southern part of the North Sea. This was the first area and species complex to be fully exposed to the impact of steam trawling (Went 1972; Cushing 1988).

SUSTAINABILITY AS A GOAL OF FISHERIES SCIENCE

Overfishing made fisheries science one of the first natural history disciplines to be fully structured around the concept of sustainability. Major conceptual advances in fisheries science include the first-catch curves and yield per recruit analyses (Baranov 1918), the first functional definition of overfishing (Russell 1931), of "maximum yield" (Bückmann 1938) and of "surplus production" (Graham 1943), all of which may be seen as attempts to render the concept of sustainability operational. Such interpretations then logically led to the concept of maximum sustainable yield (MSY) (Schaefer 1954; Beverton and Holt 1957), a concept which, for several decades, was at the very heart of fisheries science (figure 5.2). Given basic economic considerations, this leads to maximum economic yield, an even worthier goal.

From the very beginning there has been a gap between the theories and advice of fisheries scientists and the praxis of fishing industry (Mace 1997). This has largely limited the profession to one that diagnoses and prognoses, but cannot solve problems on its own. Fishery regulations and management have been, so far, the responsibility of governments and industry. The results have been stock declines, and a sustainability that appears very difficult, if not impossible to achieve (Ludwig et al. 1963), even for well-studied, staple fish such as cod in the North Atlantic, where fisheries research has emerged as scientific discipline in its own right, with a high concentration of prestigious scientific fisheries research institutions.

We are faced with a worldwide surplus of high technology fishing vessels. Excess fishing mortality in single-species fisheries implies—at least in theory—that fishing becomes unprofitable when low biomass levels are reached. This should result in a reduction of fishing effort; thus, in theory, fishing effort should be self-regulating. But in practice this is not the case, partly because of the massive subsidies that governments provide to fisheries (see figure 5.2) and partly because of differential fishing costs within heterogeneous fleets. Rothschild (personal communication) suggests that a lack of property rights might make a significant contribution to excess capital in fisheries. This is illustrated in box 5.1, which deals with an unsteady market-driven fishery on blue whiting and hake on the Patagonian shelf.

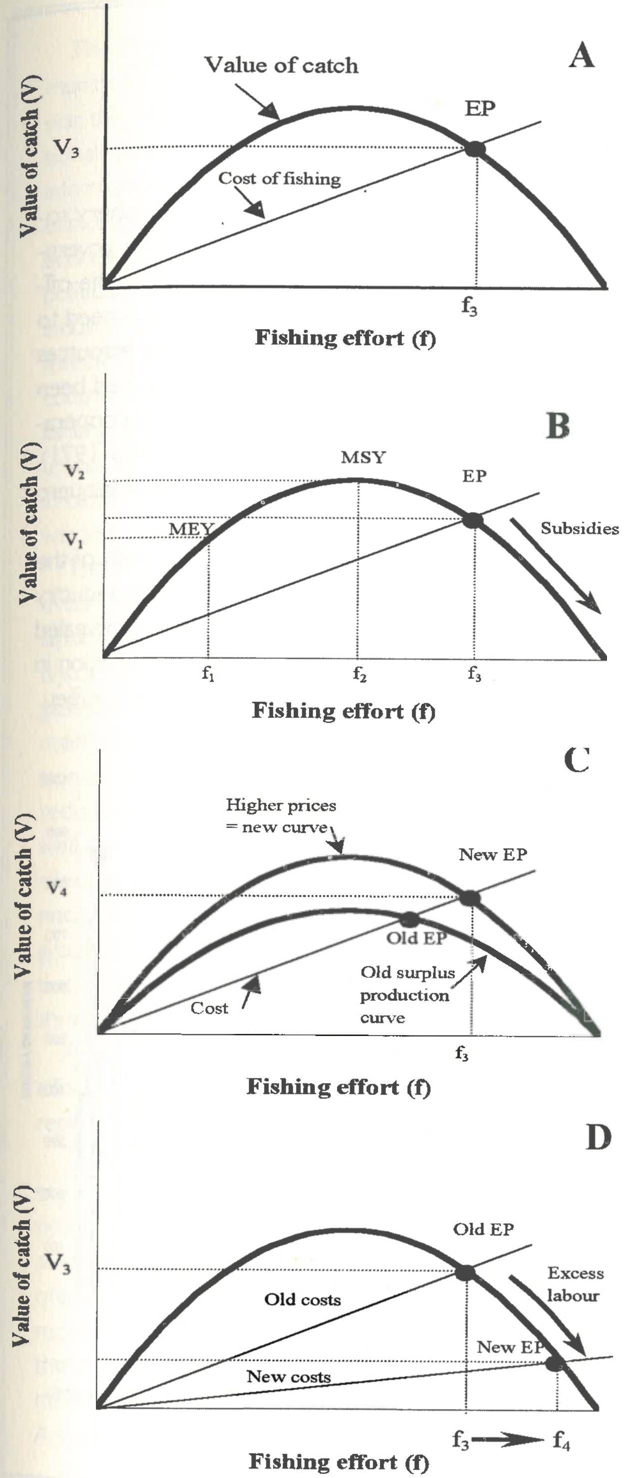

Figure 5.2. Schematic representation of the key economic factors affecting open-access fisheries: A: Basic model, in which fishing costs are assumed proportional to fishing effort (f), and gross returns are a parabolic function of effort, whose maximum defines maximum sustainable yield (MSY). B: Under open access, f will increase past maximum economic yield (MEY) at ±f_1 (where the economic rent, i.e., the difference between total costs and gross returns is highest), and past MSY (at f_2), until the equilibrium point (EP, at f_3), where costs and returns are equal, i.e., where the economic rent is completely dissipated. In this situation, subsidies, by reducing costs, increase the level of effort at which EP occurs, and thus decrease catches. C: Price increases, by increasing gross returns, increase the level of effort at which the rent will be dissipated (i.e., from f_3 to f_4), and hence foster overfishing, just as subsidies do. D: In small-scale fisheries, labor is a major cost factor; when its value tends toward zero (as occurs when there is a large excess of rural labor), resources may become severely depleted, leading to "Malthusian" overfishing (Pauly 1997).

Box 5.1. The Role of Science in an Unsteady Market-Driven Fishery: The Patagonian Case

Ramiro Sánchez

It was not until the second half of this century that commercial fishing and fishery science began to move ahead in Argentina. During the 1960s and 1970s the government took a series of measures that aimed at promoting the expansion of the offshore fleet, the hake fishery, and the development of Patagonia. There was a need to carry out systematic research, with established programs covering the main resources inhabiting the largest continental shelf in the Southern Hemisphere, which had been latent for decades. This need was met first through international technical cooperation programs, noticeably a Food and Agricultural Organization project (1966–1971), and later by the creation of Instituto Nacional de Investigación y Desarrollo Pesquero (INIDEP) (1977) and the incorporation of three research vessels.

These initiatives, however, were not enough to ensure the sustained growth of the fishery. For nearly thirty years, political and economic instability affected both industry and science in different ways (figure BX5.1). The crisis in the early 1980s also revealed some structural weakness in the organization of the industry and the first reduction in the biomass of the hake stock—a notion that did not go beyond the scientific milieu.

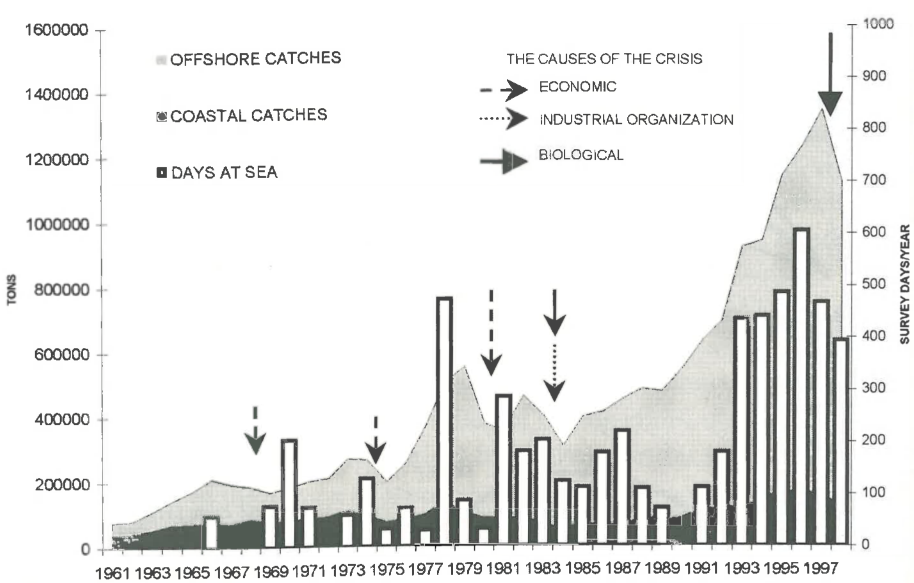

Figure BX5.1. The evolution of fishery research (vertical bars = survey days) in Argentina with fleet development and fishing crises as a background. Sources: Argentine official statistics and Fishery Economy Project, INIDEP/University of Mar del Plata.

The Malvinas (Falklands) War in 1982 drew the attention of the international community toward the southern extreme of the continental shelf off Argentina. After the war, the fishing scenario in the region changed dramatically. The activity of the international fleet grew constantly throughout the decade. In spite of acknowledged information gaps, Argentinean scientists expressed their concern for the high levels of exploitation of squid, hake, and blue whiting (INIDEP 1986). The downfall of the local economy caused a gradual decline in the support given to marine science. There were political and economic changes and a new legal framework aimed at reinvigorating the industry and encouraging foreign trade and investments. These were the basis for a threefold rise in the catches of the offshore fleet from 1988 to 1997. Several factors contributed to this uncontrolled rise, including the development of a managed squid fishery with a chartering regime, the incorporation of large factory vessels, and the unwanted outcome of a fishing agreement with the European Union. A historic peak in catch (1.34 million tons) was reached in 1997. A large fraction (80 percent) of this was accounted for by only three species: squid, hake, and southern blue whiting.

The Argentine fishery is, at present, undergoing the worst crisis of its comparatively short history. It is also unique in that it is largely based on the biological collapse of several of its main fish resources. Blue whiting and hake show clear signs of uncontrolled exploitation (figure BX5.2). The high catch levels internationally suggested for the blue whiting during the 1980s (Csirke 1987) could clearly not be maintained. No other resource has been so greatly affected by the present expansion of the local fishery as hake. Fall of the spawning biomass, recruitment failure, reduction in the size and age of the population structure, and other symptoms are well documented (Pérez et al. 1999). Technical advice is definitely not lacking. The allocation of sea survey time to this resource is unprecedented. But aside from science, the recovery of the stock will necessarily imply intensified control. Nursery grounds, although well identified, are not yet completely closed to the fishery. Selective gear to reduce the unwanted catch of juvenile hake and the bycatch in the shrimp fishery have been designed, though not yet enforced or effectively applied.

A new legal tool was drawn up in 1998 as a means to regulate fishing capacity and effort. The basis for the assignment of quotas and the species to be included in the new regime were matters of considerable debate. The system has not yet been implemented.

The present crisis brought with it a drastic change in the relationship between fishery scientists, administrators, the industry, and the press. The avenues of communication between the different participants are quite open, and we have the feeling that scientific results matter, even if they are not immediately enacted. A new generation of scientists was forced to move from the backstage to the footlights. In spite of being molded by the old—and valuable—tradition, they have so far succeeded in meeting the challenge. Research, albeit proactive, must transcend the constraints of operational management. The academic world has yet to react accordingly. The future of the Argentine fishery will require a new type of scientist.

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Box 5.1. Continued

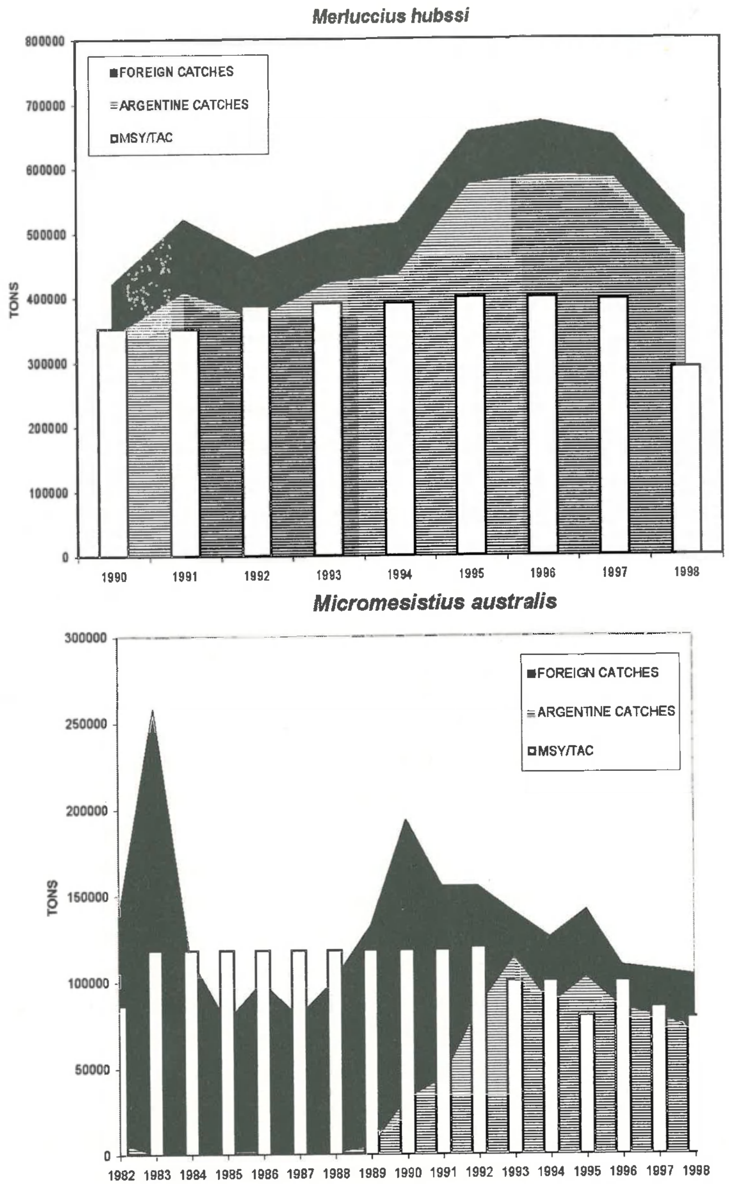

Figure BX5.2. Exploitation beyond scientific advice and regulations by Argentine and foreign vessels. Bars indicate maximum sustainable yield/total allowable catch (MSY/TAC) values for hake and blue whiting. Based on INIDEP Hake Assessment and Austral Fisheries Projects.

ENVIRONMENTAL INFLUENCES ON FISH STOCKS

Fisheries exploiting, for example, coral reefs are very different from those exploiting temperate soft bottom shelf seas, deep continental slopes, eastern boundary upwelling regions, or the open ocean realm. Each of these systems, therefore, calls for an individual management strategy.

In the various parts of the world ocean and its shelf regions, temperature and current regimes differ in the pattern and extent of their variations. Fish stocks are susceptible to those changes, which impact their recruitment, but also their distribution and spawning migrations. Much of the controversy among fisheries biologists about the relative importance of "environment" versus "fishing" as causes of stock variations results from the differences in the susceptibility of various stocks to changes in the environment. Strategies for sustainable exploitation of fish stocks will vary with the longevity and growth of the targeted species, but also with the natural variations of their environment. Thus, fishing is not the only reason why fish stocks fluctuate. Sediment cores in upwelling regions demonstrate periodic shifts in the abundance of anchovies and sardines alternating back in time long before fishing commenced. Long-term observations have further suggested that ocean climate and fisheries might interact to cause multidecadal fluctuations in stocks.

But, factors others than ocean climate are also involved. The various fish species that are targeted by fisheries are parts of ecosystems, which also must persist in a certain state for the fisheries to be sustainable. This requirement was not widely acknowledged until recently. It seemed hard enough to deal with the assessment of single species populations, let alone whole ecosystems.

THE MULTISPECIES PROBLEM

In multispecies fisheries, the self-regulatory process hypothesized above does not occur even in principle, because a fishery that continues to exploit a much-depleted species (e.g., of large fish in a shrimp trawl fishery) catches fish that it has not targeted. Hence, shrimp fisheries contribute substantially to the discarding problem mentioned above (see figure 5.1 and Alverson et al. 1994). The implications of removing such large amounts of fish and invertebrates from the marine ecosystems, then dumping them—mostly dead—back in the water, are still not understood.

Bottom trawl fisheries are able to control the overall numbers of fish that are killed, but not the relative mortality of the different species in a multispecies fishery. In a commercial fishery not using highly selective gear, some species will always be subjected to excessive, nonsustainable mortality, leading populations to drop to very low levels. But each species reacts differently to changes in stock size and to changes in the environment, making predictions even more difficult.

Biological interactions cannot be ignored, especially feeding interactions. First of all, it is not possible to exploit simultaneously a species of predatory fish as well as its prey species and to expect both species to produce their stock-specific MSY. Catching the prey fishes reduces the food base for the predators and hence their productivity and potential yield. Many predators feed on a variety of fish and invertebrates simultaneously, and hence predator depletion can lead to unwanted prey becoming abundant. On the other hand, exploiting forage (prey) species can reduce stocks of predator fish. This may seem trivial, but there are very few governance arrangements for predator fisheries that explicitly reduce fishing on the prey species, for example, by compensating those who want to target the latter. One example where such a policy is practiced is Iceland, where attempts are made to boost the cod (predator) population by limiting the shrimp and capelin (prey) fisheries.

FROM SPECIES CHANGES TO FISHING DOWN MARINE FOOD WEBS

Changes in species dominance in ecosystems, and hence in fishery catches, have been known to occur for decades. Indeed, not all of these changes are due to fishing (Daan 1980; Skud 1982). But analyses of a large number of cases of species changes in different regions, at least over the past two decades, show a disturbing, common pattern. Almost everywhere, large, long-lived fish high in the food web tend to decline, both in the catches and in the ecosystem. They are then replaced by species of small, fast-growing fish with lower trophic levels (Pauly et al. 1998.) (figure 5.3). This process of "fishing down food webs" would be acceptable—at least to some—if the decline of mean trophic levels was accompanied by a corresponding increase in catch size. But, while such an increase often occurs at the outset of fishing down, it is usually short-lived. Moreover, average fish sizes in the catch decrease, whereas the proportion of invertebrates in the catch increases. This might be welcome if they are highly prized shrimps, but not if they are starfish.

CONFLICTS BETWEEN USERS

Coastal habitats differ widely, ranging from sandy and muddy shores and estuaries to hard rock, mangroves, and coral reefs. Each habitat has its spe-

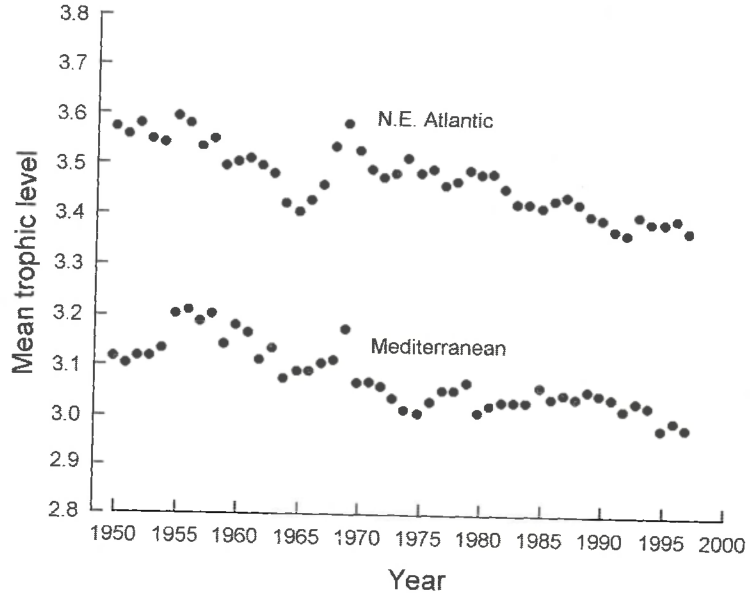

Figure 5.3. Trends of mean trophic level of fisheries catches in the Northeastern Atlantic and the Mediterranean, documenting that fisheries increasingly rely on fish from the lower parts of marine food webs. Similar trends are observed in other parts of the world (Pauly et al. 1998). Note that most commercial fish have trophic levels between 2.5 and 4.5, implying that the trends in question cannot continue for long without major disruption of marine food webs. Based on data in FishBase; see Froese and Pauly 2000 and www.fishbase.org.

cific fauna, interacting with that of neighboring habitats and with the fish stocks of the open sea. The natural resources include not only many kinds of fish, but also mollusks, shrimps, and other invertebrates as well as algae.

Nearshore fisheries are more ancient and more diverse than open-water fisheries. Fishing methods and practices vary widely, and most of the nearshore catch consists of a multitude of species. Landings are spread over many small places, often without passing through a centralized sales system. As a result, statistics of efforts, catches, and landings for nearshore fisheries are often poor. Still, small-scale, nearshore fisheries make a substantial contribution to world fisheries in terms of total landings and value. In addition, these fisheries are the main source of both protein and income for large parts of the coastal populations, particularly in tropical and subtropical zones.

Naturally, the inherent wealth and diversity of coastal waters attract not only fishers and fish farmers, but also a variety of other uses, such as tourism, transport, and the extraction of nonliving resources (e.g., sand, coral stone, oil, and gas). Coastal waters are also abused as sinks for pollutants and nutrients.

With such a diversity of stakeholders, some conflict is inevitable, with the fishers often on the losing side. Fishing may appear to be incompatible with, for example, some industrial uses like pipelines, wind parks, and traffic lanes. But conflicts also occur within the fisheries sector itself, for example, trawlers versus longliners, recreational versus commercial fishing, artisanal fishers versus large-scale operators, or inshore capture fisheries versus mariculture. Conflict resolution thus must include representatives of these stakeholders as well as conservation biologists, and nongovernmental organizations (NGOs) representing the interests of local communities or advocating nature conservation.

Knowledge of the key features of the coastal and oceanic food webs is essential for the biologists involved here, along with information on the demographic, social, and economic features of the people who depend exclusively or partly on fishing. A new generation of integrated approaches will have to combine ecological and fisheries knowledge with information on the socioeconomic framework of fishing. Those approaches, even in their simplest form, must also include a co-management component, allowing for the interaction of fishing communities, industry, NGOs and conservationist groups, and government managers.

Fisheries management uses a number of regulatory tools, such as catch and effort limits, minimum landing size, gear restrictions, closed seasons, and, recently, marine protected areas. But we need to know more about their effects on the exploited and unexploited parts of the resource, the economics of the fisheries, and their impacts on biodiversity and exploited ecosystems.

Fisheries, like most other human activities at sea, alter the marine environment on various scales of space and time. Recently, Jackson et al. (2001) identified overfishing as the most important human impact on a variety of shelf and coastal ecosystems, with past overfishing of large marine animals blamed not only for collapses of the targeted stocks, but also for drastic changes in the overall structure of the underlying ecosystems. In nearshore waters, semiclosed seas and estuaries, eutrophication may play a similar role by causing algal blooms and oxygen depletion. Other anthropogenic impacts include the introduction of alien species as predators, competitors, and pathogens. In the long run, our impact on the climate change will, as well, add to the effects of those impacts on marine ecosystems.

Apart from top-down effects of fisheries on marine food webs resulting from removal of predators, marine ecosystems are often impacted directly, for example, by bottom trawls. The fishing grounds of the North Sea and the northern North Atlantic shelves are ploughed again and again, many times per year and for many decades: the rougher the sea floor, the heavier the gear.

In their search for new resources, the patch disturbers reach now for pristine areas 1000 m down the continental slopes. There, the unique communities of the cold-water coral *Lophelia* become endangered even before they have been scientifically explored (see box 5.2). The rock-hopper gear of heavy bottom trawls bulldozes the coral banks hitherto exploited only by nondestructive longlines and gill nets.

Modern fisheries science has to provide the scientific knowledge needed for sustainability, that is, for obtaining a continuous supply of fish and other seafood. On the one hand, fisheries science should analyze the ecological impacts of fisheries and mitigate these with regard to biodiversity and ecosystem integrity. On the other hand, fisheries science will have to contribute its bit to the peaceful coexistence of fisheries with other marine stakeholders. In order to meet all those demands, fisheries science must become a multidis-

Box 5.2. Deep-Water Coral Ecosystems

Johan H. Fosså

Several species of deep-water corals form reefs. *Lophelia pertusa* is the most widespread and best known. It is almost cosmopolitan, but occurs most commonly in the Northeast Atlantic. It thrives in oceanic water, usually between 6 and 12°C, at depths of between 60 m to several thousand meters and on hard substrates of several kinds: on continental slopes, seamounts, ridges, and banks and in fjords (e.g., Rogers 1999). Deep-water banks of these corals can be up to 13 km long and 350 m wide.

A highly diverse fauna is associated with these banks, where the complex architecture of the skeletons provides a variety of different microhabitats. Along the Norwegian coast alone, a total of 614 associated species have been documented. Almost nothing is known about ecological relationships within the *Lophelia* reef community. Longline fishing shows that catches of *Sebastes marinus*, *Molva molva*, and *Brosme brosme* are significantly higher in coral areas than on the surrounding bottoms.

Bottom trawling and oil exploration seem to be the two most probable threats to the reefs. *Lophelia* reef areas have traditionally been rich fishing grounds for longline and gill-net fisheries. During the past decade, bottom trawlers with rock-hopper gear have extended their fishing grounds into the coral reefs. Trawlers often crush the corals to clear the area before fishing starts. Reports from fishers suggest that large areas have been cleared and that catches are significantly lowered in cleared areas. There is growing evidence that the destruction of corals is one of the most severe forms of habitat destruction in Norwegian waters (Fosså et al., in press). Extensive

(continues)

Box 5.2. Continued

damage to reefs has also been reported from Iceland, the Faeroe Islands, and the western side of Great Britain. Investigations on southern Tasmanian seamounts have revealed extensive damage to deep-water reefs formed by *Solenosmilia variabilis*, caused by a trawl fishery for orange roughy and oreos.

Because *Lophelia* grows slowly, the recovery rate of damaged reefs is also likely to be extremely slow, which makes the damage of these habitats a serious environmental problem.

To gain information about the presence and status of deep-water coral reefs, the most promising approach seems to be mapping the seabed by multibeam echo sounder, combined with deep-towed side-scan sonar and information from fishers. Provisional maps can then be validated using remotely operated vehicles (ROVs) equipped with video cameras to determine the exact location of the reefs in order to advise fishers where to set nets or longlines to avoid losing gear or damaging the corals. Enforceable regulations to protect the corals are urgently needed. In Norway, fishers, scientists, and environmental organizations persuaded the government to create regulations to protect the reefs. As a result, trawling is now banned in the Sula area, where coral is abundant. It is also forbidden to damage corals deliberately. All bottom trawling can be forbidden in new areas.

To improve understanding of these corals and the ecosystems of the coral reefs, fundamental research is needed on the biology of *Lophelia* (where the larva is completely unknown) and on other reef-building deep-water corals. Research is further required into the possibilities for restoring damaged reefs. We need to know more about the potential importance of the reefs as nursery areas, feeding chambers, and refuges for commercially important fish.

ciplinary, ecologically, and socioeconomically oriented science, while maintaining the skill of its practitioners in the areas of single-species and multispecies modeling.

FISHERIES IN ECOSYSTEMS

Fish populations are increasingly understood as elements of marine ecosystems. Over their life spans, fish interact with other animals while progressing from one trophic level to the next during the development from the larval stage to the adult fish. Fisheries interfere with the interactions this implies, by removing fish (whether targeted species or bycatch) from the ecosystems in which they act as both predators and prey. Fisheries also destroy habitats (box 5.3) and disturb fish and especially marine mammals acoustically. Many modern fisheries ecologists see their primary role in analyzing and mitigating these effects to make fisheries tolerable for the ecosystem in the long run.

The ecosystem approach to fisheries management has been adopted for the entire Southern Ocean by CCAMLR (Commission for the Conservation of Antarctic Marine Living Resources). The exploitation of seals and whales, followed by the catch of finfish and of (relatively small quantities of) krill, led to very successful scientific studies on the life history of the exploited species, their interactions, and their dependence upon the oceanographic regime and sea-ice extent, and consequently upon primary and secondary production and the varying composition of plankton, benthos, and sea-ice fauna. For example, the waters around South Georgia and their potential for

Box 5.3. The North Sea Herring: A Case Study for Single Species Fisheries Management

Christopher Zimmermann

The North Sea herring is believed to have had a spawning stock biomass (SSB) of more than 2 million tons before large-scale fishing started in the 1950s. Heavy exploitation led to a collapse of the stock in the late 1970s (figure BX5.3). The closure of the (directed) herring fishery for four years, accompanied by years of good recruitment, led to a recovery of the North Sea herring stock. After the fishery reopened in 1981, it adopted a simple total-allowable-catch (TAC) approach applicable to adult fish for human consumption to avoid detrimental stock depletion in the future. However, the stock showed another rapid decline in the mid-1990s, mainly due to two factors: TACs were significantly exceeded and, even more important, greater numbers of juvenile herring were caught as bycatch in the increasing industrial fishery for fish meal and oil production, targeted on sprat.

The North Sea herring therefore became the first stock to be managed according to the precautionary approach in European Union waters. Now an emergency plan restricts catches on adults and juveniles to allow for fast rebuilding of the stock as soon as the SSB falls below the agreed reference points. Equally important, a new control system has been implemented to limit the bycatch of juveniles in the industrial fishery effectively.

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Box 5.3. Continued

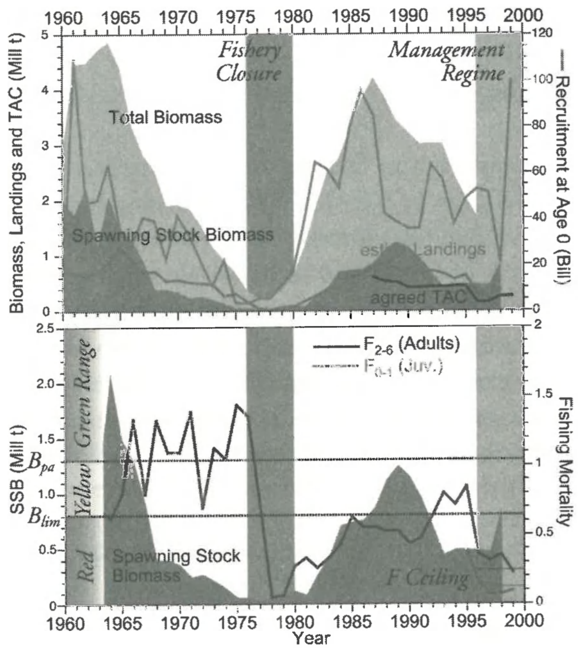

Figure BX5.3. North Sea herring (autumn spawners). Top: Total biomass, spawning stock biomass (SSB), recruitment at age 0, landings, and agreed total allowable catch (TAC). Bottom: SSB and fishing mortalities (F; adult and juvenile) and management reference points. The phases of the fishery closure and the management regime are indicated. See text for more details and explanation of terms.

The management plan is based on biomass reference points, derived from stock recruitment relationships, as follows:

- Red range below the limit biomass reference point B_{lim}, set to 800,000 tons—the emergency plan to reduce fishing mortality (F) on adults and juveniles automatically comes into force.
- Yellow range between B_{lim} and the upper reference point, B_{pa}, set to 1.3 million tons SSB.
- Green range above a SSB of 1.3 million tons—the fishing mortality is allowed to reach F = 0.25 for adults and F = 0.12 for juveniles. All bycatch is considered for the bycatch quota. The industrial fishery for fish meal is closed as soon as the ceiling is reached.

Soon after the management regime was implemented in 1996, there was a significant recorded reduction in fish mortality. After a few years of good recruitment, the

stock rapidly rebuilt itself. Since then, fishing mortalities have been limited to F_{2-6} = 0.2 and F_{juv} = 0.1. As a result, the SSB was estimated to exceed B_{lim} at the beginning of 1998, so it can be expected that status quo fishing in 1999 and 2000 will lead to an SSB of 0.9 million tons in 2000.

Scientific advice and biomass estimates on the North Sea herring stock are provided by the International Council for the Exploration of the Sea (ICES 1999a, and 1999b). A variety of different input data build the basis for the assessment: commercial landings (usually official figures) and sampling data as well as indices from (currently) four fishery-independent surveys conducted yearly. Both are provided by the National Institutes; only the surveys are internationally coordinated.

North Sea herring recruitment did not seem to be strongly dependent on environmental or climatic fluctuations. The currently conducted single-species assessment and management benefits from the fact that there is little species mixing in the managed herring fishery. However, there are some severe problems with the management. The impossibility of differentiating stocks or stock components within the North Sea stock complex may lead to the collapse of small populations, for example, the Downs herring, even under the current management regime. Furthermore, sampling of the commercial catches is often not adequate. This could be solved by coordination of the national sampling schemes (e.g., by a common European fisheries institute). Misreporting as well as exceeding TACs may lead to an overshoot of TACs by up to 30 percent. This introduces a significant (and avoidable) uncertainty into the assessment, which is finally to the detriment of the fishermen.

North Sea herring management is now used as an example of the way European fish stocks can be managed (ICES 1999a, 1999b). However, there are serious limitations in transferring the single-species herring regime to multispecies fisheries, like most demersal fisheries. In order for these to be managed intelligently, there needs to be progress in multispecies modeling in the coming years. This will require a significant increase in our knowledge of ecosystem mechanisms, which can only be achieved by a substantial increase in targeted research effort.

harvesting at different trophic levels have been the subjects of long-term studies for over seventy years since the series of Discovery Expeditions, which, incidentally, was financed by the revenues of the whaling industry. We now understand the waters off South Georgia as a cold, highly productive ecosystem, surrounded by the less productive open Southern Ocean (Atkinson et al. 2001). In some, but not all years, krill play a prime role both as consumers of phytoplankton and as the staple food for large colonies of seals and penguins. Krill, however, does not reproduce off South Georgia but is advected into the area from the south.

Long-term, comprehensive studies on the upwelling systems off California and southwestern Africa are further examples of programs that were initiated—and are still driven—by concern about the decline of fisheries. These studies grew into holistic approaches for the analysis of the functioning and interannual and decadal variability of ecosystems, with the aims of predicting fluctuations in catch and of managing the fisheries in an ecologically and economically sound way.

Similar studies have demonstrated the importance of total stock abundance and age composition on the geographical distribution of cod, Atlanto-Scandian herring and capelin, sardines, and anchovies (see, e.g., Bakun 1996).

SUSTAINABLE FISHING? REASONS FOR CAUTIOUS OPTIMISM

We have questioned the utility of much fisheries research with regard to sustainable exploitation of the living resources of the sea. The tools of input control (fleet size, engine power, mesh regulations, restricted areas, closed seasons, etc.) and output control (total allowable catch, landed catches, minimum fish sizes, catch quotas, etc.) have proven inadequate and inefficient in many cases. They did not prevent the "tragedy of the commons" syndrome in fisheries, where the resources are inevitably overexploited. An ever-increasing complexity of regulations and restrictions fosters neither common sense nor altruistic behavior. Instead, it creates a climate of tension, leading to resistance and confrontation between the fishing industry, public authorities, and scientists.

Nowadays, fisheries science increasingly accepts the notion of maintaining both fish populations and marine ecosystems as public assets. The ultimate goals are continuous high yields on the one hand, and protection of the marine environment and its biodiversity on the other. This calls for multidisciplinary research programs, supported by scientific capacity building, particularly in developing countries, where there is an urgent need for the management of rapidly dwindling marine resources.

In recent years there has been evidence of positive trends in the management of marine living resources and ecosystems. In some countries and fishing industries, there is a rapidly increasing public awareness of the need for precautionary measures in fisheries. Also, there are a number of cases

where scientific advice has succeeded in stabilizing single species fisheries (see box 5.3).

Improvements in resource modeling should help identify critical factors and thus enhance the credibility of scientific advice by warning of impending disasters and helping to track the collapse and rebuilding of stocks. User-friendly and graphic-oriented simulation models could help managers visualize the effects of a planned management decision. These models would provide the nonexpert with clear illustrations of the effects of varying fishing efforts. This might improve the dialogue among scientists, administrators, the fishing industry, and conservationists.

One of the reasons for cautious optimism regarding greater sustainability in fisheries is the rapidly growing realization, among fisheries scientists, that marine protected areas (MPAs; also known as marine reserves) may help address some of the overfishing and sustainability issues discussed above. This is particularly the case in tropical and subtropical seas, but not exclusively so. It took a great deal of research, notably in the Philippines, New Zealand, and off the southeast coast of the United States, for a consensus to emerge (see Roberts et al. 1995; NRC 1999) that MPAs "enhance fisheries, reduce conflicts and protect resources" (Bohnsack 1993).

Small-scale fisheries tend to generate little discarded bycatch, because they frequently use highly selective, passive gear. The closeness of their ports to the fishing grounds also means they are more energy efficient. This proximity also gives small-scale fisheries a stake in the state of local resources, a feature often lacking in distant-water fleets. However, ocean resources cannot be exploited by small-scale fisheries alone. Large-scale fishing operations supply the global market for human consumption and animal feeds, and some companies are players on a global scale. Fisheries science must therefore continue to address the concerns of those fisheries.

In areas where small- to medium-scale vessels can adequately exploit the resource (as was the case for cod around Newfoundland), allocation of exclusive access to coastal resources would go a long way to putting fisheries, at least in developed countries, on a path toward sustainability. This is with the proviso that management strictly follows the best possible scientific advice and resists the pressure of various stakeholders in the community. In developing countries, population growth and lack of land work against sustainability in small-scale fisheries (Pauly 1997).

Research to monitor small-scale fisheries needs close collaboration with the fishing communities themselves. This would probably have beneficial effects on both the scientists and the science, making it both human centered and ecosystem based. The increasingly important voice of the conservation community also needs to be heard, because it often expresses a broader-based desire for the oceans and their resources to remain "healthy," to be a legacy for future generations. The expectation of society at large is that the resource will continue to be valuable in the long term.

Fisheries management has traditionally worked top-down. Government regulations are formulated on the basis of stock assessments, and the industry often strives to get around or subvert the regulations. Recently, the concept of co-management has modified the regulation/implementation part of this top-down model. Co-management means a form of shared responsibility between the government and the industry, which is increasingly involved in monitoring and tactical management. In some areas, one or two major multinational firms own all the fishing fleets and dominate the market. These firms claim to be abandoning a short-term "pillage and run" mode of operation and exhibiting more interest in sustainable management of the resources and in long-term strategic ecosystem-oriented approaches. This claim, however, must be taken with a grain of salt, because the fishing industry tends to go for high discount rates.

Some new approaches to fisheries management are structured around partial or even complete privatization of fisheries resources, that is, a move toward private ownership, sometimes within a system of co-management by stakeholders from the public and the fishing sectors. Except in a few cases where complete privatization can be achieved without major social conflict, consultative approaches will have to be developed to manage fisheries in which fishers and the various sectors of the industry, public authorities, scientists, conservation organizations, etc., all take part in decision making and management of the fishery. Such integrated groups will have to

- define the socioeconomic framework for the fishery (e.g., a balanced relation between fleet sectors, limited ownership, regional coastal development, etc.);
- define ecosystem-based management objectives (e.g., minimum stock sizes of commercial species, acceptable impacts on nontargeted species and on biodiversity);
- decide on (and pay for) all measures deemed necessary for input or output control;
- decide on scientific stock assessment procedures, gear development, technical measures, etc., to obtain the desired economic results;
- punish infringements, e.g., by withdrawing fishing licenses from individuals or producer organizations; and

- mitigate conflicts between fisheries, other users of the sea, conservationists, and the general public.

There is no global formula for managing the living resources of the sea. The variety of the targeted species and the complexity of the natural systems, on the one hand, and conflicting societal, economic, and political interests, on the other, call for different kinds of scientific advice. And not all marine animals should be considered as "resources" to be exploited by fisheries, even if, like whales and turtles, they are edible.

FISHERIES RESEARCH BEYOND 2000

The great economic and social importance of fisheries has been a strong driving force for marine research in general, including basic science. Fishery research and its time-series observations have made major contributions both to the development of population ecology and to monitoring changes in the marine environment and its food webs. Nowadays, fisheries scientists are particularly confronted with the tasks of understanding recruitment and multispecies interactions in relation to changing environmental conditions, as well as to fisheries and their management. Furthermore, fishery scientists see the living marine resources and any fish as part of a complex system and understand fisheries as an element of coastal and marine management.

Technological developments over the past decade in locating, catching, and processing fish have rendered fishing operations and fisheries science more effective. New instrumentation makes it possible to monitor—and hence predict—stocks and their environment with greater precision and to maintain surveillance of sea areas and fishing fleets. Differential GPS (global positioning system) allows fishing vessels to return to productive fishing areas, to trawl around obstacles, to recover lost gear, etc. The safety benefits of accurate position fixing are obvious, while the built-in monitoring systems in the vessel provide full external control of a multitude of processes and maneuvers. Modern sensors and communication systems make fishing vessels suitable platforms for many kinds of routine observations. The U.N. Food and Agricultural Organization is currently pushing for the use of these technologies, including "black boxes" with built-in GPS for satellite monitoring of fishing vessels. Both are important tools for the control and surveillance of fishing operations. Improvements in satellite imagery in terms of spectral bands and resolution in space and time have turned tuna fishers into fishery oceanographers. The demands on fisheries science and technology as seen by the large-scale fishing industry are summarized in box 5.4.

In recent years, the market for fish and fisheries commodities became increasingly globalized, with over 75 percent of the world catch sold and consumed in countries other than those in whose exclusive economic zones it was caught. Fish from Lake Victoria partly replaced North Sea plaice in German food stores; shrimps from Thailand, and Peruvian fishmeal, are in demand everywhere. European distant-water fleets operate off western and eastern Africa, and fleets from East Asia operate worldwide, catching tuna, squid, and other high-price species. Much of the large-scale fisheries and fish trade are in the hands of a few big firms, though globalization also affects many small-scale local fisheries.

How should marine science be tailored to the requirements of fisheries to help them meet the growing demands of a global market as well as the needs of local populations? Government-sponsored fisheries science has, until recently, largely concentrated on providing expertise for fishing industries exploiting large, often mixed populations of pelagic and demersal fish in the open shelf seas. Very different advice is required to manage inshore fisheries,

Box 5.4. Demands on Fishery Science and Technology: A Fishing Perspective

Richard Ball

OBJECTIVES

Commercial fishing and fishers have a common interest in effective resource management, research, and logically consistent policies. Much of the responsibility for poor fisheries management lies at the political level and at the level of institutional management. Answers lie in the development of logically consistent fisheries management decision strategies (operational management plans), and the rigid application of cost-benefit analyses. There is insufficient use of market mechanisms to encourage and require responsible behavior.

PRIMARY OBJECTIVES OF COMMERCIAL FISHERIES: TO MAXIMIZE THE NET PRESENT VALUE OF CATCHING STRATEGIES—WITHIN CONSTRAINTS

- Commercial fishers have common interests in markets, sustainability, and stability.
- The best protection for a resource is that it is owned by those who have an interest in its good management and have assurance of their long-term participation.
- The fisher is the last residue of the hunting culture, where the benefits of the rights of property and legal certitude have had only limited application.

TECHNOLOGICAL IMPROVEMENTS IN PAST DECADE

Improved *position fixing* leads to:

- identifying previous viable areas;
- trawling accurately around hazards, recovering lost gear, and safety benefits;
- building better fishing database;
- vessel monitoring systems.

Satellite imagery of temperature and chlorophyll can identify thermoclines, gyres, fronts, and upwelling and can measure biological activity.

Improvement in *resource modeling* helps:

- identify critical factors;
- credibility;
- move toward parameterized decision making; and
- multispecies management, including interspecies, impacts, and environmental collateral damage control.

Comparative analysis of *alternative fishing strategies:*

- Technological advances should allow commercial platforms to partly substitute for expensive survey vessels and research ships.

REALISTIC OBJECTIVES OF THE NEXT TWENTY YEARS

- Move to bioeconomic analysis
- Cost-benefit disciplines
- Congruence of objectives with Marine Stewardship Council
- Better understanding of macro events like El Niño
- Improved management by integrating technologies above
- Effective application of electronic networks to deliver information and for dialogue with interest groups
- Application of farming and stock enhancement technologies for the development of genetically modified species and more active intervention in resource recovery
- Cooperation between marine science and commercial fishing, which have common interests (cost effectiveness and profit) and common threats: social concerns about resource management.

which intensively exploit coastal fish populations, and fisheries science is not yet very advanced in this area. Scientific and cultural adjustments to the prevailing practice of fisheries science are required (Finlayson 1994). We have to improve our understanding of several factors, such as the impact of local fishing practices and other marine activities (e.g., tourism, shipping, pollution) as well as shifts in species interactions, global climate change, and climate-driven teleconnections. Of course, attempts to improve the status of our fisheries should not wait until "everything is known." But in the long run, sustainable exploitation has to be based on broad scientific knowledge for ecosystem management.

Fishing mortality and recruitment are the most important factors determining the size, age, structure, and hence productivity of heavily fished stocks. In addition, to avoid overfishing in the traditional way by regulating fishing mortality, we must quantify the relative impacts of top-down fishing and of bottom-up physical and biological oceanographic factors, both of which affect abundance, size composition, and productivity of fish stocks largely by controlling recruitment. Mann (2000) argues that the most important principle of management in the foreseeable future is to match the level of fishing effort to the environmental fluctuations. Stocks should not be fished hard when they are experiencing adverse environmental conditions. Long-lived fish in cool-temperate waters (e.g., cod) have evolved to survive decadal-scale environmental fluctuations by living long enough to have successful recruitment once in a while after many years of unfavorable conditions. Heavy fishing removes the large, old, and most fecund fish that are no longer there to spawn when a "good year" recurs. The combination of heavy fishing and decadal-scale environmental variation was presumably the cause of many stock collapses, particularly in temperate and cool conditions (Longhurst 1998). Managers must develop ways to allow survival of older fish to restore these fisheries. This principle may also apply to the shorter-lived sardine and anchovy fisheries of upwelling systems, on a shorter time scale (e.g., Mullin 1993). In years of good recruitment, heavy fishing of anchovy will do little harm, but in years of poor recruitment, fishing pressure should be relaxed to allow survival of short-lived fish to spawn again.

The future of fishery research will be in the right blend of studies in population dynamics and fisheries economics on one hand and in fisheries ecology and ecosystem research on the other hand. Studies in the feeding and migratory behavior of fish in relation to anthropogenic and natural changes in the environment will help to direct fishing actions, in order to make them

more economical and less destructive to the bycatch and marine habitats and their biodiversity.

Ideally, scientific advice to fisheries management has to be based on broad ecological knowledge of single-stock dynamics, including the "classic" parameters of growth, recruitment, and mortality but also of population genetics as well as of ecosystem structure and functioning. We need to improve the monitoring of fisheries, that is, statistics of catches, discards, and landings. The geographical information systems (GIS) have great potential here, given their capacity to combine data on the geographical and oceanographic features of a given area with its resources and fishing operations, while considering variations in space and time.

The first task for fisheries science vis-à-vis stakeholders from both the fishing industry and the public sector is population assessment (see box 5.4). This means providing managers with information on the state of the stock of fish and other organisms and the ways that stock biomass and composition fluctuates with changes in environment and fisheries. In addition, multispecies interactions must be investigated on both an experimental and a strategic basis. A next step is to develop precautionary approaches for the formulation of management objectives that consider the sustainable use and preservation of the ecosystems and their resources. These approaches must assess the impact of several factors, such as fisheries, pollution, and climate, on the populations and systems. And, for this, a baseline of long data series is needed.

This opens a wide field of academic research on genetic population structure, recruitment processes, sources of mortality, climate effects, and so forth. Similarly, the specific socioeconomic constraints on the fisheries sector must be investigated within interdisciplinary groups aiming at a theoretical basis for approaches that limit the ecosystem impacts of fishing.

The overall goals of sustainable use of the living resources of the ocean are widely accepted. But they are difficult to implement, because they conflict with the immediate demands of coastal populations and with global market forces. The basic needs to protect the biodiversity and other marine bounties and beauties conflict with the tendency to maximize ocean exploitation.

Ecosystem-oriented research, combined with socioeconomic studies, should provide blueprints for the further development of both fisheries and nature conservation. New ways of management have to be found, based on new scientific approaches.

Both old and new questions continue to arise and have to be addressed. There is the issue of anthropogenic versus natural causes for population declines and stock collapses, for example, or small-scale local fisheries versus large fleets and industries operating globally, and the new protective measures, including marine reserves versus the traditional system of catch quotas and minimum length and mesh regulations.

Fisheries science for nearshore areas needs to be a mix of applied marine ecology and socioeconomics. Its main objectives must be to advise local user groups and national administrations on more sustainable management approaches, taking into account the common goal of maximizing national income as well as the social and economic constraints of local people.

Mariculture plays an increasing role, although fish and shrimp cultures consume more fish biomass (small pelagics and other fishes turned into fish meal and oil) than they produce in the form of shrimps, salmon, and other table fishes. Many believe in the continued rapid development of mariculture, provided that measures can be developed to protect fish and shrimp farms against diseases and to minimize the negative effects of such farms on both the environment and on wild fish populations, including those that serve as the basis for fish feed.

Here again, fishery research and management can no longer be seen as a matter of simply applying ecological recipes, but must involve issues of economics and equity at all levels, from the global market to the fishing village.

CONCLUSIONS AND RECOMMENDATIONS

The Marine Stewardship Council, devoted to ecolabeling of fisheries products, has identified three principles of fisheries sustainability:

1. Exploitation should not result in overfishing. In case of overfishing or exhaustion, the stocks have to be rebuilt.
2. The fishery should retain structure, productivity, function, and diversity of the ecosystem, including its habitats and nontargeted species.
3. The fishery should be governed by effective management systems.

Each of those principles requires a set of research activities:

- Detailed life history studies, stock assessment and predictive modeling for precautionary management under the conditions of varying recruitment and of multispecies interactions.
- Ecosystem research at different scales of space and time to understand the interactions of the targeted species with the system as a whole and to identify the collateral effects of fishing operations.

- Socioeconomic research to optimize fisheries within the ecological limits of fisheries and nature conservation.

RESEARCH PRIORITIES

- Defining the concept of "ecosystem-based management" in operational terms.
- Devising indicators of ecosystem status (or "health") and their implications for management of single-species populations.
- Identifying generic rules for optimal size and location of marine reserves as a major ecosystem-based fisheries management tool.
- Devising management regimes that provide fishers with incentives for conservative modes of resource exploitation.
- Developing fishing technologies with small ecological footprints (especially low habitat and other ecosystem impacts, and low energy consumption).
- Understanding recruitment processes in relation to environment and the interactions between top-down and bottom-up control in early life history.
- Understanding shifts in population genetics caused by fishing.

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ENDNOTES FOR FURTHER READING

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