ECOSYSTEMS

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ECOSYSTEM EFFECTS OF FISHING

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Introduction

In comparison with conventional fisheries biology, which examines the population dynamics of target stocks, there have been relatively few research programs that consider the wider implications of fishing activity and its effects on ecosystems. With growing recognition of the need to conduct and manage our activities within a wider, more environmentally sensitive framework, however, the effects of fishing on ecosystems is increasingly being debated by scientists and policy makers around the world. As with many other activities such as waste disposal, chemical usage or energy policies, scientists and politicians are being asked whether they fully understand the ecological consequences of fishing activity.

The scale of biomass removals and its spatial extent make fishing activity a strong candidate for effecting large-scale change to marine systems. Coarse global scale analyses provide a picture of our fish harvesting activities as being comparable to terrestrial agriculture, when expressed as a proportion of the earth's productive capacity. It has been estimated that 8% of global aquatic primary production was necessary to support the world's fish catches in the early 1980s, including a 27 million tonne estimate of discards (see below). Perhaps the most appropriate comparison is with terrestrial systems, where almost 40% of primary productivity is used directly or indirectly by humans. Although 8% for marine systems may seem a rather moderate figure in the light of terrestrial demands, if one looks on a regional basis, the requirements for upwelling and shelf systems, where we obtain most fisheries resources, are comparable to the terrestrial situation, ranging from 24 to 35% (**Table 1**). Bearing in mind that the coastal seas are rather less accessible to humans than the land, these values for fisheries seem considerable, leading many to agree that current levels of fishing – and certainly any increases – are likely to result in substantial changes in the ecosystems involved. It is generally accepted that the majority of the world's fish stocks are fully or overexploited.

When considering ecosystem effects it is useful to distinguish between the direct and indirect effects of fishing. Direct effects can be summarized as follows:

1. fishing mortality on species populations, either by catching them (and landing or throwing them back), by killing them during the fishing process without actually retaining them in the gear or by exposing or damaging them and making them vulnerable to scavengers and other predators;
2. increasing the food available to other species in the system by discarding unwanted fish, fish offal and benthos;
3. disturbing and/or destroying habitats by the action of some fishing gears.

In contrast, indirect effects concern the knock-on consequences that follow from these direct effects, for example, the changes in the abundances of predators, prey and competitors of fished species that might occur due to the reductions in the abundance of target species caused by fishing, or by the provision of food through discarding of unwanted catch.

By-catch and Discards

In many areas of the world a wide variety of fishing gears are used, each focusing on one or a few species. Unfortunately, this focus does not mean that nontarget species, sexes or size-classes are excluded from catches. Target catch is usually defined as 'the catch of a species or species assemblage that is primarily sought in a fishery' – nontarget catch, or by-catch as it is usually called, is the converse. By-catch can then be further classified as incidental catch, which is not targeted but has commercial value and is likely to be retained

Table 1 Global estimates of primary production and the proportion of primary production required to sustain global fish catches in various classes of marine system

Ecosystem type	*Area (10^6 km^2)*	*Primary production (g C m^{-2} y^{-1})*	*Catch (g m^{-2} y^{-1})*	*Discards (g m^{-2} y^{-1})*	*Mean % of primary production*	*95% CI*
Open ocean	332.0	103	0.01	0.002	1.8	1.3–2.7
Upwellings	0.8	973	22.2	3.36	25.1	17.8–47.9
Tropical shelves	8.6	310	2.2	0.671	24.2	16.1–48.8
Nontropical shelves	18.4	310	1.6	0.706	35.3	19.2–85.5
Coastal reef systems	2.0	890	8.0	2.51	8.3	5.4–19.8

Reproduced from Hall (1999).

if fishing regulations allow it and discard catch, which has no commercial value and is returned to the sea.

The problem of by-catch and discarding is probably one of the most important facing the global fishing industry today. The threat to species populations, the wastefulness of the activity and the difficulties undocumented discarding poses for fish stock assessment are all major issues. A recent published estimate of the annual total discards was approximately 27 million tonnes, based on a target catch of 77 million tonnes. This figure, however, did not include by-catch from recreational fisheries, which could add substantially to the total removals, and the estimate is subject to considerable uncertainty. **Figure 1** shows how these discard figures break down on a regional basis. Just over one-third of the total discards occur in the Northwest Pacific, arising from fisheries for crabs, mackerels, Alaskan pollock, cod and shrimp, the latter accounting for about 45% of the total. The second ranked region is the Northeast Atlantic where large whitefish fisheries for haddock, whiting, cod, pout, plaice and other flatfish are the primary sources. Somewhat surprisingly, capelin is also a rather important contributor to the total, primarily because capelin are discarded due to size, condition and other market-related factors. The third place in world rankings is the West Central Pacific, arising largely through the action of shrimp fisheries. These fisheries, prosecuted mainly off the Thai, Indonesian and Philippine coasts, accounted for 50% of the total by-catch for the region, although fisheries for scad, crab and tuna are also substantial contributors. Interestingly, the

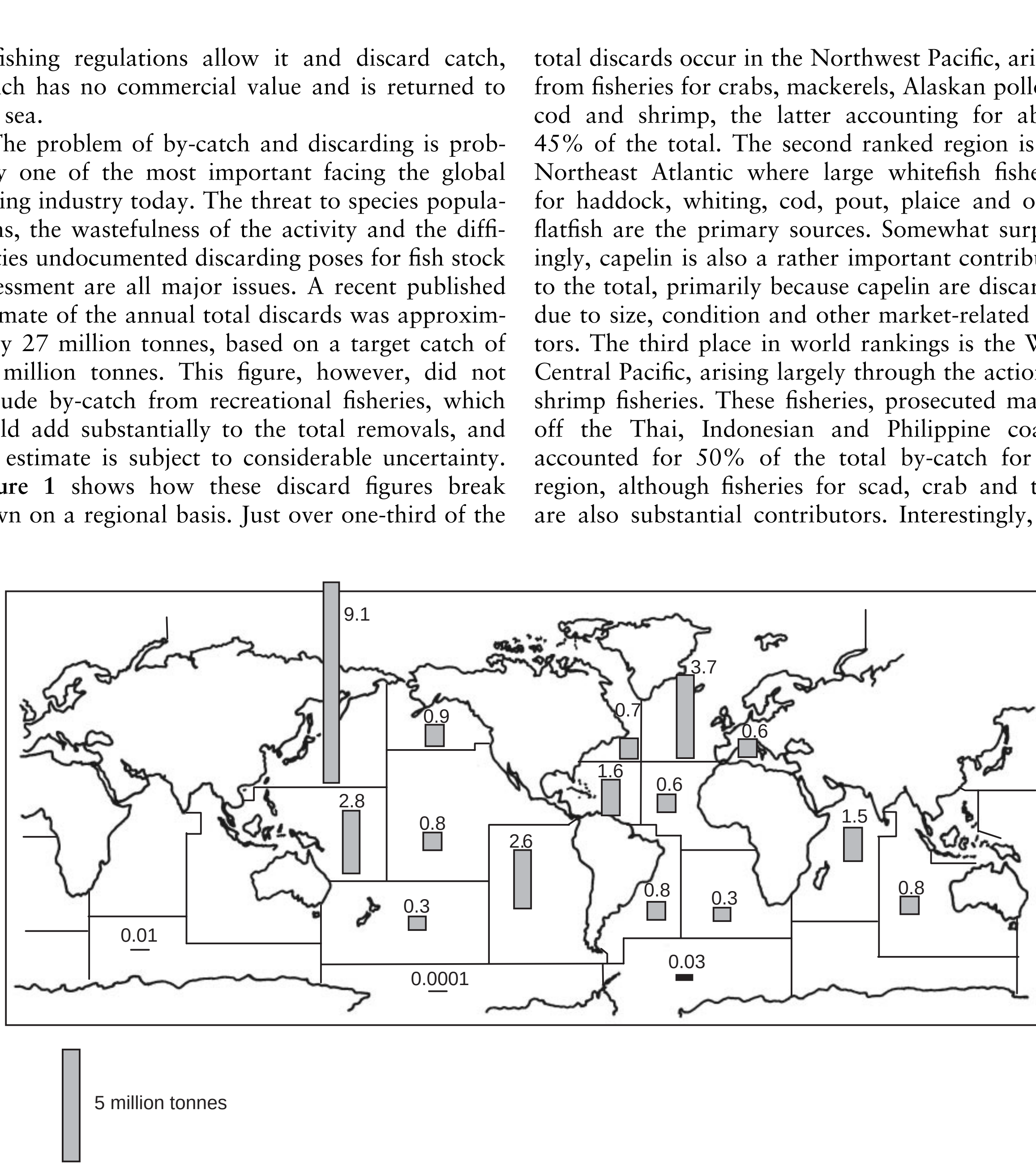

Figure 1 The regional distribution of discards. (Reproduced from Hall, 1999.)

South East Pacific ranks fourth, not because the fisheries in the area have high discard ratios (on the contrary, the ratios for the major anchoveta and pilchard fisheries are only 1–3%), but simply due to the enormous size of the total catch. For the remaining tropical regions, by-catch is again dominated by the actions of shrimp fisheries, although some crab fisheries are also significant.

One characteristic difference between temperate and tropical fishery discards is worthy of note. In the tropics, where shrimp fisheries dominate the statistics, discards mainly comprise small-bodied species which mature at under 20 cm and weigh less than 100 g. In contrast, for the temperate and subarctic regions discards are generally dominated by sublegal and legal sizes of commercially important, larger-bodied species. Thus, in the temperate zone discarding is not only an ecological issue, it is also a fisheries management issue in the strictest sense. Fish are being discarded which, if left alone, would form part of the future commercial catch.

A cause of particular concern is the incidental catch of larger vertebrate fauna such as turtles, elasmobranchs and marine mammals. Catch rates for these taxa are generally highest in gillnet fisheries, which increased dramatically in the 1970s and 1980s, particularly for salmonids, squid and tuna. In some fisheries, the numbers caught can be very substantial. In the high seas longline, purse seine and driftnet fisheries for tuna and billfish, for example, migratory sharks form a large component of the catch, with some 84 000 tonnes estimated to have been caught from the central and south Pacific in 1989.

As with the other nonteleost taxa for which by-catch effects are a concern, the life-history characteristics of sharks make them particularly vulnerable to fishing pressure. Slow growth, late age at maturity, low fecundity and natural mortality, and a close stock recruitment relationship all conspire against these taxa. Such life-history attributes have also led to marked alterations in the absolute and relative abundance of ray species in the North and Irish Sea, which are subject to by-catch mortality from trawl fisheries. In the Irish Sea for example, the ‘common skate’ (*Raja batis*) is now rarely caught.

For some species (e.g., some species of albatross and turtle species) levels of by-catch are so great that populations are under threat. But even if the mortality rates are not this great (or the data are inadequate) there is a legitimate animal welfare perspective which argues for strenuous efforts to limit by-catch mortalities regardless of population effects. Few people like the idea of turtles or dolphins being needlessly drowned in fishing nets, regardless of whether they will become locally or globally extinct if they continue to be caught.

Although declines in populations as a result of by-catch are the most obvious effect, there are also examples where populations have increased because of the increase in food supply resulting from discarding. The most notable among these are seabirds in the North Sea, where in one year it was estimated that approximately 55 000 tonnes of offal, 206 000 tonnes of roundfish, 38 000 tonnes of flatfish, 2000 tonnes of elasmobranchs and 9000 tonnes of benthic invertebrates were consumed by seabirds. There is good evidence that populations of scavenging seabirds in the North Sea are substantially larger than they would be without the extra food provided by discards.

Solving the By-catch and Discard Problem

There is no universally applicable solution for mitigating by-catch and discard problems. Each fishery has to be examined separately (often with independent observers on fishing vessels) and the relative merits of alternative approaches assessed. One obvious route to reducing unwanted catch, however, is to increase the selectivity of the fishing method in some way. In trawl fisheries, in particular, technical advances, combined with a greater understanding of the behavior of fish in nets has led to the development of new methods to increase selectivity. These methods adopt one of two strategies. The first is to exploit behavioral differences between the various fished species, using devices such as separator trawls, modified ground gear (i.e., the parts of the net that touch the seabed) or modifications to the sweep ropes and bridles that attach to the trawl doors. For example, separator trawls in the Barents Sea have been shown successfully to segregate cod and plaice into a lower net compartment from haddock, which are caught in an upper compartment. In Alaska this approach has been used to allow 40% of bottom-associated halibut to escape while retaining 94% of cod, the target species.

The second approach is to exploit the different sizes of species. In many fisheries it is the capture of undersized fish that is the main problem and regulation of minimum permissible mesh size is of course a cornerstone of most fisheries management regimes. Such a measure can often, however, be improved upon. For example, the inclusion of square mesh panels in front of the codend can often allow a greater number of escapees, because the meshes do not close up when the codend becomes full. In addition, recent work that alters the visual stimulus that the net provides by using different colored netting in different parts has been shown to improve the efficiency of such panels considerably. At the other end of the scale excluding large sharks, rays or turtles from the catch can be achieved by fitting solid grids of various kinds. In some fisheries such devices are now mandatory (e.g., turtle exclusion devices in some prawn fisheries), but there is often resistance from fishermen because they can be difficult to handle and catches of target species can fall. For nontrawl fisheries, examples of technical solutions can also often be found. For example, new methods of laying long-lines have been developed to avoid incidental bird capture and dolphin escapement procedures that are now used in high seas purse seine fleets.

Although many technical approaches have met with considerable success in different parts of the world it is important to recognize that technical fixes are only part of the solution – the system in which they have to operate must also be considered. The regulations that govern fisheries and the vagaries of the marketplace often create a complex web of incentives and disincentives that drive the discarding practices of fishermen. The situation can be especially complicated in multispecies fisheries.

The Effects of Trawling and Dredging on the Seabed

Disturbance of benthic communities by mobile fishing gears is the second major cause for concern over possible ecosystem effects of fishing, threatening nontarget benthic species and perhaps also the longer-term viability of some fisheries themselves if essential fish habitat is being destroyed. With continuing efforts to find unexploited fish resources, hitherto untouched areas are now becoming accessible as new technologies such as chain mats, which protect the belly of the net, are developed. In Australia, for example, new fisheries are developing in deeper water down to depths of 1200 m.

A prerequisite for a rational assessment of fishing effects on benthos is an understanding of the distribution, frequency and temporal consistency of bottom trawling. On a global basis, recent estimates obtained using Food and Agriculture Organization catch data from fishing nations suggest that the continental shelves of 75% of the countries of the world which border the sea were exposed to trawling in 1996. It would appear, therefore, that few parts of the world's continental shelf escape trawling, although it should be borne in mind that in many fisheries trawl effort is highly aggregated. Although we have an appreciation of average conditions, these are derived from a mosaic of patches, some heavily trawled along preferred tows, others avoided by fishermen because they are unprofitable or might damage the gear. Unfortunately, lack of data on the spatial distribution of fishing effort prevents estimates of disturbance at the fine spatial resolution required to obtain a true appreciation of the scale of trawl impacts. Nevertheless, there is little doubt that substantial areas of the world's continental shelf have been altered by trawling activity.

For the most part the responses of benthic communities to trawling and dredging is consistent with the generalized model of how ecologists expect communities to respond, with losses of erect and sessile epifauna, increased dominance by smaller faster-growing species and general reductions in species diversity and evenness. This agreement with the general model is comforting, but we have also learnt that not all communities are equally affected. For example, it is much more difficult to detect effects in areas where sediments are highly mobile and experience high rates of natural disturbance, whereas boulder or pebble habitats, those supporting rich epifaunal communities that stabilize sediments, reef forming taxa or fauna in habitats experiencing low rates of natural disturbance, seem particularly vulnerable. However, despite the body of experimental data that has examined the impacts of trawling on benthic communities, it is often not possible to deduce the original composition of the fauna in places where experiments have been conducted because data gathered prior to the era of intensive bottom-fishing are sparse. This is an important caveat because recent analyses of the few existing historical datasets suggest that larger bodied organisms (both fish and benthos) were more prevalent prior to intensive bottom trawling. Moreover, in general, epifaunal organisms are less prevalent in areas subjected to intensive bottom fishing. Communities dominated by sponges, for example, may take more than a decade to recover, although growth data are notably lacking. Such slow recovery contrasts sharply with habitats such as sand that are restored by physical forces such as tidal currents and wave action.

Habitat Modification

An important consequence of trawling and dredging is the reduction in habitat complexity (architecture) that accompanies the removal of sessile epifauna. There is compelling evidence from one tropical system, for example, that loss of structural epibenthos can have important effects on the resident fish community, leading to a shift from a high value community dominated by Lethrinids and Lutjanids to a lower value one dominated by Saurids and Nemipterids. Similar arguments have also been made for temperate systems where structurally rich habitats may support a greater diversity of fish species. Importantly, such effects may not be restricted to the large biotic or abiotic structure provided by large sponges or coral reefs. One could quite imagine, for example, that juveniles of demersal fish on continental shelves might benefit from a high abundance of relatively small physical features (sponges, empty shells, small rocks, etc.) but that over time trawling will gradually lower the physical relief of the habitat with deleterious consequences for some fish species. Such effects may account for notable increases in the dominance of flatfish in both tropical and temperate systems. Our current understanding of the functional role of many of the larger-bodied long-lived species (e.g., as habitat features, bioturbators, etc.) is limited and needs to be addressed to predict the outcome of permitting chronic fishing disturbance in areas where these animals occur.

Although fishing-induced habitat modification is probably most widely caused by mobile gears, it is important to recognize that other fishing methods can also be highly destructive. For coral reef fisheries, dynamite fishing and the use of poisons represent major threats in some parts of the world.

Perhaps the only effective approach for mitigating the effects of trawling in vulnerable benthic habitats is to establish marine protected areas in which the activity is prohibited. Given the widespread distribution of trawling, it is not surprising that the establishment of marine protected areas is a key goal for many sectors of the marine conservation movement, although it should be borne in mind that it is not only trawling effects that can be mitigated by the approach. A key driver for the establishment of marine protected areas has come from The World Conservation Union (IUCN) and others who have called for a global representative system of marine protected areas and for national governments to also set up their own systems. A number of nations have already taken such steps, including Australia, Canada and the USA, with other nations likely to follow suit in the future.

Species Interactions

Even species that are not directly exploited by a fishery are likely to be affected by the removal of a substantial proportion of their prey, predator or competitor biomass and there are certainly strong indications that interactions with exploited species should be strong enough to lead to population effects elsewhere. For example, an analysis of the energy budgets for six major marine ecosystems found that the major source of mortality for fish is predation by other fish. Predatory interactions may, therefore, be important regulators for marine populations and removing large numbers of target species may lead to knock-on effects. Unfortunately, however, gathering the data necessary to demonstrate such controls is a major task that has rarely been achieved. Without studies directed specifically at the processes underlying the population dynamics of specific groups of species, it is difficult to evaluate the true importance of the effects of fisheries acting through species interactions in marine systems. Despite this caveat, some general effects appear to be emerging.

Removing Predators

For communities occupying hard substrata, there is good evidence that some fisheries have reduced predator abundances and that this has led to marked changes lower in the food web. Both temperate hard substrates and coral reefs provide good examples where reductions in predator numbers have led to change in the abundance of prey species that compete for space (e.g., mussels or algae), or in prey that themselves graze on sessile species. Such changes have led in turn to further cascading changes in community composition. For example, in some coral reef systems, removal of predatory fish has led to increases in sea urchin abundance and consequent reductions in coral cover.

Examples of strong predator control are much less easy to find in pelagic systems than they are in hard substratum communities. This perhaps suggests that predator control is less important in the pelagos. Alternatively, the lack of evidence may simply reflect our weak powers of observation; it is much harder to get data that would support the predator control theory in the pelagic than it is on a rocky shore.

Removing Prey

Fluctuations in the abundance of prey resources can affect a predator's growth and breeding success. Thus, if prey population collapses are sustained over the longer term due to fishing this will translate into a population decline for the predator. Examples of such effects can be found, particularly for bird species, but also for other taxa such as seals. Since many people have strong emotional attachments to such taxa, there is often intense interest when breeding failures or population declines occur. In the search for a culprit fishing activity is often readily offered as an explanation for the prey decline, or at least as an important contributory factor. In assessing the effect of prey removal, however, one must consider whether the fishery and predator compete for the same portion of the population, either in terms of spatial location or stage in the life cycle. For example, if the predator eats juveniles whose abundance is uncorrelated with the abundance of the fishable stock, the potential for interactions is greatly reduced. Such a feature seems rather common and probably needs to be examined closely in cases where a fishery effect is implicated. Nevertheless, there can be little doubt that unrestrained exploitation increases the likelihood of fisheries collapses and this is turn will take its toll on predator populations.

Removing Competitors

Unequivocal demonstrations of competition in most marine systems are rare. Perhaps the only exception to this is for communities occupying hard substrates where competition for space has been demonstrated and can be important in determining community responses to predators (see above). For other systems (e.g., the pelagic or soft-sediment benthos), we can only offer opinions, based on our assessment of the importance of other factors (e.g., predation, low quality food, environmental conditions). One system where fishing activity has been generally accepted to have an impact through competitive effects is the Southern Ocean, where massive reductions in whale populations by past fishing activity has led to apparent increases in the population size, reproduction or growth of taxa such as seals and penguins. A recent assessment, however, has even cast doubt on this interpretation, concluding that there is little evidence that populations have responded to an increase in available resources resulting from a decline in competitor densities.

Species Replacements

Despite the difficulties of clearly identifying the ecological mechanism responsible for the changes, there are some examples where fishing is heavily implicated in large-scale shifts in the species composition of the system and apparent replacement of one group by another. The response of the fish assemblage in the Georges Bank/Gulf of Maine area is, perhaps, the clearest example (**Figure 2**). During the 1980s the principal groundfish species, flounders and other finfish, declined markedly in abundance after modest increases in the late 1970s. It seems almost certain that the subsequent decline was a direct result of overexploitation by the fishery. In contrast, the elasmobranchs (skates and spiny dogfish) continued to increase during the 1980s. It would appear, therefore, that the elasmobranchs have responded opportunistically to the decline in the other species in the system, perhaps by being able to exploit food resources that were no longer removed by target species. Other possible examples of species replacements are the apparent increase in cephalopod species in the Gulf of Thailand, which coincided with the increase in trawl fishing activity and reduction in the abundance of demersal fish, and the increase in flatfish species that seems to have occurred in the North Sea and elsewhere.

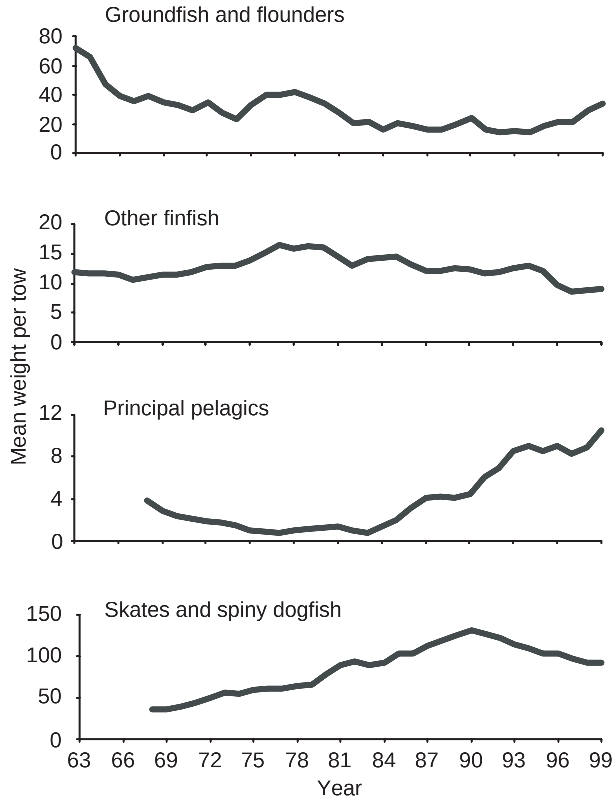

Figure 2 Trends in the relative contribution to total biomass (numbers) made by major taxonomic fish groups. Data from National Oceanographic and Atmospheric Administration, National Marine Fisheries Service, Woods Hole, MA, USA (personal communication).

Conclusion

A final perspective on the system-level effects of fisheries come from an examination of changes over the last 45 years in the average trophic level at which landed fish were feeding (**Figure 3A**). This

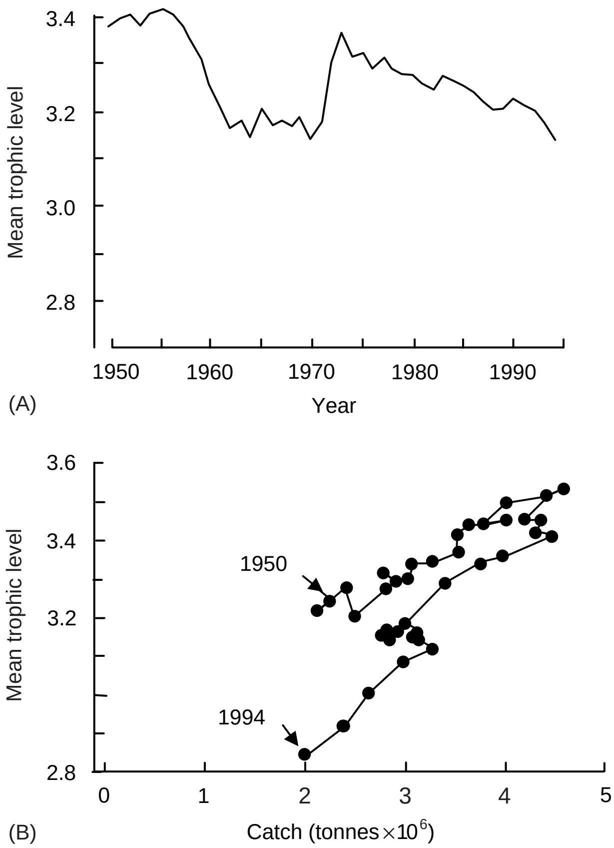

Figure 3 (A) Global trends in mean trophic level of fisheries landings from 1950 to 1994. (B) Plot of mean trophic level versus catch for the north-west Atlantic. (Reproduced from Hall, 1999.)

analysis indicates that there has been a decline in mean trophic level from about 3.3 in the early 1950s to 3.1 in 1994. Very large landings of Peruvian anchoveta, which feeds at a low trophic level, account for the marked dip in the time series in the 1960s and early 1970s. When this fishery crashed in 1972–73 the mean trophic level of global landings rose again. For particular regions, where fisheries have been most developed there have been generally consistent declines in trophic level over the last two decades.

Plots of mean trophic level against catches give a more revealing insight into the system-level dynamics of fisheries (**Figure 3B**). Contrary to expectations from simple trophic pyramid arguments, highest catches are not associated with the lowest trophic levels. This is important because it has been suggested in the past that fishing at lower trophic levels will give greater yields because energy losses from transfers up the food chain will be less. It appears, however, that the global trend towards fishing down to the lower trophic levels yields lower catches and generally lower value species – features indicative of fisheries regimes that are badly in need of restoration. Care needs to be taken when interpreting data such as these, particularly because catches of fish at different trophic levels are influenced by a number of factors including the demand for and marketability of taxa and the level of fishing mortality relative to optimum levels. Declines in catches at the end of the time series, for example, may well reflect depleted stocks of fish at all trophic levels. Nevertheless, these analyses are clear warning signs that global fisheries are operating at levels that are certainly inefficient and probably beyond those that are prudent if we wish to prevent continuing change in the trophic structure of marine ecosystems.

See also

Benthic Organisms Overview. Coral Reef and other Tropical Fisheries. Dynamics of Exploited Marine Fish Populations. Fish Predation and Mortality. Fisheries: Multispecies Dynamics. Fisheries Overview. Large Marine Ecosystems. Marine Mammal Overview. Marine Mammal Trophic Levels and Interactions. Network Analysis of Food Webs. Sea Turtles. Seabirds and Fisheries Interactions.

Further Reading

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