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By-Catch: Problems and Solutions

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By-catch is one of the most significant issues affecting fisheries management today. Incidental mortality of species which are long-lived and have low reproductive rates is a conservation problem affecting marine mammals, sea birds, sea turtles, sharks and other groups. By-catches can affect biodiversity through impacts on top predators, the removal of individuals from many species, or by elimination of prey. The by-catch issue is also one of waste; the millions of tons of protein dumped in the ocean, and the waste of animal lives is often condemned on moral grounds. For the economist, it generates additional costs without affecting the revenues, and may hinder profitability. For the fishers, it causes conflicts among fisheries, it gives fishers a bad public image, generates regulations and limitations on the use of resources, and frequently has negative effects on the resources harvested through the mortality of juvenile and undersized individuals of the target species before they reach their optimal size from the point of view of future yield.

Several examples of major by-catch issues are described, focusing also on the solutions to the problems which have been developed by scientists, fisheries managers and members of the fishing industry itself. By-catch is an extremely complex set of scientific issues, not only an economic, political, or moral one. Although only a few fisheries include by-catches of the target species in their stock assessment (e.g. Pacific halibut), it is clear that by-catch management will be an integral part of most future ecosystem management schemes. These considerations, together with the introduction of environmental variability and a better handling of scientific uncertainty, should lead to more intelligent ways to harvest our resources.

Introduction

The ecologist has never been asked before how to harvest an ecosystem optimally. In the mid 1950s, population dynamicists developed the quantitative models that have been the basis for 50 years of management. They were single-species models and, with many, the control mechanisms were simply the selection of optimum or minimum size to be taken. One of the early problems for gear technologists was to develop nets to fulfil these requirements. Selective fishing, as a concept, meant catching the desirable sizes of the target species.

More recently, the concept of selective fishing has changed, and its new meaning includes avoiding not only undesirable sizes of target species, but also avoiding forbidden species or those without economic value. If ecologists, rather than population dynamicists, had recommended a way to harvest an ecosystem, it would probably have resulted in a very different scheme. To concentrate all the impact of the harvest on a narrow range of sizes of one species seems, intuitively, a very unlikely way to preserve ecosystem structure and function (Hall, 1996). Economics and technology rather than ecological principles, have determined the way an ecosystem is exploited. Very selective fishing may be desirable in some cases but, from the ecological point of view, there is no experimental or theoretical evidence showing that this is the best, or the least harmful, way to extract a sustainable harvest from an ecosystem. The complexities of handling and processing the mixture of species and sizes, together with the lack of markets for many of the products, prevent the alternative ('non-selective') strategy of exploitation from happening. But this does not mean that things will never change. Sooner or later, the human species will have to give ecological principles a higher priority when choosing a foraging strategy.

Another area where ecologists and markets collide is in the choice of target species. If exploitation is targeted on a few species, the ecologist may recommend taking those at lower levels of the food chain on the grounds that fewer transfers between trophic levels should allow a much larger biomass harvest. However, markets in developed nations demand and pay a high price for swordfishes, tunas, sharks, and other top predators. Targeting these large species requires gear that frequently causes by-catches of other large and frequently long-lived species such as marine mammals, sea turtles, sea birds, and invertebrates. Purse-seines, gillnets, longlines and trawls take a toll of these groups (Northridge, 1984, 1991a; Magnuson *et al.*, 1990; Brothers, 1991; Andrew and Pepperell, 1992; Stevens, 1992; Alverson *et al.*, 1994; Bonfil, 1994; IWC, 1994; Jefferson and Curry, 1994; Wickens, 1995; Williams and Capdeville, 1996; Dayton *et al.*, 1995; Alexander *et al.*, 1997; Hall, 1998; Vinther, 1999).

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Fig. 1 Crew shovelling by-catch from the vessel deck (photo D. Bratten).

By-catches (Fig. 1) can create a conservation problem when endangered species are affected (i.e. the vaquita porpoise; Rojas-Bracho and Taylor, 1999), or when the level of take is not sustainable for the non-target species. They can affect biodiversity, and can disturb the ecosystem by transferring biomass between water layers (i.e. discards of bottom trawls on surface waters; Hill and Wassenberg, 1990), or by causing accumulations of biomass that affect the normal flow of nutrients and matter, may cause anoxia, or have other impacts on the benthos (ICES, 1995; Dayton *et al.*, 1995). They may become a subsidy to those species that learn to utilize the fishing operations to find feeding opportunities at the expense of their competitors (Furness *et al.*, 1988; Wickens, 1995; Ramsay *et al.*, 1997; Laptikhovsky and Fetisov, 1999). On longer time scales, biomass discarded in deep water may not be recycled vertically, but may enter the circulation patterns of bottom water masses, that may take centuries to return its components to the ecosystem of origin. For decades, by-catches were mostly ignored by scientists working on stock assessment, by fisheries managers, and by environmentalists. There were several reasons for this neglect:

1. It was not visible. With most fisheries data being collected in ports, events happening at sea were not witnessed by scientists. There was ignorance on the existence or level of the problem. The by-catch issue became highly visible when the public found out about cases involving charismatic species such as dolphins (Perrin, 1968), or endangered species such as sea turtles (Magnuson *et al.*, 1990).
2. It was probably smaller in magnitude. The increase in scale of industrial fisheries has resulted in evolution of gear that covers huge volumes of water, moving in some cases at high speeds, and is much less selective. Examples of this are the transition of tuna fisheries from pole-and-line to purse seining, or from small coastal gillnets to large pelagic driftnets.
3. It was less significant for stock assessment. With resources in earlier stages of exploitation, the waste of some of the target species was not perceived as a major factor affecting fishing mortality estimates. With fisheries closer to their upper limit, by-catches make a difference.
4. The interference among fisheries was less intense. One of the main constituencies of the by-catch issue today are fishers affected by the waste of some gears or fleets. The more diversified the fisheries, and the higher the level of effort, the more intense is competition for the resources.
5. The ecosystem concerns were not a management priority. The emphasis on single-species management models and schemes did not leave much room for consideration of by-catches.

But this has changed, and although often difficult to assess, the by-catch issue is now globally important, and a source of conflicts. By-catches of marine mammals, sea birds and sea turtles are a very significant if not dominant factor in the present management of some fisheries (Alverson *et al.*, 1994; Alverson and Hughes, 1996; Hall, 1996, 1998). By-catches of fishes (i.e. halibut; Clark and Hare, 1998) or crustaceans (i.e. crabs) and other invertebrates in one fishery may cause or accelerate the closure of another.

Alverson *et al.* (1994) have provided a global assessment of fish discards of 27.0 million Mt with a range of 17.9–39.5 million Mt. This means that a significant proportion of the world catch, estimated at around 100 million Mt, is discarded. After examining over 800 articles concerning by-catch and discards in the world fisheries, the authors estimated that the region with the highest discard level is the northwest Pacific Ocean. Shrimp trawl fisheries were found to have higher by-catch/catch ratios in weight than any other gear type and accounted for over one third of the global total. On a weight basis, 14 of the highest 20 by-catch/catch ratios were associated with shrimp trawls. This is clearly a significant quantity in a planet with an increasing human population, and this review emphasized the wasteful nature of some exploitations. An update (Alverson, 1998) reviews many of those figures in view of changes in gear or fishing practices in the different regions and of additional data provided by several researchers.

Discards and by-catch are neither new issues nor new problems. Many authors (Saila, 1983; Alverson *et al.*, 1994) point out that by-catches have existed since fishing first began. Programmes and techniques designed to reduce capture of non-target species or undersized target species are not just the product of recent fishery managers. Attempts to deal with problems caused by the use of non-selective fishing gears have been tried many years ago. Regulations to reduce the catch of undersized target species and to limit catch of non-target species constitute long-accepted fisheries management measures (Alverson and Hughes, 1996).

Definitions

McCaughran (1992) defined by-catch as that 'portion of the catch returned to the sea as a result of economic, legal or personal considerations, plus the retained catch of non-targeted species'. This definition can be misleading, and it lumps together a waste product with an additional source of income. Sometimes it is difficult to establish which is the target of a fishery. The definition used here is that of Hall (1996): 'it is that part of the capture that is discarded at sea, dead (or injured to an extent that death is the result)'. *Capture*, in turn, means all that is taken in the gear. The capture can be divided into three components: (a) the portion retained because it has economic value (*catch*), (b) the portion discarded at sea dead (*by-catch*), and (c) the portion released alive (*release*). In this sense, the term by-catch has a clear negative connotation for fishers or environmentalists, and programs and actions to 'reduce by-catch' can be considered as ways to improve the fishery, without being detrimental to the fishers.

Catch could be subdivided further into two main components: *target catch* and *non-target catch*, the latter including other species caught incidentally but retained because of their economic value. By-catch and release have the same components. If necessary, one could distinguish primary and secondary target species.

But not all the catch loaded in the vessel reaches consumers. Once the catch reaches port, buyers or processors may reject some because of size or condition. This proportion of the catch is the *rejects,* the rest is the *marketable catch*. While the latter is being prepared for sale or processed, another fraction, the *processing waste*, is lost; what remains is the *yield*. In very efficient fisheries, the yield should be a high proportion of the *capture*, or more accurately of the difference *capture – release*.

Special cases of by-catch exist also: *Prohibited species*: any species which must by law be returned to the sea, and *High Grading*: the discard of a marketable species in order to retain the same species at a larger size and price, or to retain another species of higher value.

Reasons for Discarding

Some of the above definitions have already clarified the main reasons for discarding fish species. A fisher is a business-person, and with the best of intentions intends to make a living. It is likely that any incidental or extra catch is purely accidental, and he then makes a decision whether or not to land it or to risk searching for higher priced fish. Clucas (1997) summarized the main reasons:

- Fish caught are of the wrong species, size or sex, or the fish are damaged.
- Fish are incompatible with the rest of the catch (from the point of view of storage).
- Fish are poisonous.
- Fish spoil rapidly (i.e. before it is brought on board).
- Lack of space on board.
- High grading.
- Quotas reached.
- The catch was of prohibited species, in prohibited season or fishing ground, or with prohibited gear.

For some gears, most of the fish discarded will be dead. In other cases, even if the fish are alive when returned to the water, their survival rate is low.

Besides these discards, there is another type of loss of fish that also adds to mortality. Sometimes the net, or other type of gear, is ripped apart, or breaks under the stress of its load because of malfunctions, defective materials, etc. This is not strictly a by-catch, because there is no intent to discard, but the complete or partial loss follows. This source of mortality is probably negligible in some fisheries, but it is never accounted for in the estimation of fishing mortality because there are no data available on its frequency or the magnitude of its impact.

Regulations and Guidelines

The first and most obvious set of regulations and guidelines are the UN FAO Code of Conduct and the Kyoto Convention.

FAO code of conduct for responsible fisheries

The FAO code of conduct for responsible fisheries (FAO, 1995) encourages nations to establish principles and criteria for the elaboration and implementation of national policies for responsible conservation of fisheries resources and fisheries management and development, and states precisely that discarding should be discouraged. But besides its obvious good intentions, implementation faces many challenges. The fisheries sector in many countries constitutes powerful lobbies, or groups large numbers of participants (i.e. artisanal small-scale fishers). As many restrictions concerning by-catch affect the productivity of the fishery, at least initially, there is a strong resistance to the constraints that should be imposed. The economic costs of gear modifications or replacements add to the costs of the fisheries, and unless major incentives are offered or significant outside pressures exerted, changes will not happen.

In some of the relevant articles, the Code states:

8.4.5 States, with relevant groups from industry, should encourage the development and implementation of technologies and operational methods that reduce discards. The use of fishing gear and practices that lead to the discarding of catch should be discouraged and the use of fishing gear and practices that increase survival rates of escaping fish should be promoted.

8.4.6 States should co-operate to develop and apply technologies, materials and operational methods that minimize the loss of fishing gear and the ghost fishing effects of lost and abandoned fishing gear.

8.4.8 Research on the environmental and social impacts of fishing gear and, in particular, on the impact of such gear on biodiversity and coastal fishing communities should be promoted.

11.3.3 States should simplify their laws, regulations and administrative procedures applicable to trade in fish and fishery products without jeopardising their effectiveness.

11.1.8 States should encourage those involved in fish processing, distribution and marketing to: (a) Reduce post harvest losses and waste, and (b) improve the use of by-catch to the extent that this is consistent with responsible fisheries management practices.

12.4 States should collect reliable and accurate data, which are required to assess the status of fisheries and ecosystems, including data on by-catch, discards and waste. Where appropriate, this data should be provided, at an appropriate time and level of aggregation, to relevant State and sub regional, regional and global fisheries organizations.

12.10 States should carry out studies on selectivity of fishing gear, the environmental impact of fishing gear on target species and on the behaviour of target and non-target species in relation to such fishing gear as an aid for management decisions and with a view to minimizing non-utilized catches as well as safeguarding the biodiversity of ecosystems and the aquatic habitat.

12.12 States should investigate and document traditional fisheries knowledge and technologies; in particular those applied to small-scale fisheries, in order to assess their application to sustainable fisheries conservation, management and development.

Some individual nations are developing their own versions of a Code of Conduct. In some cases, the industry has taken the initiative (i.e. Canadian Code of Conduct for Responsible Fishing Operations, Consensus Code 1998).

Of particular interest is the case of Norway, which has adopted a policy of 'No discards'. Fishers are not allowed to discard anything caught in the net, and that forces them to fish selectively by avoiding periods, areas or times of the day with high by-catches, and by developing technology that contributes to that goal. Norway is the only country that has prohibited discards by law and fishermen are obliged to bring all their catch ashore (Olsen, 1995; Isaksen, 1997). Fishermen also have to keep logbooks with detailed records of their operations. This is controlled by frequent inspections, but the success of efforts like this depends on the good faith of the fishers, or on a very extensive and costly monitoring system based on on-board observers. Without being too pessimistic about human nature, the need for monitoring stands as a clear pre-requisite to the implementation of this type of programme.

These programs (a) encourage research on by-catch reduction gear and techniques with a clear economic disincentive, which is to fill the boat with low-value fish; (b) encourage behavioural changes in fishers with regard to avoiding areas and seasons of high by-catches; (c) help reduce the waste of life and protein caused by the fishery, by forcing the utilization of what was already harvested. However, they are costly; and may result in the development of markets for undersized fish, juveniles, etc.

The Kyoto declaration and plan of action

The States that met in Kyoto for the International Conference on the sustainability contribution of fisheries to Food security in December 1995 endorsed the provisions of the FAO Code of Conduct and in Declaration 15 stated that 'they would promote fisheries through research and development and use of selective, environmentally safe and cost effective fishing gear and techniques'. This resulted in the following being included in the plan of action (Clucas, 1997):

- to increase efforts to estimate the quantity of fish, marine mammals, sea birds, sea turtles and other sea life which are incidentally caught and discarded in fishing operations;
- to assess the effect on the populations or species;
- to take action to minimize waste and discards through measures including, to the extent practicable, the development and use of selective, environmentally safe and cost effective fishing gear and techniques;
- to exchange information on methods and technologies to minimize waste and discards.

Classification of By-Catch: Why is it Useful?

By-catch is not a phenomenon that exists by itself; it is simply the result of deficiencies in our ability to select what we harvest from the ocean. As such, the label covers a wide variety of situations. By-catches happen for many different reasons, and have widely different characteristics, so it helps to analyze the problem by classifying by-catches to illustrate how they happen, their ecological or economic origin, and their significance. The classifications proposed by one of us are based on eight different criteria that highlight some special characteristics of the problem, and in many cases point to likely approaches for its solution (Hall, 1996):

1. by the spatial pattern of by-catch rates (more or less aggregated in space);
2. by the temporal stratification (more or less 'aggregated in time');
3. by the level of control (controllable or uncontrollable by the fishers);
4. by the frequency of occurrences (rare or common);

5. by the degree of predictability (predictable or unpredictable);
6. by the ecological origin of the by-catch (species associated with the target or random encounters);
7. by the level and type of impact;
8. by legal or economic considerations.

Criteria 1 and 2 illustrate cases where closures (spatial or temporal) are effective in reducing by-catch. This is not the only piece of information necessary to make an intelligent decision on the matter. The spatial and temporal distribution of the catches is also relevant. If the distribution of catches and by-catches is similar, then the cost in catch losses of the closures will be high. The key variable is the ratio by-catch to catch in all spatial or temporal strata considered. When it is high, the potential value of closures is high. The models proposed by Hall (1996) allow an approximate assessment of the costs incurred when applying a closure system to control by-catches. If reasonable assumptions can be used to reallocate effort from the closed areas or periods to alternative ones then the model can be modified to introduce the new effort distribution; otherwise, the basic model will produce a worst-case scenario.

If a by-catch is controllable to some extent (criterion 3), then fishers may be required to meet performance standards. The incidental dolphin mortality in the eastern Pacific is a clear example; the more capable skippers, with the best trained crews, have much lower mortality rates than others. It is possible then to demand minimum performance standards by those participating in the fishery on dolphins. Some countries implemented maximum acceptable values of average dolphin mortality per set, and skippers exceeding those were removed from the fleet. The whole international fleet is managed with a system of individual vessel limits that has been steadily declining; this decline is a reflection of the fact that the fleet can modify its behaviour. But it is not sensible to set standards for the fisher that got a whale entangled in a lobster trap; there is no modification of the fishing technique that could have avoided that incident. Between these extremes, there is a continuum of levels of control. A gill-netter may affect his by-catch rates by selecting fishing areas known to him to have lower by-catches, or by moving away from areas where results were negative.

Very infrequent events (criterion 4) make planning for prevention impossible. Patterns cannot be established, methods cannot be tested, but still the impact may be important if the event is catastrophic (i.e. a massive entanglement due to special circumstances).

Predictability (criterion 5) is a requirement for the effectiveness of closures. Consistent migrations, such as sea turtle 'arribadas' are easy targets for management controls, and there are many other situations where predictability can be used to mitigate impacts. Species that are known to be active at night, and not during the day, or that are especially active when there is a full moon or high tide, etc., provide the manager with an opportunity.

When by-catch species are ecologically associated with the target species (criterion 4), a difficult choice is offered. A selective fishery may result in an imbalance in the ecosystem. The harvest of a predator but not the prey, or vice versa, or of one of a guild of competitors, is likely to result in changes in community structure, but unfortunately, for most ocean basins, there is very little baseline data to compare with. From the point of view of ecosystem utilization, a diversified harvest may be a better way to preserve its structure and function, than a very selective one (Hall, 1996).

The level of the by-catch (criterion 7) gives a good idea of the priority it deserves. Unsustainable by-catches, especially those of species in danger of extinction, will generate a need for actions that could be drastic and with high economic and social impacts (i.e. coho salmon in British Columbia). It is these types of by-catches, together with those of charismatic species, that have brought the issue to the forefront of fisheries management. Today, by-catch considerations play a significant role in the regulation of several major fisheries.

The last criterion (criterion 8) simply separates by-catches that are imposed by regulation from those that are generated by economic considerations (low price, no market etc.) This second type can be reduced through marketing campaigns, changes in food processing, or other ways to increase the value of the discarded products.

By-Catch as a Component of Fishing Mortality

A basic need of fisheries management is to quantify the mortality caused to the resource (Chopin *et al.*, 1996). This value, together with natural mortality, constitutes the total loss of individuals from the target population. The traditional formula for total mortality (Z) is the sum of the natural mortality (M) as well as mortality due to fishing (F). That is

$$Z = M + F.$$

As total mortality can be estimated from catches by age or other techniques, and natural mortality has proven very difficult to estimate independently, many thought that a good approximation to F could be obtained from fisheries data. But omissions and incomplete or biased nature of the data have been a problem. An ICES study group (review in Chopin *et al.*, 1996), tried to explore all possible sources of fishing mortality, and of other uncertainties in the data. The total impact of fishing was quantified as an aggregate of all catch mortalities including discards, illegal fishing and misreported mortalities.

The complexity of the F term is described by decomposing it into a series of components that identify the potential sources of fishery-induced mortality and complete the picture by adding non- or under-reporting. The equation to specify all the components is the following, where F is the sum of all direct and indirect fishery-induced mortalities:

$$F = (F_{\mathrm{cl}} + F_{\mathrm{rl}} + F_{\mathrm{sl}}) + F_{\mathrm{i}} + F_{\mathrm{d}} + F_{\mathrm{o}} + F_{\mathrm{a}} + F_{\mathrm{e}} + F_{\mathrm{g}} + F_{\mathrm{p}} + F_{\mathrm{h}},$$

where F_{cl} is the commercial landing mortalities, F_{rl} the recreational landing mortalities (these are mortalities associated with sport fishing). In the UK for example there are many anglers but there is no licensing system for sea fishing. This mortality is therefore largely unknown despite the fact that over one million people fish at the sea), F_{sl} the subsistence landing mortalities (this is a mortality associated with fishing by indigenous people), F_{i} the illegal and misreported landing mortality, F_{d} the discard mortality, F_{o} the drop-out mortality, F_{a} the mortality resulting from fish or shellfish that avoid gear but die from stress or injuries, F_{e} the mortality resulting from fish or shellfish contacting but escaping gear that subsequently die, F_{g} the mortality resulting from fish or shellfish that are caught and die in ghost fishing gears, F_{p} the mortality resulting from predation of fish or shellfish escaping from or stressed by fishing gear that would otherwise live and F_{h} is the mortality due to gear impacts on the habitat (i.e. increased predation because of loss of shelters or disturbances, etc.).

This equation helps point out the need for research plans aimed at understanding and quantifying each of these components, and eventually to devising programs to reduce waste. It also serves to emphasize the small amount of data available on most of these sources of mortality in the majority of our fisheries.

By-Catch Reduction Programs

As Alverson and Hughes (1996) point out, the emergence of by-catch as a major management issue can be traced to the rapid growth of world fisheries and their increasing competition, the rise of environmental groups and resulting efforts to protect populations of marine mammals, birds and turtles affected by commercial fisheries. Facing the task of reducing by-catch, it quickly became apparent that there were only two levers that could be moved to achieve reductions (Hall, 1996). Either the level of effort is reduced or the average by-catch caused by each unit of effort is reduced (Table 1).

TABLE 1

Basic by-catch equation ('two lever system') and ways to reduce both terms.

Bycatch	=	"effort"	x	bycatch-per-unit "effort"
		Regulatory bans Regulatory limits Trade sanctions Consumer boycotts Gear changes		Technological changes Operational changes Training Management actions

Reductions in effort

Reduction in the level of effort amounts to a reduction in the fishery, and it is frequently a costly solution. The United Nations Driftnet ban is an example (Burke *et al.*, 1994; Bache and Evans, 1999). A reduction in effort is often imposed indirectly when a total by-catch limit is established as has been done in the Tuna–Dolphin Programme (Hall, 1998). Temporal or spatial closures may result in effort limitations if the fishers cannot increase the level of effort in open areas or seasons to compensate for the closures. Policies such as the 'dolphin-safe' one, that try to eliminate the market for the catch produced by a specific gear or type of effort, have the target of reducing or eliminating it (Scott, 1996).

Reductions in BPUE

Technological changes in gear and other equipment. The options to reduce BPUE are many. Technological changes in equipment may be used. This has proved very successful in many fisheries, provided that some conditions are met during the experimental stage (Pikitch, 1992). Traditionally, changes in mesh size or type have been used to improve selectivity; hook size and bait type have been used in longline and hook-and-line fisheries; addition of Turtle-Excluder Devices (TEDs) to trawls has reduced sea turtle mortality dramatically (Magnuson *et al.*, 1990); sorting grids, mesh changes and other modifications are also used (Larsen and Isaksen, 1993; Stone and Bublitz, 1996; Kennelly, 1995; Kennelly and Broadhurst, 1996). The Medina Panel and many other changes of the basic purse-seine gear have helped reduce dolphin mortality (Coe *et al.*, 1984; Francis *et al.*, 1992). Sorting grids are also in use or have been tested in some purse seine fisheries (Misund and Beltestad, 1994; Beltestad and Misund, 1996) and bird-scaring lines have been successful in reducing bird by-catches in longlines (Alexander *et al.*, 1997). Other examples are provided by Alverson (1998).

Deployment and retrieval changes. Sometimes changes in the procedures used to deploy or retrieve the gear are sufficient to alter its selectivity, and it is not necessary to modify it. The backdown procedure applied to purse-seining on dolphins has been a major contribution to the reduction in dolphin mortality from 133 000 in 1986 to under 2000 in 1998 (Hall, 1998; Anon., 2000). Deploying longlines at night, or bringing the point of release to 1.5–2 m below the surface reduces seabird by-catches (Alexander *et al.*, 1997; Løkkeborg, 1998). Gillnets and longlines can be deployed at different levels in the water column. The speed, depth or duration of a trawl haul can also affect selectivity.

Training. Training of fishers includes providing them with information that helps them avoid conditions that lead to high by-catches, as well as specific training in the use of the gear and manoeuvres (Bratten and Hall, 1996).

Management actions. Many options are available, including programs and approaches pursued in different countries and fisheries (Olsen, 1995; Duthie, 1997; Everett, 1997; Isaksen, 1997; Witzig, 1997; Alverson, 1998). Considering that the goal is to reduce the average BPUE, any change which switches effort from areas or time periods with high BPUE to those with lower values will result in an average decrease. Closures can be effective if the areas or periods closed have higher averages. When by-catches are controllable, selection of skipper and crews that meet some performance standards could also lower averages. But even more effective has been the setting of individual vessel by-catch limits. In the tuna purse seine fishery of the eastern Pacific, the total dolphin mortality limit set by participating nations in the international programme is divided by the number of vessels requesting a limit, and each of them is allowed to make sets on dolphin-associated tuna until its individual limit is reached (Hall, 1998; Gosliner, 1999).

Management actions which improve performance include: selective licensing; economic advantages so that those with the best performance get licenses for the best areas, or for longer periods, or for preferred species; total retention of by-catch; acknowledging fishers with outstanding records or, as is done in some fleets, publishing lists of worst offenders; use of labels identifying responsible fishers that meet required standards, to allow consumers to use their buying power to provide an incentive.

History of the By-Catch Issue: Some Early Examples

The emergence of the by-catch issue was a result of a few highly visible cases. From the typical, early responses to the by-catch of charismatic species, the more ecologically-minded groups moved on to face effects of by-catches at the ecosystem level. The former had economic successes, while the latter were less glamorous but addressed the very significant issues of effects on ecosystems.

The Tuna–Dolphin problem

Incidental mortality of dolphins in the tuna purse-seine fishery in the eastern Pacific Ocean during the 1960s was the first by-catch problem that generated intense public attention. Initially tuna was fished with pole and line, using live bait. In the late 1950s, the US fleet switched to purse-seine gear, following several technological developments. This fishery had much higher catch rates. The tunas were detected in three ways: association with floating objects, association with herds of dolphins, and as free-swimming schools visible at the surface. When tunas were associated with dolphins, the net encircled both, many of the latter being killed. When environmental groups became aware of this (Perrin, 1968), the reaction was intense, leading to the passing of the Marine Mammal Protection Act (MMPA) in 1972 (Gosliner, 1999). Dolphin mortality during the 1960s was estimated to be several hundreds of thousands of animals per year, but estimates are not solid (Francis *et al*., 1992). Most dolphin populations declined into the early 1970s, and several stocks were declared depleted in the early 1990s because their levels were much lower than in earlier assessments (Gosliner, 1999). The association of yellowfin tuna and dolphins has also been observed in other oceans but the frequency of setting in the eastern Pacific is much greater (Hall, 1998). The National Marine Fisheries Service and, since 1979, the Inter-American Tropical Tuna Commission (IATTC), ran observer programs to produce mortality estimates and other data (Fig. 2).

Mortalities of dolphins through fishing which were estimated at 133 000 in 1986 were only 1877 in 1998 (Table 2). Recent levels of mortality are not significant from the population point of view; mortality levels for all stocks are less than 0.1%, much lower than the 2% value used as a conservative estimate of net recruitment (Hall, 1998). All dolphin stocks have estimated population sizes between 400 000 and 2 200 000, and the most recent survey shows much higher numbers for the depleted stocks. As additional surveys are planned for the coming years, a more solid estimate will be available at the end of these studies. But in any case, it is quite safe to state that declines in these populations have been halted, and that their recovery is under way.

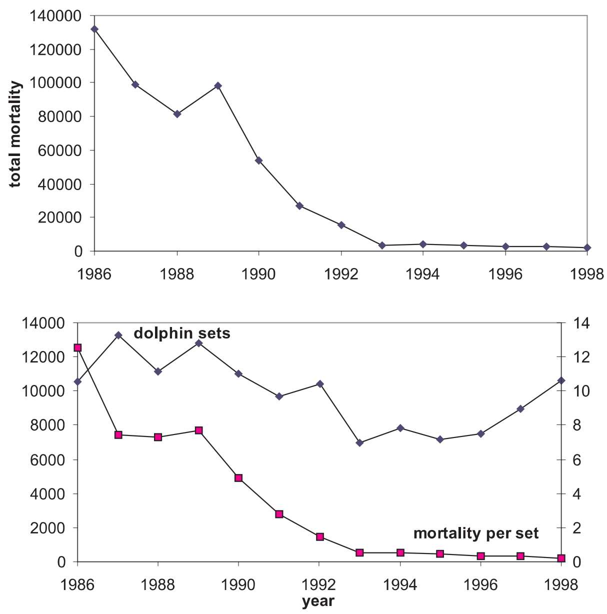

Fig. 2 Evolution of the total by-catch, and the components of the by-catch equation for the tuna–dolphin problem (1986–1998).

TABLE 2

Estimates of population abundance (pooled for 1986–1990), of incidental mortality in 1998, and of relative mortality.

Stock	Population abundance[a]	Incidental mortality	Relative mortality Estimate 95% Cl
Northeastern spotted	730 900	298	0.04% (0.031, 0.061)
West/Southern spotted	1 298 400	341	0.03% (0.020, 0.037)
Eastern spinner	631 000	422	0.07% (0.042, 0.101)
Whitebelly spinner	1 019 300	249	0.025 (0.015, 0.032)
Northern common	476 300	261	0.05% (0.030, 0.118)
Central common	406 100	172	0.04% (0.022, 0.083)
Southern common	2 210 900	33	≪0.01% (0.001, 0.004)
Other dolphins	2 802 300	101	≪0.01% (0.002, 0.004
All	9 576 000	1877	0.02% (0.017, 0.022)

[a] From Wade and Gerrodette (1993).

What brought the mortality down? Public awareness and pressure were critical, and kept the process moving, while campaigns of environmental organizations were effective. When it became clear that a large sector of the public would not accept the high levels of mortality, the industry abandoned a policy of fighting restrictions. It was clear that they were fighting for their survival, which provided the motivation. Most of the change originated in technological improvements, and on the performance in releasing dolphins. Most solutions came from the fishers themselves; the role of the scientists was to facilitate communication, identify the causes of high dolphin mortality, promote the testing of new ideas and validate statistically experiments performed. Several changes in the gear (additions of fine mesh panel, rescue platforms, etc.) and in the procedures used (backdown, hand rescue, etc.) were instrumental for the solution of the problem. The training of skippers and crews run by the Tuna–Dolphin Programme of the IATTC (Bratten and Hall, 1996) played a role in the quick diffusion of new ideas, and communicated to all crews the standards that were expected (Fig. 3).

Management actions covered a broad spectrum, going from global quotas for dolphin mortality, to more detailed approaches such as prohibitions of night sets, mandatory use of equipment, and gear of specified characteristics, etc. Probably the most successful approach proposed by the Tuna–Dolphin Programme of the IATTC was the establishment of individual vessel dolphin mortality limits. A total limit was divided by the number of participating vessels, and each vessel received an individual limit. This was fair to individual vessels, and was convenient because it avoided conflicts over resource allocation. Those capable of staying within the limit were allowed to continue fishing on dolphins; those reaching the limit had to cease fishing on dolphins, which entailed a considerable economic impact. This set in action what can be called the 'Darwinian selection of fishers'. Less-skilled captains became a liability and were replaced. Good captains became valuable and were sought after. The individual limits decreased year after year, which forced the continued improvement. In the early years of the fishery, the levels of mortality made it a conservation problem, but by the early 1990s, the by-catch had become sustainable and dolphin populations were no longer declining. Public pressure required that the reductions continued, and they did so until reaching the current level of under 2000 individuals taken from populations probably numbering over 10 million individuals.

Fig. 3 Crewman rescuing dolphin from the net (photo D. Bratten).

Many lessons were learned from this first major battle against a by-catch problem (Hall, 1996, 1998), and the solution came from a combination of factors (Hall, 1996): Fishers began to avoid large herds, or herds of those dolphin stocks whose behaviour made them more vulnerable. They also changed deployment conditions, avoiding sets in areas with strong currents, or at night. The major improvements came in the release process; the backdown manoeuvre was adopted by all fleets and refined. Additional changes in the net such as a fine mesh panel to reduce entanglements, and a highly motivated hand rescue effort based on rafts, swimmers, and divers, completed the process.

The solution came from a combination of actions and changes. Change was gradual, but between 1986 and 1998 mortality declined by 98%. The fishing industry proved very effective in setting standards, and the fishers themselves produced most of the solutions. The process was fairly transparent; environmental and industry NGOs were deeply involved, and had direct access to the basic information on compliance, etc.

The shrimp–sea turtle problem

Trawls are used in most countries of the world to harvest valuable resources of shrimps and prawns. Sea turtles are one of the most critically endangered groups of species to be taken incidentally in some of these trawl fisheries. With the possible exception of the olive ridley (*Lepidochelys olivacea*) which number in the hundreds of thousands, numbers of other species are low, and some populations have declined markedly. The urgency to reduce the by-catch reflected a clear conservation issue.

Again technology played a role in mitigating the problem. TEDs were installed in nets to let go sea turtles that entered. TEDs consist of rigid or soft structures that direct out of the net those species larger than the spacing of vertical bars that create a grid. They proved extremely efficient in releasing sea turtles, and became mandatory after some years (Magnuson *et al.*, 1990). In addition, some closures reduce captures when high numbers of sea turtles are present, especially during peak nesting periods. In some cases captured turtles can be released alive after a 'resuscitation' procedure. The major difficulty has been the spread of this technology to all nations that trawl for shrimp in areas with sea turtles present. The USA has used its very large market share to threaten embargoes on countries not using TEDs. There are other threats for the sea turtles – by-catches in other fisheries, habitat destruction, excessive harvest of individuals or eggs, etc. – but the solution to the by-catch in shrimp and prawn trawls is available.

Discards in shrimp and prawn trawls

Sea turtles are not the only problem caused by shrimp and prawn trawls. Alverson *et al.* (1994) show that these trawls have the highest discard/catch ratios of all fisheries considered. Of the 16 worse offenders in this category, 14 are shrimp or prawn trawls. The ratios go from 3:1 to around 15:1 kg discarded per kg landed. These fisheries are perceived by the public as extremely wasteful, and environmentally harmful, not only by the removal of biomass and diversity, but also by the potential impact on habitat, and the impacts of the discards on pelagic and bottom communities. In some fisheries, the lack of markets results in the discard of most of the species caught with the shrimps or prawns; by-catches are high, and the moral condemnation of the fishery follows these wasteful practices. But in many others, most of the biomass captured is utilized for human consumption or animal feeds (Clucas, 1997). In developing nations, the utilization of the capture is almost 100%; there is no by-catch. The fact that non-target species are utilized may remove the moral problem of the protein waste, but it does not remove the problem of the poor utilization of most of those species. They are still taking individuals at sizes that are much smaller than desirable. The solution reached in many countries, that of utilization of the by-catch, is not the most satisfactory way to utilize the resources (Table 3).

Although the number of studies on the fate of discards is very limited, they are a clear subsidy to some components of the pelagic and benthic communities (scavengers, etc.), and cause changes in structure and function of these communities (Hill and Wassenberg, 1990; Kennelly, 1995; Dayton *et al.*, 1995; Wickens, 1995; Ramsay *et al.*, 1997). Of particular significance in the Gulf of Mexico is the incidental mortality of juvenile red snappers (Gutherz and Pellegrin, 1988; Graham, 1996) that is the cause of friction between different groups of fishers. Even though the use of by-catch-reduction devices has helped mitigate the problem, some authors believe that they are not as effective as needed for the recovery of the red snapper stock (Gallaway and Cole, 1999).

By-catch-reduction devices (BRDs) are being developed to deal with the issue of finfish by-catches. Differences in escape responses, size and shape between fishes and the target crustaceans are being used for these new designs (Kennelly, 1995; Kennelly and Broadhurst, 1996; Broadhurst *et al.*, 1997). One of the concepts used is the so-called 'fish-eye', which is an opening, or group of openings, strategically placed in the trawl to allow the escape of the finfish. But rigid grids such as the Nordmøre are the most effective solution available for some fisheries (Broadhurst *et al.*, 1997).

Another way to reduce by-catch from these trawls is to improve the handling and survival rates of the individuals captured (Ross and Hokenson, 1997). Some species have relatively high survival rates after capture, while others are fragile (Alverson *et al.*, 1994). The impact of trawls is clearly a priority issue. These fisheries produce roughly 2% of the world catch of fish in weight, but result in more than one third of the by-catch (Alverson *et al.*, 1994), although there are some changes to these figures in a recent update of that work (Alverson, 1998). However, their economic and social significance is also out of proportion to their landings weight. Continued research on the technology may produce more efficient solutions, and there are experiments in progress testing several modifications of the by-catch reduction devices (i.e. Rogers *et al.*, 1997).

Gillnets and cetaceans

Cetaceans of many species are killed incidentally in gillnets. These can be deployed at different levels in the water column according to the target, and because of their low cost and effectiveness, they are used by a large number of small inshore boats throughout the world. A major review of the mortality of cetaceans in gillnets was produced a few years ago (Perrin *et al.*, 1994), and some of the proposed solutions are considered there. Probably the best studied interaction of cetaceans–gillnets is in the

TABLE 3

By-catches in numbers of individuals per 1000 metric tons of tuna loaded for the different types of sets.[a]

	Dolphin sets ($n = 33927$)	School sets ($n = 19210$)	Log sets ($n = 21567$)
Dolphins	19.47	0.15	0.40
Billfishes			
Sailfish	4.02	6.86	0.42
Black marlin	0.40	1.28	4.60
Striped marlin	0.53	1.39	1.12
Blue marlin	0.41	1.55	6.01
Unidentified marlin	0.22	0.36	0.83
Swordfish	0.07	0.19	0.10
Shortbill spearfish	0.06	0.02	0.08
Unidentified billfish	0.67	0.15	0.43
Large bony fishes			
Mahi-Mahi	2.13	182.12	4288.51
Wahoo	3.67	23.54	2307.38
Rainbow runner	0.05	36.82	383.77
Yellowtail	14.12	448.22	330.24
Other large bony fish	0.27	367.69	206.09
Sharks			
Blacktip shark	22.08	98.78	163.07
Whitetip shark	2.06	3.25	31.52
Silky shark	3.57	16.48	73.97
Hammerhead shark	0.99	8.41	6.72
Other sharks	3.02	9.57	29.78
Unidentified sharks	5.70	11.83	43.53
Rays			
Mantaray	3.77	29.84	0.93
Stingray	2.19	8.72	1.02
Sea turtles			
Olive ridley	0.18	0.41	0.42
Green-black	0.01	0.08	0.07
Loggerhead	0.01	0.03	0.01
Unidentified turtles	0.07	0.14	0.14

[a] Combined data for 1993–1998.

Bay of Fundy and Gulf of Maine fisheries. Demersal gillnets, which target cod, pollock and hake, have by-catches of several dolphin species, long-finned pilot whales, humpback, minke, fin and right whales (IWC, 1994), as well as harbour porpoises. Many large whales survive entanglement, although they may carry off portions of gear. A rescue group has been put together to try to help in the release of entangled individuals (Lien *et al*., 1994).

Entanglement is almost always fatal for small cetaceans. Harbour porpoises *Phocoena phocoena* are the most frequently killed cetaceans in these nets. In the North Sea annual mortality estimates can range to several thousand per year (Vinther, 1999). A number of studies (Northridge, 1984, 1991a,b; Read *et al*., 1993; Palka, 1995; Read and Gaskin, 1988; Lien, 1994; Jefferson and Curry, 1994) have attempted to assess the by-catch levels in different regions and fisheries. In the Gulf of California, the vaquita, *Phocoena sinus* is in danger of extinction, and the major risk factor is the incidental mortality caused by gillnets (Rojas-Bracho and Taylor, 1999).

To minimize the impact of these entanglements, special devices have been developed (Lien *et al*., 1994). These 'pingers' or sound-emitting alarms on nets have decreased by-catch considerably (Kraus *et al*., 1997). Some experimental studies, notably in the Bay of Fundy (Trippel *et al*. 1999), and in the California coast (Cameron, 1999) have shown a reduced by-catch of small cetaceans by 77% and 70% respectively for nets with pingers. The reasons why the entanglements are reduced are still poorly known (Nachtigall *et al*., 1995). The pingers may affect the distribution of the prey items of the small cetaceans, and indirectly affect their distribution, or they may make the net 'visible' to the cetaceans.

Trawls and cetaceans

Midwater trawls have a much greater potential to capture cetaceans than bottom trawls (Read, 1994). The nets can be towed much faster, and their targets are often fish or squid that are important prey for marine mammals. Thus dolphins and small whales may be captured while feeding on schools of these species, or they may learn to associate the presence of midwater trawls with concentrations of food in a patchy environment. Couperus (1997) reviewed the interactions between cetaceans and trawling and also reported target fish species in the stomachs of by-caught common and bottlenose dolphins, but these were absent from stomachs of white-sided dolphins. Descriptions of cetaceans feeding associated with trawls were first reviewed by Fertl and Leatherwood (1997). At least 16 cetacean species all over the world are known to feed in association with fishing trawlers.

A recent study to quantify midwater trawl by-catch in the eastern Atlantic showed that most dolphin by-catch occurred during night or close to dawn (Morizur *et al.*, 1999). Some factors which may be important in the cetacean–trawl interaction include the target fish species, time of day, tow duration, level of tow, size of net opening, haul back speed and gear design. A better understanding of these factors should help find the solutions to the problem.

Other studies such as Tregenza *et al.* (1997) in the Celtic Sea, Tregenza and Collet (1998) in the northeast Atlantic, Dans *et al.* (1997) and Crespo *et al.* (1997) in Patagonia, and Lens (1997) southeast of Newfoundland, show that the incidental takes happen in many trawl fisheries. Without observers on the vessels in most cases, a solid quantification of these impacts will not be feasible. Some technological approaches to a solution have been explored (de Haan, 1997) including acoustic deterrents (i.e. pingers) in the trawl, and excluder panels. But a solution is not yet available and, given the widespread use of trawls, even low BPUE values may still yield important impacts.

High seas driftnets

Pelagic driftnets came to the public's attention in the mid 1980s. This type of fishing had developed a few years earlier, and was based on the deployment of nets that were miles long. Although some European nations had fisheries of this type in the mid 1970s, the Pacific Ocean was the first to be extensively exploited with this technique. The technique was effective, but by-catches in some fishing grounds were high, and involved charismatic species (Northridge, 1991b; Hobbs and Jones, 1992). NGOs started campaigns to ban the 'walls of death'. Only a few countries participated in this fishery in the Pacific (Japan, Korea, Taiwan), but the level of effort they deployed at its peak was very high. Some coastal nations from the Pacific region, especially island nations, felt threatened because of the potential impact of this fishery on their artisanal fisheries. The Mediterranean Sea is another area where ecological impacts of driftnets were significant (Silvani *et al.*, 1999). The issue was brought to the UN by a coalition of nations and NGOs, and a moratorium was imposed on the use of nets of more than 2.5 km long. Some authors questioned the scientific basis for these actions, because the analyses performed had been incomplete (Burke *et al.*, 1994), or simply stated that the support for them by some nations had been politically motivated rather than science-based (Bache and Evans, 1999) In any case, with only a few nations participating in the fishery it was easy for the coalition opposing it to pass a moratorium. The impacts on the countries participating in the fishery were high; employment losses alone were estimated at more than 15 000 jobs (Huppert and Mittleman, 1993). This is one example of a fishery where the by-catches were eliminated by reducing the effort to zero or close to zero.

Longlines and sea birds

Longlines are used in many ocean areas of the world to catch a variety of species including tunas, swordfishes, sharks and toothfishes, etc. Bait and offal discarded from the boats attract seabirds, which become hooked and drown. When longlines are set on the surface, the probability of hooking persists during the set; when they are set on the bottom, hooking can occur while deploying or retrieving the lines. Two of the fisheries where these interactions play a major role in their management are the albacore fisheries off Australia (Brothers, 1991; Murray *et al.*, 1993; Gales *et al.*, 1998), and the North Pacific longline fishery for Pacific cod, halibut and blackcod. There is special concern with the by-catches of several species of albatross, and in some cases declines in population numbers have been observed (Weimerskirch and Jouventin, 1987; Croxall *et al.*, 1990; Brothers, 1991; Murray *et al.*, 1993). A variety of solutions have been proposed, and their implementation is resulting in major reductions in by-catch levels. Some solutions are very simple: an object is towed or an additional line carrying streamers is placed to scare the birds; weighting lines or thawing the bait to increase sink rates of the line; changes in the method of setting (Løkkeborg, 1998) or in the time of deployment (i.e. at night to reduce the visibility of the baited hooks). Other solutions are more expensive: a lining pipe to take longlines to 1–2 m deep to 'hide' the baited hooks from the birds (see Matsen (1997) for illustrations). Also, offal can be discharged away from the place where the line is being set. Many of these modifications also reduce the loss of bait. The developments from the Australian zone fisheries were quickly adopted in the North Pacific. The FAO has set in motion an International Plan of Action for reducing incidental catch of seabirds in longline fisheries (see www.fao.org). An excellent review, also produced by FAO, covers the problem and techniques available for mitigation (Brothers *et al.*, 1999). Many nations have developed policies to deal with the issue (Bergin, 1997; Bache and Evans, 1999). An excellent review of the longlines-Albatrosses problem can be found in Alexander *et al.* (1997), and a manual produced for fishers by CCAMLR (1996) is a good example of how to communicate with fishers to promote awareness.

Coastal gillnets and sea birds

Because of the very large number of coastal gillnets deployed, this type of interaction is probably much more common than suggested by the literature. Diving birds, mostly Alcids, are entangled in gillnets while diving for prey, or when trying to steal the catch from the net. The best known example of a by-catch reduction programme is that of the salmon drift gillnet fishery of Puget Sound, Washington State, USA (Melvin, 1995; Melvin and Conquest, 1996; Melvin *et al.*, 1997, 1999). Again, options were found that would allow a substantial reduction of the by-catch without a significant impact on the catches. The solution is not simple, but is a combination of technological modifications, changes in deployment, and management of seasonal closures. The technological modifications include the addition of a visual alert (a strip of highly visible netting in the upper part of the net), and an acoustic alert (a 'pinger' Lien, 1996). The deployment time, (i.e. eliminating dawn sets) would contribute to the reduction in by-catch. Finally, managing the opening and closing of the fishery to coincide with periods of high target catch rates and low by-catch rates provides an additional mechanism to increase selectivity. The implementation of these measures is held up by legal issues (Melvin *et al.*, 1999), but the key to the solution is available, without significant losses in catches.

Longlines and sea turtles

Unlike many other fisheries, the incidental capture of sea turtles in longlines is one with no clear solution (Balazs, 1982; Bolten *et al.*, 1996). Besides some obvious options, such as closing areas where high densities of sea turtles aggregate near nesting beaches, it is difficult to find technological answers because of the heterogeneity of the problem. Sea turtles are taken in longlines when trying to take the bait (especially piscivorous sea turtles, i.e. loggerheads), or they get snagged by a hook, or become entangled with the fishing line (Witzell, 1984). Given that sea turtles can survive for long periods of time underwater, there has been considerable effort in establishing the conditions that will reduce the mortality rate of those captured. As the turtles dive quite deeply, changes in the depth of gear deployment may not be very effective.

After the sea turtles have taken a hook, it is still possible to release them, so a good deal of research has gone into the mortality caused by the hooks (Balazs and Pooley, 1994). If the hook has been ingested, mortality may follow, but few cases are fully documented (Skillman and Balasz, 1992), and there are no statistics showing what proportion recovers fully. Further research may produce hooks or baits that reduce the incidental captures. The effect of injuries and evidence that a release will result in survival, still needs to be examined.

Northeast Pacific groundfisheries

By-catch became an issue in the Bering Sea during the late 1950s following the development of the Japanese high seas salmon fisheries. The issue was first brought to the attention of fishery managers when it was found that birds and marine mammals were taken in the high seas gillnet fishery. However, fisheries managers of the region (Alaska) became greatly concerned following the development of the extensive trawl and line fisheries by the Japanese and Soviets during the 1960s and later, by Korean, Polish and other foreign nationals. Fishery scientists pointed out that there were extensive by-catches of halibut and crab taken in these fisheries as well as salmon. These concerns led to the development of a foreign observer programme which documented by-catch of 'preheated species', species being fully used by US and Canadian fishermen, of great economic and social interest to the coastal fishermen of the regions.

Following unilateral extension of fisheries jurisdiction by the US and Canada during the late 1970s and the development of US domestic fisheries for bottom fish off Alaska, particularly during the 1980s, the National Marine Fisheries Service (NMFS), in response to management actions taken by the North Pacific Fisheries Management Council (NPFMC), implemented a 100% observer programme on vessels over 125 ft and 30% for vessels between 65 and 125 ft. This programme led to one of the most comprehensive documentations of by-catch rates in the world.

Regulation of by-catch of the fisheries of the region was ultimately based on control of the level of prohibited species taken (quota and area management), closed areas for trawling and other fishing gears, required landing of by-catch taken in certain fisheries having bottom fish quotas, and seasonal quotas and closed periods.

The overall by-catch and discard rate in the Alaska groundfishery is not exceptional compared with other fisheries of the world (about 16%) and is much lower in the large pollock fishery of the region (Alverson *et al.*, 1994). However, the 2–3 million tonne fishery is so immense that the total by-catch volume, and forgone opportunities they may represent, have driven efforts to further reduce by-catch levels. For example the 1995 mid-water pollock fishery landed a total of 1.1 million tonnes of which 46 000 t was by-catch of undersized pollock-a small percentage, but still a high quantity of discards. However, some of the region's trawl fisheries have relatively high discard rates, e.g. rock sole and flat head sole (NMFS, 1998), and further regulation is expected.

Conclusions: into the Twenty-first Century

This list of case studies is very incomplete. Sections on shark by-catches in longlines, pinnipeds in trawls and many others could have been included. Presenting these case studies in a simplistic form (one by-catch group of species × one type of gear) has the merit of focusing attention on a specific problem, but readers should keep in mind that by-catch problems cannot be isolated or generalized. The same longlines that affect sea turtles may be taking sharks and billfishes. Shrimp and prawn trawls have high by-catch/catch ratios in some fisheries, but they are considerably lower in others. Because of the nature of the problem, solutions have to include a complete analysis of the consequences of the current practices, and of proposed changes. They also have to be specific to the circumstances of each fishery. Switching gear or modes of fishing to avoid one problem may create or exacerbate others (Hall, 1998). Closing an area or season to reduce by-catch of some species may concentrate the effort in other areas or periods with other problems (Table 4).

The case studies synthesized above do not cover all by-catch issues, but they provide a broad sketch of the direction in which programs are moving. In most of them, attempts are being made to keep a viable fishery. The fishers usually play a major role in developing and testing the modifications proposed. Most solutions involve relatively minor changes in gear and procedures, and usually a combination of technology and management achieves the desired improvements. But not all the problems listed above yet have a satisfactory solution, and it is necessary to think of the fisheries as dynamic systems, where evolution is taking place, and changes should be expected.

Understanding the behavioural and ecological differences between target and non-target species, and their responses to fishing gear pays off, showing any opportunities available. But given the multitude of problems we are facing, the research needs are massive, and only with vigorous research programs and with the active involvement of the fishers will progress be made. But many of the battles are being won. Whenever the challenge is faced, the solutions appear. The first step towards the solution is the commitment to finding one.

The fishers of the world are evolving, and must continue doing so. The process that has started is a process of natural selection. Only the fishers that can adapt to the new conditions will 'survive'; those that can produce catches with the lowest ecological costs, with the least waste, with the least impact on the habitat, will inherit the fisheries. Adaptation happens through education and technological change; the ways of fishing that have become maladaptive must be replaced by others that are sustainable.

Technology played a role in the generation of the problems, but it is also a major contributor to the solutions (Prado, 1997; Alverson, 1998). An area of especial interest is the development of instruments that can help fishers make better-informed choices before setting gear. If fishers know in advance the species and size composition of the potential targets in an area, they could make better decisions concerning whether to make the set or not, modify the deploy-

TABLE 4

Measuring the impact of by-catch on the ecosystem: BPUE is the by-catch caused per-unit of effort.[a]

	Dolphin sets ($n = 33927$)	School sets ($n = 19210$)	Log sets ($n = 21567$)
Dolphins	0.371	0.002	0.001
Billfishes			
Sailfish	0.065	0.093	0.012
Black marlin	0.007	0.017	1.129
Striped marlin	0.009	0.019	0.031
Blue marlin	0.007	0.021	0.168
Unidentified marlin	0.004	0.005	0.023
Swordfish	0.001	0.003	0.003
Shortbill spearfish	0.001	0.000	0.002
Unidentified billfish	0.011	0.002	0.012
Large bony fishes			
Mahi-Mahi	0.035	2.472	120.202
Wahoo	0.060	0.319	64.673
Rainbow runner	0.001	0.500	10.757
Yellowtail	0.230	6.084	9.256
Other large bony fish	0.004	4.991	5.777
Sharks			
Blacktip shark	0.359	1.341	4.571
Whitetip shark	0.033	0.044	0.884
Silky shark	0.058	0.224	2.073
Hammerhead shark	0.016	0.114	0.188
Other sharks	0.049	0.130	0.835
Unidentified sharks	0.093	0.161	1.220
Rays			
Mantaray	0.061	0.405	0.026
Stingray	0.036	0.118	0.029
Sea turtles			
Olive ridley	0.003	0.006	0.012
Green-black	0.000	0.001	0.002
Unidentified turtles	0.001	0.002	0.004

[a] Example is by-catch per set for different set types, Eastern Pacific tuna fishery 1993–1998.

ment conditions, etc. In this way, sets with high by-catches, or with high numbers of endangered species, would be reduced or avoided. This will also allow a more sophisticated management system. Acoustic, optical, laser, or other devices could provide this information.

Scientists need to quantify the impacts of by-catches on the target species and others, and to incorporate them into management schemes. But even more important is to understand the effects of the discard process on the ecosystem (Kennelly, 1995; Hall, 1999). The tonnage discarded is so large that we cannot continue ignoring its impact on the marine communities and ecosystems involved (Furness *et al*., 1988; Garthe *et al*., 1996). Research on this subject, hampered in many cases by technological difficulties and high costs, has been incredibly limited.

Finally, scientists and managers need to maintain a close cooperation with fishers, to develop practical solutions and regulations that allow the process of change to continue, without unnecessarily strict regulations. The natural selection process develops because there is variability, and that variability needs to be preserved.

Box 1: Measuring the impact of by-catch on the target species: Target utilization efficiency.

Target utilization efficiency

$$\text{TUE} = \text{Yield target species}/(\text{Catch target species} + \text{By-catch target species}).$$

How many tons of the resource are used (catch + by-catch) to bring one ton to the consumer.

This measure includes the impact of by-catch plus other losses due to transportation, storage and production losses.

Measuring the impact of by-catch on the ecosystem: Biomass transfer efficiency.

Biomass transfer efficiency

$$\text{BTE} = \text{Yield of all species}/(\text{Catch all species} + \text{By-catch all species}).$$

How many tons of biomass (catches + by-catches of all species) are needed to produce one ton of target species to the consumer.

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