Managing by-catch and discards: how much progress are we making and how can we do better?

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Abstract

There appears to be considerable potential for further reduction in global by-catch. This reduction is most likely to be achieved by focusing even greater attention on the technical, regulatory and social approaches that are currently practiced. With respect to the technical approaches, meta-analysis indicates that overall reductions in by-catch of between 25% and 64% could be achieved if global fishing fleets could match somewhere between the minimum and median performance of gear modifications used in experimental studies. If such benefits are to be delivered, however, engaging fishers more comprehensively in solving the problems will be essential. Further developing legislative and institutional arrangements will also assist. However, notwithstanding the potential gains that can be achieved, it must be recognized that careful analysis will often be required to ensure that a proposed measure will achieve the desired objective at an acceptable cost.

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Introduction

The generation of by-catch (here, we define by-catch as the fishing mortality resulting from the catch that is not accounted for in the landed catch. In effect, this definition equates to the discard mortality and represents the focus of the vast majority of the quantitative literature on by-catch levels), is a well-publicized consequence of commercial fishing operations. After the sustainability of the stocks themselves, the management and mitigation of by-catch is, perhaps, the most pressing issue facing the commercial fishing industry worldwide. By-catch has also emerged as a major concern to conservation bodies (both governmental and non-governmental) and the wider public. Indeed, the profile, voice and influence of this wider opinion on the subject of by-catch has never been stronger (Dobrzynski *et al.* 2003; EJF 2003).

Probably the first by-catch issue to generate substantial public attention was the incidental mortality of dolphins in the tuna purse-seine fishery of the eastern Pacific Ocean during the 1960s. The level of dolphin mortality during this period was estimated to be several hundreds of thousand of animals per year and it was outcry from the public on this issue that was one of the driving forces behind the passage of the Marine Mammal Protection Act of 1972 by the US Congress (Hall 1998, 2000). It was not until the 1980s, however, that the degree to which global fishing practices threatened populations of non-target fauna became evident. At this time by-catch really started to develop into a priority issue in fisheries as can be seen from the sharp rise in scientific publications on the topic around this time (Fig. 1). By-catch issues that have been (and continue to be) highly prominent include discards from prawn trawls; cetacean catch in gill nets and trawls; high sea drift nets; seabirds on longlines; seabirds in coastal gill nets; sea turtles on longlines; sharks on longlines; and pinnipeds in trawls (Alverson 1999; Hall *et al.* 2000).

By-catch estimates are somewhat incomplete for many areas and fisheries of the world, but a number of global estimates have been attempted. Of these, the most widely cited is that of Alverson *et al.* (1994) who calculated a most probable total value of 27 million metric tonnes. This 1994 estimate was based on data from the late 1980s and was, by the authors' own admission, of a provisional nature. A subsequent FAO Technical Consultation in 1996 concluded that Alverson *et al.* (1994) had almost certainly over-estimated by-catch in some FAO statistical areas and that amounts were declining in many fisheries (FAO 1997). Re-examination of the issue by Alverson himself acknowledged the deficiencies identified by the Technical Consultation, but also pointed out that other factors, such as lack of information for artisinal fishers and illegal fishing, could lead to under-estimation and that the estimates published in 1994 for the by-catch in the late 1980s were probably reasonable (Alverson 1998). However, Alverson went on to examine data for the 1994–1995 period in the same report and concluded that a significant reduction in global by-catch had occurred in the early 1990s (Alverson 1998). This conclusion was supported by an effort to update the global figure in 1998, which provided a revised estimate of approximately 20 million metric tonnes (FAO 1999), a figure at the lower bound of Alverson *et al.*'s original estimate for the late 1980s of 17.9–39.5 million metric tonnes.

Alverson *et al.*'s original assessment was derived from the FAO database of national catches, which

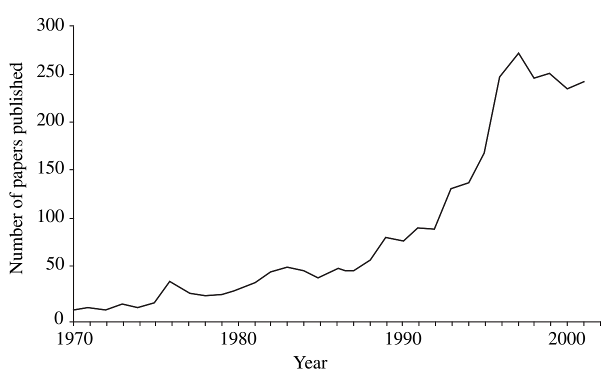

Figure 1 Time series for the number of scientific journal articles indexed in Cambridge Scientific Abstracts on the topic 'fisheries by-catch'.

contains information on catch, country, FAO area and species (or species group). In essence, the by-catch estimate is derived from landings by species data. More recently, an alternative approach has been developed by Kelleher (2004), who points out that there is no *a priori* reason why the by-catch quantities of a species should bear any relationship to the landings of the target species. An alternative premise, and the one that Kelleher (2004) based his methodology upon, is that by-catch is a function of the fishery, rather than a function of the landings of a species. Here, a fishery is defined in terms of an area, a fishing gear and a target species.

In addition to establishing an alternative methodology, Kelleher (2004) derived a new estimate of the level of global discards of 6.8 million metric tonnes. While this figure implies a very dramatic decline in global by-catch since 1998, the author stresses that this estimate is not comparable with previous estimates because of the different methodology employed. Given the dramatic difference between Kelleher's estimate and those published previously, there is likely to be considerable debate about the relative merits of the methodologies employed. A detailed analysis of the strengths and weaknesses of the two approaches is not appropriate here, but our own view is that, while the fishery-based approach adopted by Kelleher might be more sound in principle, the uncertainties surrounding definitions of fisheries and the paucity of data reported at the fisheries level makes its current utility questionable.

In fairness, Kelleher (2004) explicitly states that the report was not intended to provide a definitive estimate of discards at the global level. Rather, the intent was to establish a more robust process for estimation that engages national governments and should, over time, lead to better assessments of the magnitude and trend in global discarding (Kelleher 2004). This is an entirely reasonable ambition, but the publication of a global estimate (however provisional) that is substantially lower than previous estimates is bound to raise concerns among those who feel that maintaining pressure on fishers and fisheries management to continue their efforts to reduce by-catch is essential if the problem is to be fully solved.

While efforts to derive global and regional by-catch estimates are essential if we are to fully appreciate the magnitude of the problem faced and our progress towards solving it, there are other perspectives on the problem that must be considered. For example, there is now a large literature on the ecological impacts of by-catch and discarding and on approaches for their reduction; there are also some excellent reviews of these topics (see, for example, Andrew and Pepperell 1992; Kennelly 1995; NMFS 1998; FAO 2000). No purpose would be served, however, by our reprising these efforts. However, in contrast, beyond the global estimation approaches described above, there have been relatively few efforts to evaluate the extent to which overall progress in by-catch mitigation has been made. In this paper we seek to address this latter issue by asking the following three questions:

1 Which approaches are proving to be particularly successful for mitigating by-catch?

2 What is the potential for by-catch reduction from existing approaches?

3 How might further improvements be effected?

Our purpose, therefore is to examine the extent to which measures have been actively adopted, the potential for further improvement and the factors that need to be addressed to achieve this goal.

Approaches for solving the problem

The problem of uncontrolled and escalating by-catch, as with overfishing, emerged largely because of the rapid development of fishing technologies, the growth of commercial fisheries, and the lack of a parallel advance in regulation to prevent overfishing, by-catch and environmental side-effects. While recognizing that solutions to by-catch will often need to be tailored to specific fisheries and may differ between regions of the world (Alverson 1999; Bache 2002), we argue that there are three generic (and somewhat overlapping) systems that must be considered and dealt with in an integrated fashion if effective solutions are to be obtained. We label these as the technical, regulatory and social systems. Below, we outline the components of each of these systems and illustrate with examples how they have been used.

The technical system

The fishing method, gear used and the types, sizes and power of vessels all have a bearing on by-catch rates. In using the term 'technical system', we are simply referring to these practical means by which fishing is conducted. Three classes of technical approach can be distinguished: selectivity, deterrence and avoidance, the first two of which involve modifications to fishing gear.

Selectivity

When a fishery operates in a region of high species diversity (which is often when a large proportion of the by-catch is caught), it is possible to limit the amount of by-catch by exploiting the various behavioural and morphological differences between fished species. Devices such as separator trawls, modified ground gears or modifications to the sweep ropes and bridles that are attached to the trawl doors all operate using this principle and can reduce the unwanted fraction of catches (Cook 2003; Valdemarsen and Suuronen 2003).

As a result of their low selectivity and the highly diverse ecosystems in which many of them operate, solutions for reducing by-catch in prawn fisheries have received particular attention. Broadly speaking the problem for prawn trawl fisheries is threefold: first, the weight of the by-catch is often greater than the weight of prawns; in Australia's Northern Prawn Fishery, for example, over 400 teleost species contribute 73% of the by-catch weight. Second, prawn fisheries are often prosecuted in areas where turtles are present and vulnerable to capture by the trawl (Chan *et al.* 1988; US National Research Council 1990; Stobutzki *et al.* 2001). Third, there can often be a significant by-catch of commercially important target species from other fisheries; In the Gulf of Mexico (GOM), for example, the impact of prawn trawling on juvenile red snapper is a contentious issue (Gallaway and Cole 1999).

Modifying prawn trawls to include By-catch Reduction Devices (BRDs) and Turtle Exclusion Devices (TEDs) has been the primary approach for addressing these problems. The successful development of such devices has led to both BRDs and TEDs becoming mandatory in a number of prawn and shrimp fisheries. Over the period from 1989 to 1994, for example, concern over turtle population declines led to the introduction and subsequent legislative requirement for TEDs in the GOM and South Atlantic shrimp fisheries; BRDs were then mandated for these fisheries in 1997, primarily in an effort to reduce catches of juvenile red snapper. Similarly, a BRD device called the Nordmore grate, first developed and put into use by regulation in Norway, has been required since April 1992 to reduce by-catch of regulated groundfish in the Gulf of Maine northern shrimp fishery. In 1996 European Community legislation also made the use of a separator trawl or sorting grid mandatory in certain European shrimp fisheries because of the significant quantities of juvenile commercial species discarded. In Australia, it was not until May 1999 that the Queensland east coast trawl fishery was required to use BRDs and TEDs – a situation that was quickly followed by similar requirements for the Northern prawn trawl fishery in January 2000.

Of course, increasing the selectivity of fishing gear has not only occurred in prawn fisheries. In Iceland's groundfish fishery, for example, there is a mandatory requirement for sorting grids to protect the juveniles of commercial species such as cod, haddock and saithe.

Deterrence

As passive fishing gears such as longlines, drift nets and fish traps operate either by attracting species through use of baits or because the target (and non-target) species cannot sense the gear, considerable potential exists to deter unwanted species from approaching these gears while continuing to catch the target.

The fisheries where, perhaps, most attention has been paid to finding deterrent solutions are longline fisheries that have problems with the by-catch of seabirds – a controversial and widely publicized consequence of this fishing method. According to the IUCN, of the 61 species of seabirds affected by longline fisheries, 25 are threatened with extinction – incidental mortality from longline fisheries as a significant contributing factor (FAO 1998; Robins *et al.* 1999).

Seabird by-catch mitigation methods have now been established in many fisheries worldwide. Deterrence methods that have been used, and which are mandatory in some fisheries, include lines of streamers trailed behind vessels over the area where the hook enters the water; setting baited lines in total darkness; adding weights to longlines to accelerate sink rates; setting longlines deep underwater through tubes, thereby eliminating visual cues that seabirds rely on to take bait; dying baits blue so that the birds do not see them as easily; discharging offal from areas on the vessel that discourage birds from the baited hooks; and thawing baits and puncturing the swim bladders of bait fish so that baits sink faster (Bergin 1997; Furness 1999; Belda and Sanchez 2001; Loekkeborg and Skeide 2001; Anderson and McArdle 2002; Loekkeborg and Robertson 2002; Robertson *et al.* 2003). In some cases, such approaches have been shown to be capable of reducing by-catch to close to zero. A further recent development has been the setting of lines over the side of the vessel, rather than the stern; the proximity of the line to the hull of the vessel deters birds from taking the bait and is proving to be very successful (M. Hall, personal communication).

The potential for a high degree of deterrence also exists for gill net fisheries. For example, a suite of approaches have been proposed to reduce seabird by-catch in the coastal salmon drift gill net fishery in Puget Sound, USA (Melvin *et al.* 1999). The authors compared fish catch and seabird by-catch in traditional monofilament nets with the catch in modified nets with highly visible netting in the upper section or acoustic pingers. In conjunction with seasonal/area closures and time of day restrictions (see below), the authors suggest that a reduction of 70–75% in seabird by-catch is possible without a significant reduction in the efficiency of capture for the target species (Melvin *et al.* 1999).

The use of acoustic pingers has also been explored for deterring dolphins and porpoises from entanglement in drift nets. Early indications were that this was a particularly promising approach, with the potential for large reductions in by-catch. In one particularly well designed study conducted in New Hampshire, for example, reductions in by-catch of harbour porpoise of up to 92% were recorded in sink gill nets equipped with acoustic pingers (Kraus *et al.* 1997). As a result of such studies there is a current legal requirement to use pingers in the Danish North Sea wreck fishery on nets which, individually or linked in fleets, are up to 300 m long. Similar legislation has been proposed for the UK gill net fishery.

Notwithstanding such legislative measures and proposals, however, some scepticism has been expressed about the true effectiveness of acoustic deterrence (Dawson *et al.* 1998). In particular, earlier results are yet to be replicated, habituation might decrease effectiveness over time, and the mechanism of deterrence is unknown (Dawson *et al.* 1998; Cox *et al.* 2001). Also at issue are the practical constraints on pinger use, which include the size, cost and battery life of current devices, and whether their use can be monitored cost-effectively. A recent study by Carlstrom *et al.* (2002) illustrates how equivocal the results of such studies remain: in this study acoustic alarms were examined as a means to reduce harbour porpoise by-catch in bottom-set gill nets in the Swedish Skagerrak Sea. Despite the fact that no porpoises were caught in either treatment or control nets, the authors concluded that a combination of relatively high prey availability and an aversive response to pingers may have caused the displacement of porpoises from the fishing area (Carlstrom *et al.* 2002). This conclusion in favour of acoustic deterrents is weak at best – a feature that seems to be commonplace in studies of acoustic deterrence.

The quantitative effects of selectivity and deterrence

To gain a clearer appreciation of the potential for gear modifications to reduce by-catch we searched the literature for experimental studies which have quantified the effectiveness of various approaches. We found a total of 38 studies in the refereed literature, from which the following information could be extracted: gear type, target species, by-catch taxa, % change in by-catch quantity and % change in target taxa when modified gear was used. From these 38 studies a total of 74 separate cases (gear type, target species, by-catch species combinations) were extracted using the data categories shown in Table 1. When a range of values for % change in reduction of by-catch or target species were quoted the lower bound of the range was used for by-catch and the upper bound for target species. This provided the most pessimistic (conservative) data set.

Figure 2a and Table 2 summarize these data with box-whisker plots for the percentage reduction in by-catch for each target taxa. Each panel in the plot represents a particular target taxon with each box-whisker plot in the panel corresponding to a by-catch reduction approach aimed at a particular by-catch taxon. These data show that the majority of studies have been undertaken on prawns and demersal fish, both in terms of absolute number, and also in terms of the range of by-catch taxa considered. This result is, of course to be expected, given the fact that demersal trawling is the form of fishing that is most problematic with respect to by-catch. A second feature of these data is the wide range of reductions in by-catch that have been achieved. Efforts to reduce demersal fish by-catch in prawn trawls, for example, has seen success range from 20 to 99%. Similarly, modifications to flatfish trawling gear has led to reductions in benthic invertebrate by-catch ranging from 2 to 83%.

Despite the large range, it is encouraging that high levels of improvement are possible, a fact that

Table 1 Data categories used to classify by-catch reduction studies[1].

Gear type	Target species	By-catch species
Beam trawl (5)	Crabs (1)	Benthic Invertebrates (11)
Crab pot (1)	Demersal fish (8)	Demersal fish (27)
Demersal gill net (3)	Eels (5)	Dolphin (4)
Demersal longline (1)	Flatfish (5)	Flatfish (10)
Demersal trawl (5)	Pelagic fish (7)	Megafauna[2] (8)
Pelagic longline (5)	Prawns (45)	Pelagic Fish (2)
Pot net (3)	Salmonids (1)	Salmonids (6)
Pound net (2)	Tuna (1)	Seabirds (5)
Prawn trawl (45)		
Purse-seine (1)		
Salmon gill net (1)		
Trap net (1)		

Numbers in parenthesis denote number of data points for each category.

[1]NMFS (1981), Kenney *et al.* (1992), Adlerstein and Trumble (1993), Hendrickson and Griffin (1993), Hickey *et al.* (1993), Toivonen and Hudd (1993), Broadhurst and Kennelly (1994, 1997), Robins-Troeger (1994), Hall (1995), Kennelly (1995), Trumble *et al.* (1995), Wienbeck (1995, 1997, 1999), Broadhurst *et al.* (1996, 1999, 2000), DeAlteris *et al.* (1996), Dieperink and Rasmussen (1997), Rogers *et al.* (1997), Kulka (1998), Cameron (1999), Gallaway and Cole (1999), Goodyear (1999), Halliday and Cooper (1999), Melvin *et al.* (1999), Robins and McGilvray (1999), Trippel *et al.* (1999), Garcia-Caudillo *et al.* (2000), Hannah and Jones (2000), Huse and Soldal (2000), Roosenburg and Green (2000), Bordino *et al.* 2002), Fonteyne and Polet (2002), Polet (2002), Ryan and Watkins 2002), Lokkeborg (2003).

[2]Megafauna includes turtles, elasmobranchs and large fish species.

is particularly evident with dolphins, seabirds and salmonids, where median percentage reductions were 80, 88 and 80% respectively ($n = 4$, 5 and 6). Poorest performance was with respect to megafauna (which included turtles and sharks) with a median reduction of about 35% ($n = 8$).

As one would expect, the reductions in by-catch shown above are not often made without incurring cost in terms of loss of target species (Fig. 2b, Table 2). With prawn trawling for example, the median loss in catch was 14%, with values broadly similar irrespective of the by-catch reduction target. Particularly encouraging, however, are the data for demersal fish, where large reductions in by-catch appear possible, with relatively little loss of target catch. This situation is highly desirable as imposition of BRDs that result in the loss of target catch may result in an increase in fishing effort to compensate for the loss, thereby resulting in no overall improvement in by-catch levels. There was no correlation between the level of by-catch reduction in a particular instance and the loss of catch sustained. When reductions in target catch do occur, however, there is always the possibility that effort will increase to compensate for the loss, thereby negating the benefits of by-catch reduction.

Avoidance

Time and area closures are a common approach that has widespread acceptance for protecting species at certain stages of their life history, for example, protection of juvenile nursery areas or adult spawning grounds (see Hall 2002 for review). Although there can often be substantial variability in the timing and location of by-catch, careful analysis of by-catch records can often help identify areas where closure has the potential to also deliver benefits with respect to by-catch reduction. A good example of such analysis is provided by Goodyear (1999) who examined catch data reported in mandatory log books kept by US pelagic-longline fishermen between 1986 and 1991. The analyses indicated that closing areas on the basis of the percentages of billfish in the catch could have reduced marlin by-catch by up to 50%, depending on the spatial resolution employed. Testing for the temporal and spatial consistency of the by-catch by applying the time-area closures identified in the 1986–1991 logbook data to data for 1992–1995 confirmed the potential of the approach, although reductions were slightly lower (48% vs. 50%). However, with the imposition of such closures, the predicted reduction in the catch of the target species was approximately 23% – a price that may be too high for many fishers to bear.

Another good illustration of this approach is described in Ye *et al.* (2000) who examined the temporal and spatial patterns in the catch to by-catch ratios for the Kuwait shrimp fishery. This analysis showed that a seasonal fishery closure from April/May to August, that was originally established to prevent overfishing and increase the size and market value of the target shrimp, also had benefits with respect to by-catch reduction.

More permanent closures to reduce by-catch have also been established, such as the closure in

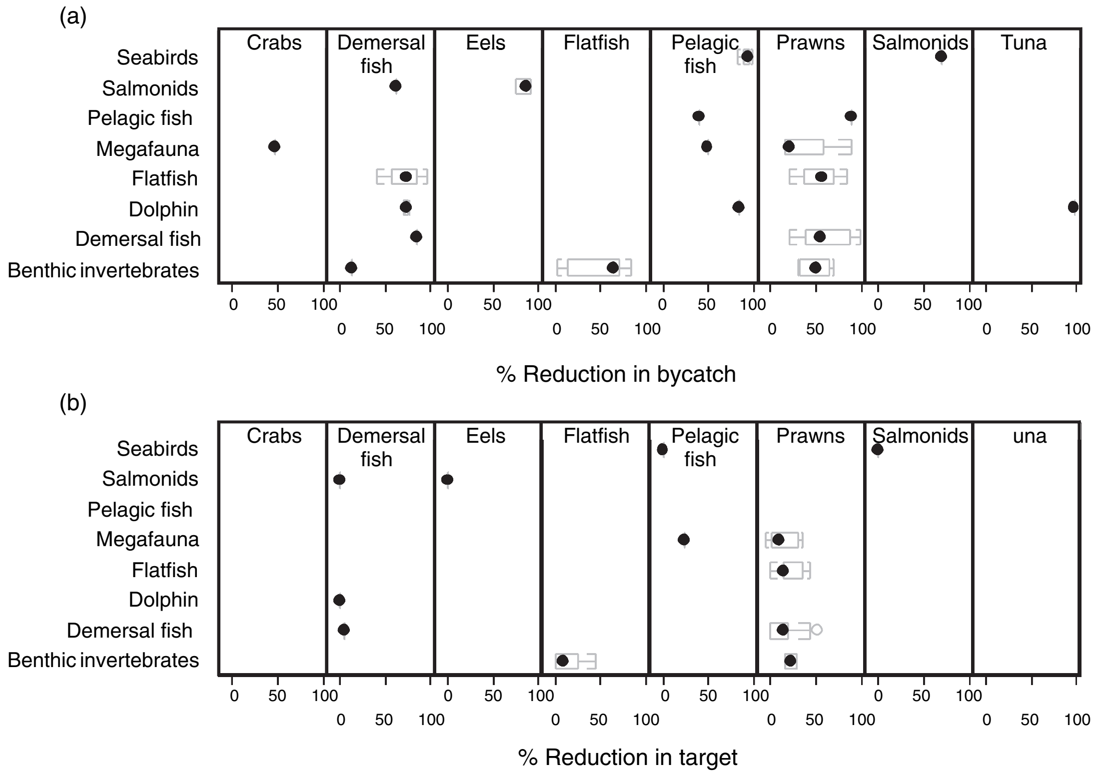

Figure 2 (a) Box-whisker plots for the percentage reduction in by-catch for each target taxa, when by-catch reduction devices were employed. (b) Box-whisker plots for the percentage change in target species catch for each target taxa. when by-catch reduction devices were employed. (All data are from experimental studies reported in the literature, see Table 1).

1991 by the Western Pacific Fishery Management Council of an area of 50 nautical miles around the north-western Hawaiian Islands to protect endangered monkseals. However, such permanent closure approaches are not without their difficulties, as illustrated by an analysis of the consequences of displacing the longline fishing effort from an area off Newfoundland that was closed to reduce the by-catch of endangered turtle species (Baum *et al.* 2003). The results of these analyses suggest that, while this measure is probably protecting turtles (along with blue and mako sharks), overall it is likely to have caused increases in the catch of 11 other shark species, and 10 depleted finfish species (Baum *et al.* 2003). This is a good example of how relatively simple measures for a single species can result in unintended consequences for others; it also emphasizes the primacy of controlling overall fishing mortality in any conservation initiative.

A more dynamic approach than closing areas permanently is hotspot reporting. Bering Sea fishers, for example, have voluntarily developed an information system to tell the fishing fleet about by-catch rates and hotspots for prohibited species (Gauvin *et al.* 1996). Observer data on catch and by-catch are electronically transmitted from participating vessels to a private contractor who analyses the submitted data and provides estimates of the spatial distribution of average catch rate per vessel for each 24-h period to participating vessels and companies. This data then allows individual vessels or company fleets to rapidly respond and avoid areas where by-catch of protected species is expected to be high. A comprehensive surveillance and monitoring programme is also in place in Norway that allows areas to be closed when by-catch rates become excessive. We have been unable to find data on how effective these approaches have been.

Table 2 Estimated changes in by-catch and target catch (million tonnes), assuming the minimum, median and maximum levels of performance from published studies where gears fitted with by-catch reduction devices were evaluated. Actual values are derived from Table 6 of Alverson *et al.* (1994) (see text for further explanation).

Target species group	By-catch				Catch			
	Actual	Min	Med	Max	Actual	Min	Med	Max
Crabs	2.89	1.53	1.53	1.53	1.32	1.32	1.32	1.32
Demersal fish	7.16	6.23	2.04	0.29	28.47	28.47	28.47	27.05
Eels	0.01	0.00	0.00	0.00	0.01	0.01	0.01	0.01
Flatfish	0.95	0.93	0.34	0.16	1.26	1.14	1.14	0.69
Pelagic fish	5.52	3.31	0.91	0.06	37.09	37.09	37.09	28.56
Prawns	9.51	8.09	4.66	0.10	1.83	1.57	1.57	0.88
Salmonids	0.04	0.01	0.01	0.01	0.77	0.77	0.77	0.77
Tuna	0.74	0.02	0.02	0.02	4.18	4.18	4.18	4.18
Total	26.82	20.13	9.52	2.16	74.93	74.56	74.56	63.45

The regulatory system

Unfortunately, obtaining a global picture of the status of legislation on by-catch is extremely difficult. Indeed, our own efforts to develop a comprehensive database on existing legal instruments resulted in very limited success. Difficulties relate in particular to the differing legal jurisdictions in which legislation is enacted and the consequent problem of obtaining access to the information about the current legal position. For example, in the United States a distinction is made between a statute, which is an enactment of a duly elected state or federal legislative body and a regulation, which is a rule or standard adopted by an administrative agency or department that has been duly empowered by law to issue such regulations. To obtain a comprehensive picture of the regulations that obtain, therefore, one would need – at the very least – the federal and all coastal state legislative records. In many cases finding and obtaining the relevant material is problematic and the information that is readily available is patchy at best – for a global assessment, the task is Herculean.

A fundamental paradox when considering the regulatory system as a means for reducing by-catch is that it is this system that can often be responsible for generating by-catch and discards in the first place. With respect to target species, for example, there are many cases where regulations enacted to try and ensure that they are not over-exploited lead to discarding of the very species they are trying to protect. A good illustration of this situation can be found in the case of trip limits, which are sometimes imposed to protect particular species in multispecies fisheries. Unfortunately, when trip limits are imposed for one species discards of other species can increase because fishers catch the limited species while fishing for others (NMFS 1998). Similarly, discarding occurs when a fisher does not possess quota for a particular species that is inadvertently caught. Thus, the mixture of incentives and disincentives that are put in place with particular legislation must be carefully evaluated and may not be easily foreseen.

It should also be remembered that for fisheries that suffer from growth overfishing, effective management of the target stocks would, in many instances lead to greatly reduced fishing effort and, as a result, significant reduction in bycatch. A recent analysis of the GOM shrimp fishery, for example, indicated that effort could be reduced by almost 50%, while maintaining the same catch (US National Research Council 2002). In many instances, therefore, dealing with the excess effort in world fisheries represents a means of reducing bycatch in the short-term that would incur no significant loss of catch for target species. (In the longer term, however, the effects of effort reductions on target species and the ramifications of these responses on by-catch species populations through changes in food web dynamics are difficult to predict).

Notwithstanding the above difficulties, a number of legislative instruments worldwide now explicitly acknowledge the by-catch problem and seek to address it in some manner. One example is the Magnuson-Stevens Fishery Conservation and Management Act in the United States. National standard 9 was added to the Act when it was amended in 1996, requiring that 'conservation and management measures shall, to the extent practicable, (a) minimize by-catch and (b) to the extent that by-catch cannot be avoided, minimize the mortality of such by-catch'. Similarly, in the New Zealand Fisheries Act of 1996, section 9 Environmental Principles, states: '(a) Associated or dependent species (including non-fish by-catch) should be maintained above a level that ensures their long-term viability (associated or dependent stocks are those stocks that cannot be lawfully targeted but may be lawfully taken as incidental by-catch of legitimate commercial fishing); (b) biological diversity of the aquatic environment should be maintained; (c) Habitat of particular significance for fisheries management should be protected'.

Adding to the protection afforded by fisheries legislation, there is also more general conservation legislation that is often of relevance. For example, the US Marine Mammal Protection Act provides a good illustration of how 'non-fisheries' legislation can be used to impose inescapable improvements in fishing practices, mandating that incidental mortality of marine mammals in commercial fisheries must be (i) biologically sustainable (as defined by a specific formula), and (ii) decrease to levels approaching zero (agreed as being 10% of the biologically sustainable limit) by 30 April 2001. Similarly, the 10 signatories the Agreement for the International Dolphin Conservation Program (AIDCP), which came into force in 1999 and is implemented by the Inter-American Tropical Tuna Commission, now accept a total dolphin mortality limit for the Eastern Pacific Ocean, a proportion of which is allocated to each vessel in the fishery. The Agreement requires all vessels to have observers present and a vessel can only keep fishing until their by-catch limit is reached. This clearly places a positive incentive on vessels to improve their efficiency and minimize dolphin mortalities. A similar approach has also been adopted in New Zealand where a squid fishery has a by-catch of Hooker's sea lion (*Phocarctos hookeri*), a threatened species. In this fishery by-catch is managed with an annual limit designed to ensure rebuilding of the sea lion population (Breen *et al.* 2003).

Another example of the use of 'non-fisheries' legislation can be found in the Alaskan region under the US Endangered Species Act where, because of its endangered species status, a limit on the incidental capture of the short-tailed albatross has been established. The Pacific Halibut hook and line fishery and the Bering Sea/Aleutian Islands and the Gulf of Alaska hook and line groundfish fisheries have been given an incidental take limits of 2, 4 and 4 individual short-tailed albatross respectively. If these limits are exceeded, consultation between department agencies is required, which may lead to modification of fishing methods. The recent opening of the Hawaiian longline fishery with an extremely low sea turtle quota is another good example of this approach.

Experience with the US Marine Mammal Protection Act, the Endangered Species Act, and with the Environmental Protection and Biodiversity Conservation (EPBC) Act in Australia, which requires all Commonwealth fisheries to undertake threat abatement plans if they impact on certain marine species, and to become accredited as an ecologically sustainable fishery, suggests that it may often be the 'non-fisheries' legislation that effects greatest change in fishing practices. The greater effectiveness of such legislation may arise because fishers have less influence on the political process surrounding the passage of legislation with a wider remit than fish supply alone. In the international domain also, there is increasing recognition that instruments such as Convention on International Trade in Endangered Species of Wild Flora and Fauna (CITES) have the capacity to effect change in fisheries. While the convention is most likely to be applied to species that are the direct target of fisheries there is certainly the potential to prevent trade in any endangered species that is caught as by-catch, but subsequently sold.

Discard bans

A number of countries have approached the problem of discarding by banning the practice through legislation. In some commercial fisheries in Norway, for example, minimum capture sizes have been specified and discarding of fish below the minimum is prohibited. This approach ensures that the fishing mortality resulting from by-catch is recorded so that more accurate 'total allowable catches' can be set. All of the 'illegal' (i.e. undersized) fish are sold through sales organizations, but the revenue from sales are not returned to the fishers so there is no incentive to catch small fish. There is some evidence that the discard ban has led to a greater acceptance of more selective fishing gears and to greater efforts to find new technical improvements. A similar ban on discarding now also operates in Canada's Atlantic groundfish fishery. However, in this case, the fish can be marketed, but must be counted against quota. Variants on this approach can also be found in New Zealand and Iceland. In Iceland the quota reduction is 50% of the landed weight of discards; in New Zealand, fishers receive 50% of the value of the fish. One danger with discard bans, however, is that, if not carefully set up, one might develop a new or expanded market for the discards and thereby establish incentives for their capture. Such a concern has currently been expressed for the ban on discarding small tuna that has been established by the Inter-American Tropical Tuna Commission (M.A. Hall, personal communication).

Although discard bans certainly have their place it is important to recognize the distinction between a discard and a by-catch ban. Discard bans only apply to species that have commercial value and are either undersized or for which a fisher does not possess quota. In contrast a by-catch ban would require all species caught to be landed, irrespective of their value. One country that has adopted this approach is Namibia, which has imposed a ban on dumping by-catch from its trawl fishery, with a requirement that all material be landed for conversion to fishmeal. A surcharge is also levied on the fishers for the processing, which acts as an additional incentive to reduce by-catch levels further (Hampton 2003). We are aware of no other such ban, but suspect that pressure on hold space and the costs of retaining unwanted material could provide a strong incentive to improve performance, although the issue of policing and compliance is clearly critical.

By-catch utilization

Another issue for the regulatory system is the extent to which it should encourage the greater utilization of by-catch. This is, of course, a sensitive and difficult issue given the history of over-exploitation of fisheries and the very real danger that adding new groups of species to the list of acceptable targets will lead to yet further depletion and other ecological consequences. This issue is further complicated by the fact that, as species become serially depleted, what was once a by-catch soon becomes a targeted resource. Perhaps the most striking example of this is Northern bluefin tuna, which, remarkable as it seems now, sold in the mid-1900s for 50 cents per pound and was an incidental take in the hunt for other species (Safina 1998). Similarly, shark species that were by-catch in pelagic longline fisheries in the 1960s evolved into targets for the fishery in the 1980s (Breen *et al.* 2003).

Conversely, however, the failure to make use of fish that are already killed is viewed in many cultures as highly undesirable, particularly in developing countries where the supply of adequate protein to the populace is a challenge. In such countries the concept of by-catch is often rather weak, particularly in most of the poorer fishing communities in developing countries where by-catch provides an important food subsidy to the poor. For some developing countries whose fisheries resources are exploited by more modern fleets, however, high levels of by-catch and discarding can still occur. One example of how legislation has been used to reduce waste can be found in Guyana where all prawn trawlers are required to land 1 tonne of by-catch per trip in order to obtain exemption from export taxation and a nominal payment (Gordon 1981 cited in Clucas 1997). A down-side to this approach is that pressure to utilize by-catch can act to deter the use of BRDs. There is now anecdotal evidence, for example, that in a number of shrimp fisheries on the Asian subcontinent, owners have started paying the crew from sales of the by-catch and that this has made it difficult to enforce use of TEDs (D.L. Alverson personal communication). However, a more fundamental and larger scale pattern that militates against increased use of by-catch reduction approaches is beginning to emerge for developing countries with rapidly growing economies such as India. Here, over-exploitation of traditional stocks, increasing demand from growing urban middle class markets with greater purchasing power and broadening tastes, and improved infrastructure (e.g. improving ice supply and transport systems) have combined to stimulate the development of new products that place greater pressures on what were previously 'minor' species.

The social system

"Why is it that conservation is so rarely practiced by those who must extract a living from the land? It is said to boil down, in the last analysis, to economic obstacles." (Leopold 1966).

As with so many other issues, Aldo Leopold was right. While the importance of conserving our marine commons is rarely questioned, our failure to do so is often (but by no means always) a result of economic considerations. The challenge, therefore, is to alter the attitudes and values of fishers and ensure that economic incentives are aligned with those for conserving marine ecosystems and communities. It is our belief that without such an alignment and shift in values to drive changes in behaviour, the effectiveness of the technical and legislative systems will be diminished.

Perhaps the first step towards achieving such an alignment is to ensure that fishers are fully aware of just how much current practices cost them. While the economic impacts of by-catch and discarding have not been extensively discussed in the scientific literature, a small number of authors have examined the topic (Leopold 1966; Alverson *et al.* 1994; Arnason 1994; Ward 1994; Boyce 1996; Pascoe 1997). Pascoe suggests that the economics of discarding can be classified into four categories: (i) foregone income associated with discarding juvenile and adult target species; (ii) interfishery costs associated with discarding juvenile by-catch species; (iii) costs associated with discarding non-commercial species and; (iv) costs associated with measuring/estimating the levels of discards. Examples of costs associated with each of these categories are provided in Table 3, but a more complete picture of the economic implications of current practices is badly needed. It is also important to bear in mind that costs can also be incurred when markets are closed because of by-catch considerations. The shrimp embargo for exporters to the US markets due to non-compliance with TED requirements is a good example of this situation. The costs of such actions are rarely included in the economic analysis of by-catch issues. The indirect effects on target species populations through changes in predator–prey relationships may also have economic consequences, but these are very difficult to predict.

Table 3 Examples of costs associated with discarding for each of the categories identified by Pascoe (1997).

Cost category	Examples	Reference
Foregone income associated with discarding juvenile and adult target species	The Bering Sea crab fishery: estimated to be losing between $40 and $50 million per year through the discarding of illegal crab	(Alverson *et al.* 1994), Clucas (1997), FAO (2000)
	In 1997 the North Sea Haddock Fishery discarded as many individuals as as were landed with a total first sale value of 100 million Euros	(Tingley *et al.* 2000)
	North-west Atlantic groundfish fishery: $50 million of forgone income to the local trawl fisheries through premature harvest and discard of the 1987 year class of yellowtail flounder	(Clucas 1997)
	Texas shrimp fishery: $9.4million increase in harvest value when closure allowed individuals to grow to harvestable size	
Interfishery costs associated with discarding juvenile by-catch species	In 1996 Gulf of Mexico red snapper stocks were assessed as unlikely to recover unless the mortality from shrimp trawling could be reduced by at least 50%. Stocks remain in a poor condition despite mandatory fitting of BRD to offshore shrimp trawlers	(Alverson *et al.* 1994), Goodyear (1995)
Costs associated with discarding non-commercial species	e.g. Costs associated with additional sorting and removal of unwanted species (e.g. additional crew, lost time, increased fuel consumption)	No references found
Costs associated with measuring/ estimating the levels of discards	$4.5billion per annum: global (conservative) estimate for the costs of monitoring	(Alverson *et al.* 1994)

While economic losses might be expected to be substantive motivators for changing behaviour, this does not appear to always be the case. For example, economic losses to longline vessels from seabird scavenging can be severe with reported bait losses affecting up to 78% of the hooks set, forcing vessels to leave an area and making the trip unprofitable. Given such potential losses, one would imagine that the incentive to improve profitability would lead all affected longliners to take advantage of the relatively simple technical solutions that could reduce bird by-catch to almost zero in some fisheries, particularly those where the baits can be set deeper in the water column and still catch the target species (Safina 2003; Sanchez and Belda 2003). Sadly, such adoption is not as widespread as one would hope with continuing high levels of seabird by-catch reported for many fisheries. Even where deterrent devices are mandatory, it would appear that fishers often ignore them or make little effort to make them work efficiently (Valdemarsen and Suuronen 2002; Safina 2003) – a fact that speaks loudly for the importance of the social context in which technical and regulatory solutions are placed.

Another aspect of the social context that should also be borne in mind is peer pressure. A good example of how such pressure can lead to positive results comes from the North Pacific longline fishery where an industry reporting system has been encouraged. This reporting system informs all fishers of the by-catch totals for each vessel and has resulted in strong pressure on participants who contribute disproportionately to the by-catch total to improve their performance (Norris *et al.* 2002). The authors argue that 'Such a system strongly promotes acceptance of new operating protocols and encourages the transfer of skills and knowledge from superior to less experienced fishers' (Norris *et al.* 2002).

The converse of economic costs is of course economic incentive; fishers, particularly in developing countries, are increasingly recognizing that clean catches and an environmentally friendly image can have economic benefits. In particular, voluntary environmental certification programmes for fisheries are gaining credence along with environmental scorecards to inform consumers and alter market preference for more sustainably fished species. Much of the emphasis with such programmes is on the sustainability of the stocks themselves, but impacts on by-catch species are also considered. For example, the Audubon Society's 'Seafood Lover's Guide' includes by-catch criteria as one of the four evaluation criteria along with management record, habitat health and species life history (Lee 2000). Seafood Watch, a similar sustainability guide produced by the Monterey Bay Aquarium includes 'Nature and Extent of By-Catch' as one of the five criteria. Perhaps the exemplar of this approach has been the 'dolphin-safe' labelling that was introduced in the 1990s. Product bearing this label was, in effect, certified that it was not captured using the 'dolphin set' technique, where fishers target the schools of dolphins with which tuna schools are associated. Armed with such a labelling system import embargoes have been imposed on other nations that do not adhere to US standards.

Among environmental certification programmes the Marine Stewardship Council (MSC) is, perhaps, the most well known and widely accepted. Although not without criticism from some parts of the conservation movement, there can be little doubt that the MSC is effecting change within some sectors of the fishing industry and that this is beginning to yield benefits both from an environmental and economic perspective. The case of the New Zealand hoki fishery illustrates both the controversy and the benefit.

New Zealand hoki, a species fished at depths of 400–700 m with both mid-water and bottom trawls, was certified by an independent certifier in March 2001 as meeting the MSC criteria for certification; it was the first whitefish to meet the MSC Standard and remains the largest fishery in New Zealand with export markets to the United States, the European Union, Japan and Australia. At the time of certification there were concerns among some conservation bodies about the sustainability of the fishery and its impact on by-catch species. The fact that the fishery was granted a certificate while at the same time having to agree to a set of improvements prior to the next audit added further fuel to the controversy over whether the certification was justified.

Soon after the decision to certify was announced, a formal objection was lodged by a New Zealand based environmental organization – an action which prompted further deliberation by an independent dispute panel made up of scientists and a retired British High Court Judge. This panel upheld the certification and also found that the further progress made by the fishery in the intervening period warranted the continuation of the certification. Among the changes that have been implemented are a number relating to by-catch. Specifically, the revision of a Code of Practice to mitigate seal by-catch and trials of a bird strike mitigation device. The extent to which these measures have translated into actual reductions in by-catch numbers are not yet available, but the changes are a step in the right direction and can be expected to yield benefits. Moreover, there is a high likelihood that future certification audits will place further performance requirements on this and other certified fisheries.

The motivation for a fishery to subscribe to such a process of continuous environmental improvement is illustrated by the economic benefits that the hoki fishery has gained from certification (Table 4). A further example of how the environmental measures required for certification can be aligned with economic drivers can be found in the case of the West Australian Rock Lobster, where the possession of MSC certification was a key factor in the European Union's decision to remove an onerous import tariff, which placed producers at a competitive disadvantage.

Table 4 Examples of the economic benefits for the New Zealand Hoki fishery from MSC certification.

Benefit
Price stability
The full quota of hoki is sold to market before being caught providing price stability for the fishers. It also means the onshore processors have instant markets for their products
Retailer preference
Processors and retailers in Europe have opted to source hoki in preference to other whitefish as part of their policies to buy seafood from sustainable fisheries
Export opportunity
Between 2001 and 2002 hoki imports in the UK rose by nearly 1300%
Value adding product diversification
Over 60 hoki products have been developed around the world specifically to carry the MSC label
UK based Young's Bluecrest has developed a sustainable seafood range, 'Fish for Life' using hoki
Third party promotional endorsements
European based private label Iglo has introduced a number of hoki products into continental Europe
UK-based roadside restaurant chain Little Chef introduced hoki and chips to its 400 restaurants as a summer promotion in 2002 and has kept it on the menu.

The route to further improvement

On the basis of the analyses above, we conclude that there are three broad approaches that, if adopted will help improve the environmental sustainability of the world's fisheries. First, we need to disseminate successful technologies more widely and encourage their adoption. Second, we must more comprehensively engage fishers themselves in finding appropriate solutions. And lastly, we must make greater efforts to understand the trade-offs that obtain when a particular approach is chosen and develop the institutional and legislative frameworks that recognize and account for these trade-offs. We discuss these approaches in more detail below.

Use more widely the techniques we know will work

There is clearly no single approach that will be universally applicable, but we have learned enough to teach us that many of the technological, legislative and social system improvements described above can have substantial impacts. If one considers the technical impacts, for example, some simple calculations illustrate the point. Taking the minimum, median and maximum estimates for achieved percentage reductions in by-catch from the meta-analysis described above (Fig. 2) and combining these with the estimated by-catch for various fisheries provided by in Table 6 of Alverson *et al.* (1994) one can obtain a crude estimate of the improvements that might be achieved from adoption of the technology and the likely effect on the catch of target species (Table 2, Fig. 3). This analysis indicates that reductions in by-catch of between 25% and 64% could be achieved if one could match somewhere between the minimum and median performance of gear modifications used in experimental studies. Our analysis also suggests that to achieve such reductions there would, with the exception of prawns, probably be limited impact on total catch of target species. While these 'back of the envelope' calculations are necessarily crude, they are indicative of the reductions that appear possible with the adoption of existing technical approaches. These, combined with other regulatory measures and incentives that motivate fishers to adopt new approaches offer considerable scope for improvement on the existing situation.

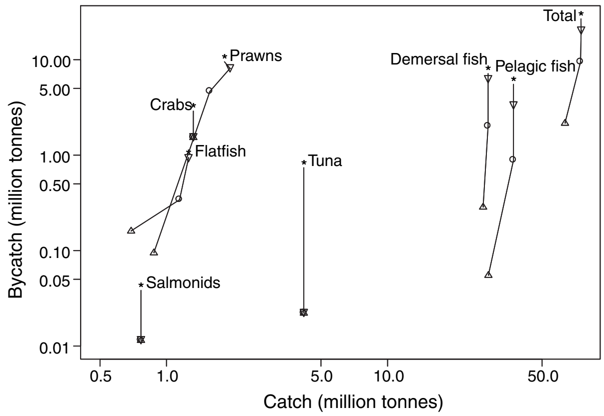

Figure 3 Illustration of the potential trade-offs between reductions in by-catch and target catch, assuming the maximum (triangle), median (circle) and minimum (inverted triangle) levels of performance from published studies where gears fitted with by-catch reduction devices were evaluated (note log–log scale, see text for further explanation).

Engage the fishing sector in finding the solutions

Of course, perceptions of mutual benefits are not universally held and the successful implementation of mitigation measures will often be a complicated matter. In particular, it is becoming increasingly apparent that the way in which fishers, processors, exporters, boat owners etc. are engaged in the debate about their activities and the approaches taken to develop and adopt new technical or regulatory (behavioural) solutions can have a profound effect on the success of the outcome.

In this regard, the social sciences have a pivotal role to play in ensuring that technological and ecological knowledge transfer is effective and that sound fisheries management decisions are made and accepted. In a broader context, Douthwaite *et al.* (2001) provide a compelling set of arguments for the blending of the 'hard' and 'soft' sciences. Although their focus is on effective technology transfer in the agricultural sector, the principles appear to also be applicable to the development and acceptance of new fishing technologies (e.g. BRD, new gears etc.) and to behavioural modification to mitigate by-catch problems (e.g. changing handling practices to release captured turtles).

Douthwaite *et al.* (2001) argue that two alternative perspectives characterize the 'hard' and 'soft' sciences and that understanding the differences between these perspectives is a prerequisite for understanding the complementarity of the approaches. The dominant perspective adopted by the hard sciences concerns the setting up of hypotheses and the testing of them with repeatable quantifiable experiments. Practitioners place emphasis on the independent objective world that their methods uncover and often consider their knowledge to be 'superior' to understanding gathered from 'non-scientific' methods. Those holding such views often also assume that to deliver benefits from their knowledge it is simply a matter of finding ways to project that knowledge into the minds of users whose job it is to receive it. Recipients are generally not expected to adapt the knowledge or question its implications if it is scientifically sound and properly delivered. Careful experiments to demonstrate the benefits of a particular BRD and the expectation that such a demonstration will be sufficient to stimulate fishers to adopt it is an example of such a 'hard' science perspective.

In contrast, the paradigm often adopted by the 'soft' sciences considers social phenomena that cannot be reduced to their component parts or easily repeated. Case studies are the mainstay of this approach, which provides the framework for a more participatory attitude towards technology transfer. Contrary to the hard science paradigm, soft science practitioners contend that knowledge is not simply received, but constructed by the recipient and fitted into an existing mental map, which may itself be a function of cultural setting.

Douthwaite *et al.* (2001) suggest that a learning selection (LS) model should be at the heart of any approach to the introduction of technologies. This model uses the features of Darwinian evolution by analogy, suggesting that technologies that are taken up may be experimented with by practitioners and that, often, novel uses or improvements emerge that were not originally envisaged. These new uses may then be transferred to other practitioners, who will start their own learning and innovation selection cycles, and to researchers who might pursue new lines of enquiry leading to selection of new technologies for transfer. 'The net effect of these learning and selection cycles is to improve the fitness of the technology, i.e. its suitability for the environment in which it is used, and hence its market appeal and adoption rate' (Douthwaite *et al.* 2001).

Despite the power of this model, however, it is important to recognize that LS only occurs if the people involved are keen on using the technology, are motivated to modify it, and have enough knowledge to generate and select beneficial changes (Douthwaite *et al.* 2001). Thus, although it is a powerful heuristic device, the LS model fails to take into account groups, social learning or social organizations that surround technologies. These deficiencies have led the authors to suggest a more complete model, termed the 'actor-oriented (AO) model' that better incorporates a understanding of people's actions (Long 1992; Douthwaite *et al.* 2001).

The importance of this thinking is that it explicitly recognizes that people have different perceptions of reality and makes understanding these difference a core objective for research. Fishers, for example, often have a very different perspective on the magnitude of a by-catch issue, which markedly affects their propensity to adopt (or adapt) and new approach. As Douthwaite *et al.* (2001) point out, this is a marked departure from the emphasis that is normally placed on scientist's understanding of problems and solutions. It is important for those involved in technology dissemination activities to be aware of these additional dimensions to the problem.

In a fisheries context, the importance of such approaches is well illustrated by a comparative analysis of by-catch reduction technology development and uptake in Australian prawn trawl fisheries (Kennelly 1999). Basing his analysis on a three-step framework for implementation of (i) identifying and quantifying the particular by-catch issue that requires new devices; (ii) developing and testing the devices; and (iii) implementing the devices into industry by voluntary acceptance and/or legislation, and using speed and rate of uptake by fishers as the indicator of success, Kennelly found that the sooner fishers were involved in all stages of the process, the sooner and more complete will be the voluntary acceptance of by-catch reducing fishing technology, and the smoother the implementation of the relevant legislation (Kennelly 1999). Based on these and other experiences, Kennelly and Broadhurst (2002) elaborated further on the above framework. Taking the insights offered by this latter work and combining it with those of Douthwaite *et al.* (2001), a generalized framework for technology adoption is offered in Fig. 4.

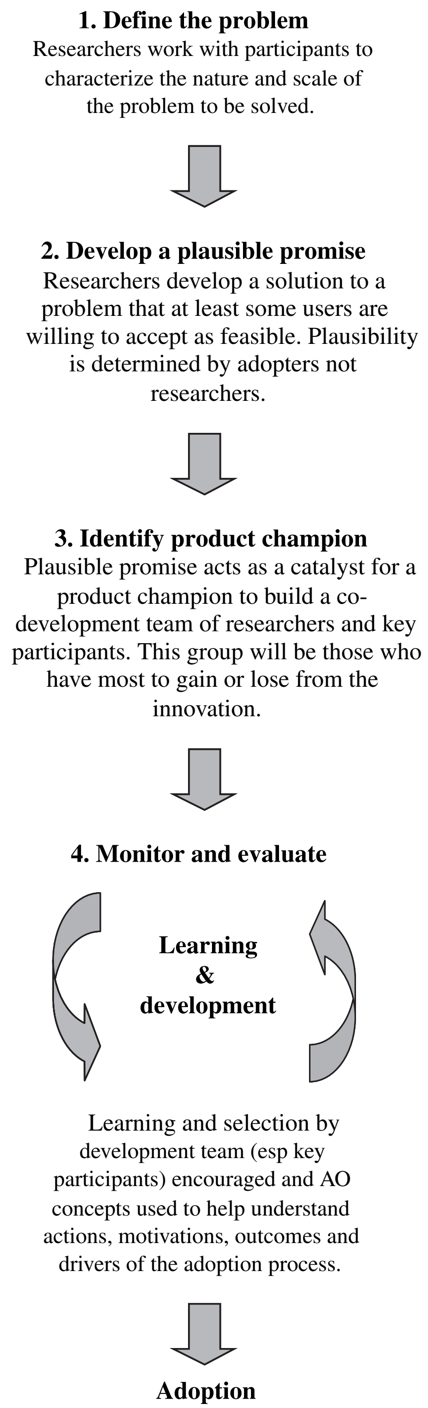

Figure 4 Technology adoption framework, based on models presented by Douthwaite *et al.* (2001) and Kennelly and Broadhurst (2002).

Examples where this kind of approach has been used to great effect is with fishers in Washington State to reduce seabird by-catch and by the Inter-American Tropical Tuna Commission (IATTC) for reducing dolphin by-catch (Melvin *et al.* 1999; Norris *et al.* 2002). In the latter case methods were devised and adopted that reduced dolphin mortality in such sets by almost 99% from 1986 to 2000 (Norris *et al.* 2002). Another good example, can currently be found in Ecuador where researchers are trying to develop new solutions to mitigate turtle by-catch in a longline fishery. First, solid evidence is required that a new design of hook (the circle hook) can reduce turtle mortality by a significant amount, and that their use does not reduce the target catch. To obtain this information researchers are testing the hooks following an experimental design that alternates control hooks with two sizes of circle hooks. This design has been set up in over 90 fishing boats, fishing in normal conditions, with the fishers testing the new hooks, directly assessing their performance, and beginning the selection of hook size, materials, baits, etc., that will be the end result of the process. In parallel with the experiment, and of no lesser significance, are the activities being taken to facilitate, catalyse and accelerate the 'evolutionary process'. Some hook sizes and materials have already been rejected, while others are clear favourites. Active communication between fishers and researchers generates this feedback mechanism. Observers, captain interviews and frequent workshops generate a steady flow of information including problems, results and proposals (M. Hall personal communication).

Among other things, such approaches to thinking about the by-catch problem helps one to understand the motivations of the various players. It may, for example, reveal that industry is collaborating with researchers, not because they believe that an improvement is likely, but because of subsidized inputs through government R & D, or development schemes. Far greater attention needs to be paid to these aspects of science delivery and the legislative and regulatory arrangements under which this occurs.

Understand the trade-offs

There is no doubt that there are many instances where further reductions in levels of by-catch can be achieved. It is important to recognize, however, that careful analysis will often be required to ensure that a proposed measure will achieve the desired objective at an acceptable cost. While a measure may, at first glance, appear entirely reasonable and may well make fishery managers and conservationists feel better, the complexities of ecological systems and the biology and population dynamics of the species within them can often conspire against good intentions and render a measure ineffective or unexpectedly costly; as with most complex decisions there are trade-offs that must be carefully weighed.

One example of an unforeseen trade-off that is gaining increasing attention concerns the measures adopted by the IATTC to deal with dolphin by-catch in the Eastern Pacific tuna fishery (Hall 1998). Data now available indicate that the 'cost' of the spectacular reduction in dolphin mortalities achieved by the fleet has been an order of magnitude rise in the by-catch of undersize, non-usable tuna and a large increase in the mortality of sea turtles, sharks, and other fish species (Norris *et al.* 2002). These increases have arisen in part because fishers have switched from targeting their efforts on the large yellowfin tuna that associate with dolphin schools to targeting the smaller yellowfin and bigeye tuna that are unable to keep up with dolphin schools and are found around inanimate floating objects, such as logs (Norris *et al.* 2002). These smaller individuals also tend not to be caught on longlines. Other example of trade-offs includes the high seas drift net ban that was enacted in 1992. This action, was certainly effective in reducing some forms of by-catch, but it also resulted in the rapid expansion of a longline fishery, which has by-catch problems of its own.

The above examples highlight the importance of careful analysis before a measure is adopted and, perhaps more importantly, a preparedness to adapt arrangements in the light of new data. An examination by Breen *et al.* (2003) of the likely effects of differing harvest control rules on the interaction between a New Zealand fishery and the threatened Hooker's sea lion (*Phocarctos hookeri*) provides a good illustration of the kind of detailed analysis that needs to be undertaken.

Since 1995 two New Zealand management agencies have collectively managed the by-catch of sea lions in the fishery for squid (*Notodarus sloanii*). This management has been achieved using the following three steps: (i) calculate the permissible catch of sea lion for the main area in which the fishery is prosecuted (the value for this permissible catch is termed MALFIRM – maximum allowable fishery-related mortality), (ii) estimate the in-season by-catch from the fishery with an observer program and (iii) close the fishery early in the season when the MALFIRM is reached. Building on earlier work (Hilborn *et al.* 1997; Maunder *et al.* 2000), Breen *et al.* (2003) examined the extent to which the current rules and two simple alternative rules contribute to the conservation of the sea lion population and impose costs on the fishery in terms of foregone catch.

This analysis was undertaken using Bayesian statistical techniques in the following way. First, a partially age-structured model was constructed to describe the population dynamics of sea lions. This model was fitted using data on pup numbers at different rookeries in different years, sea lion by-catch and fishing effort to estimate the probability distributions of the model parameters. The mode of the joint (posterior) probability distribution from this parameter set was then used in a Markov chain–Monte-Carlo (Mc-MC) simulation model to generate a large number of plausible sets of parameters for use in forward projections of the sea lion population dynamics model. In essence, the Mc-MC simulation performs a random walk through the joint distribution of possible parameter values. By taking a large number of parameter sets from these random walks and using each of them in a 100-year run of the sea lion population model one can obtain a probabilistic picture of the likely outcome. Repeating this procedure with different harvest control rules (see below) and different probabilities of a random natural catastrophe occurring for the sea lion population (representing differing 'states of nature'), an assessment of the likely outcome of any management intervention can be obtained.

The authors explored the effects of five different harvest control rules: (a) no fishing permitted (no by-catch); (b) unconstrained fishing; (c) MALFIRM rule applied; (d) adaptive rule i and; (e) adaptive rule ii. Adaptive rules i and ii adjusted the constraint on by-catch based on an estimate of pup numbers each year. For rule i, if estimated pup numbers in a year were >80% of the average abundance during a baseline period fishing was unconstrained; if it was <50% fishing was closed and if it was >50% and <80% the MALFIRM rule (rule c) applied. Adaptive rule ii was identical except that the mean of the previous 3 years' pup estimates was compared with the baseline values as a buffer against estimation error.

The results of Breen *et al.*'s analysis indicate that pup numbers have shown an overall trend of slow increase over the past 35 years. When projecting trends forward, the model suggests that, in the absence of natural and other catastrophes, sea lion by-catch had a very small effect on future population states, with no risk of extinction even with unconstrained fishing at present effort levels. When catastrophes were simulated their effects were much greater than that of fishing, but it should be borne in mind that obtaining a realistic probability for natural catastrophes such as disease outbreak, oil spills or other events is problematic. The other important finding was that harvest control rules that mitigated by-catch usually imposed high cost.

In this case the results of the analysis showed that the adaptive rule mitigated the effects of by-catch on the sea lion population better than the MALFIRM rule when population numbers were low, with the converse when the population was large. This occurs because, in contrast to the adaptive rules, the MALFIRM rule allows continued high levels of fishing at low sea lion population sizes. The adaptive rule also resulted in lower levels of forgone squid catch and reduced marginal risk of sea lion extinction through fishing (although risk under all scenarios was only a few percent). Somewhat perversely, the MALFIRM rule imposed the highest cost on the fishery when extinction risk was least. This work certainly suggests that more effective and less costly harvest rules can be devised for this fishery and the approach amply illustrates the power of such careful quantitative analysis of trade-offs.

It should be stressed that the purpose of the above analysis was not to determine whether measures to reduce by-catch were warranted. The calculus required to take issues such as animal welfare, or the legitimacy of fishing as an activity into account, cannot be readily accommodated by such models and, even if the population level impacts appear to be minimal, there remains uncertainty over natural and catastrophes. With this fact in mind, the most likely decision to be made under most circumstances of this kind is that fishing is to be allowed, but all reasonable steps should be taken to minimize by-catch. The benefit of the analytical approach described here, therefore, is that it allows comparisons between alternative mitigation approaches so that the trade-off between the benefits and costs can be properly explored.

Conclusion

The originally stated purpose of this review was to address three questions:

1 Which approaches are proving to be particularly successful for mitigating by-catch?

2 What is the potential for by-catch reduction from existing approaches?

3 How might further improvements be effected?

The short answers to these questions are (i) technical, legislative and social approaches for mitigating by-catch are many and varied, (ii) there would appear to be considerable potential for further reduction and (iii) focusing on already proven approaches, engaging fishers in solving the problem and being more explicit about recognizing the trade-offs will make a large impact.

Notwithstanding this relative positive message, two important caveats should be borne in mind. First, it should be recognized that we do not have a good picture of how widespread the adoption of currently available by-catch mitigation approaches actually is. Thus, calculating the potential for improvement is heroic at best. Second, regular comprehensive analyses of the global levels of by-catch are a prerequisite for determining our performance in this area. In this respect it is to be hoped that the approach proposed recently by Kelleher (2004), will prove in time to be credible or that an alternative approach be developed that is generally accepted.

Another issue that needs to be considered concerns the implicit assumption adopted in this review that by-catch mitigation is universally desirable. Here one gets into murky philosophical waters because what one country or constituency would consider by-catch, another will consider a vital resource – a situation that is particularly telling in developing countries where issues of food security also impinge. This situation is further complicated by the fact that when by-catch is obliged to be landed it can lead to the development of new markets, which in turn increase the demand. A case in point is the demand for 'trash fish' to feed fishmeal plants, which are increasingly supplying feed for aquaculture. Early indications are that the next global assessment of by-catch will show a large reduction because of such increased utilization. [A further irony in this picture is that the increase in demand for low value fish to support the aquaculture industry (through the provision of fishmeal) may well lead to a reduction in demand for high value fish in some areas as aquaculture products such as salmon provide low cost substitutes].

Where by-catch species are being newly viewed as a target resource then mitigation issues clearly become moot and the question of the sustainability of the resource must be addressed directly. In contrast if the philosophy is simply one of not wishing to waste what is unavoidably harvested then the optimal goal is that by-catch levels should not exceed those that would be obtained if best practice mitigation measures were adopted. In this latter case, issues of sustainability for the by-catch species should be less pressing, although not absent.

A further perspective on the question of by-catch mitigation is provided by Martin Hall of the Inter-American Tropical Tuna Commission, who during the course of writing this review offered the following observation: ''we can all see the 'dark side' of by-catch, when it threatens vulnerable species, but suppose we had a fishery where all by-catches were sustainable; should we eliminate these by-catches? Or, put differently, will the ecosystem be better off with some by-catches than with a totally clean fishery? My answer is that if we are interested in the ecosystem, then we probably have to diversify our harvest ([the] absolute opposite of cleaning-up fisheries), and learn to utilize a wider variety of products. The diversification must not be seen as an extension of fishing to other species; it must be accompanied with a reduction in fishing pressure on the current targets''.

As options for by-catch mitigation improve and become more widespread, discussion of the issue of trade-offs may need to broaden further to address the issues raised in Hall's comment. For those debates to be informed, a clearer understanding of the dynamics of marine food webs will be required.

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