The role of gear technologists in supporting an ecosystem approach to fisheries

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Central to an ecosystem approach to fisheries (EAF) is reconciling the short-term need for catches with the long-term need for sustainability of target species and other ecosystem components. We assess the role of gear technology in supporting the objectives and implementation of EAF and identify the circumstances in which investment in the environmental performance of fishing gear provides the greatest benefits. The greatest benefits are usually achieved when gear technologists embed the new technology in the management system and when there are clear incentives to use it. We propose a framework for comparing combinations of management measures that might support EAF, based on knowledge of the environmental impacts of different gears in different areas and management systems. This framework helps us assess when fishing effects "matter" and when gear technologists should contribute to mitigating unwanted effects. Incentives and effective enforcement will be key to introducing gears with lower environmental impact. We expect that future emphasis on marine spatial planning, the use of environmental impact assessment and strategic environmental assessment for fisheries, more equitable treatment of fisheries and other marine sectors, and rising oil prices will lead to greater pressure on gear technologists to support EAF.

Keywords: conservation, ecosystem approach to fisheries, gear technology, technical measures.

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Introduction

There is widespread political commitment to the transition from single-species fisheries management to an ecosystem approach to fisheries (EAF), consistent with international commitments to sustainable development. Despite this focus on EAF, the difficulty of simultaneously addressing social, economic, and ecological objectives remains and, when it comes to implementation, the will to bear the short-term costs associated with achieving sustainability is lacking. For this reason, managers tasked with implementing EAF always seek win–win solutions, where short-term catches or profits are not compromised by the requirement for long-term sustainability. Gear technologists have played a central role in searching for win–win solutions and in supporting the achievement of environmentally responsible fishing (ERF), which is central to implementing EAF.

In this paper, we review the drivers for, and implementation of, EAF. We then describe the impacts of fishing that are likely to compromise sustainability, and present the progress towards mitigation and ERF that has been achieved by modifying gear. This is followed by an analysis of the incentives and disincentives for the uptake of proposed gear modifications in fisheries, and the likelihood of achieving ERF. We suggest that the effects of management measures that could support ERF need to be rigorously assessed and contrasted, and we propose a framework for doing this. Finally, we describe how incentives and effective enforcement will be key to achieving ERF, and how gear technologists can best contribute to this process.

Foundations of EAF

EAF is part of the ecosystem approach (EA), and both EAF and EA contribute to sustainable development. Sustainable development was originally defined in the Brundtland Report (WCED, 1987) as development that "meets the needs of the present without compromising the ability of future generations to meet their own needs". The EA has been variously defined, but primarily, it emphasizes a management regime that maintains the health of the ecosystem alongside appropriate human use of the environment for the benefit of current and future generations (Garcia and Cochrane, 2005). For example, the 1992 UN Convention on Biological Diversity (CBD, 1992) defines EA as "ecosystem and natural habitats management" to "meet human requirements to use natural resources, whilst maintaining the biological richness and ecological processes necessary to sustain the composition, structure and function of the habitats or ecosystems concerned".

The broad purpose of EAF is consistent with that of EA, but focuses on the management of fisheries. So, the Reykjavik FAO Expert Consultation (FAO, 2003) agreed that the "purpose of an EAF is to plan, develop, and manage fisheries in a manner that addresses the multiplicity of societal needs and desires, without jeopardizing the options for future generations to benefit from a full range of goods and services provided by marine ecosystems". This was an obvious extension of the remit of existing approaches to fishery management, which had focused mostly on target stocks and the fishing industry rather than the environment that supports them. Indeed, the FAO (2003) text continues, "an ecosystem approach to fisheries strives to balance diverse societal objectives, by taking account of the knowledge and uncertainties about biotic, abiotic and human components of ecosystems and their interactions and applying an integrated approach to fisheries within ecologically meaningful boundaries". A comparable definition is provided by Ward (2000) who states that EAF is "an extension of conventional fisheries management, recognizing more explicitly the interdependence between human well-being and ecosystem health and the need to maintain ecosystems productivity for present and future generations, e.g. conserving critical habitats, reducing pollution and degradation, minimizing waste, protecting endangered species".

External drivers have made an important contribution to the evolution of EAF. For example, the ramifications of the 1973 CITES Convention on International Trade in Endangered Species plus awareness-raising but legally non-binding drivers, such as the IUCN Red List process (Baillie *et al.*, 2004), have drawn fisheries into wider debates about conservation and human impact on the environment. Coupled with the increased involvement of many conservation groups in the fishery management process, especially in many stakeholder forums that governments and regulatory authorities have established to develop management plans, fisheries issues are increasingly embedded in wider debates about conservation and sustainable development.

Implementation of EAF

Adoption of EA and EAF at national and international levels has been encouraged by a number of binding and non-binding political agreements. Thus, the 2002 World Summit on Sustainable Development in Johannesburg encouraged application by 2010 of an EA to "maintain biodiversity of important and vulnerable marine and coastal areas" and to use the EA to support the "elimination of destructive fishing practices". These statements built on those from the United Nations FAO Reykjavik Declaration (2001), which dealt explicitly with EAF and called on signatories to "introduce immediately management plans with incentives that encourage responsible fisheries and sustainable use of the marine ecosystem". The declaration focused on the process for introducing ecosystem concerns into conventional fishery management and recognized the need to take "into account the impacts of fisheries on the marine ecosystem and the impacts of the marine ecosystem on fisheries". It also emphasized that the reason for considering ecosystem concerns was to ensure "the effective conservation and sustainable use of the ecosystem and its resources".

National interpretations of international commitments to EA and EAF are widely incorporated into national policy and legislation specific to fisheries. For example, the revised European Community Council Regulation on the Conservation and Sustainable Exploitation of Fisheries Resources under the Common Fisheries Policy (2002) called for the integration of environmental protection requirements into the Common Fisheries Policy to "minimize the impact of fishing activities on marine ecosystems, and in particular on non-target species and sensitive habitats". Indeed, while many popular commentators have demanded that the adverse effects of fishing be considered in environmental policy, commitments to protect ecosystems from the impact of fishing and to adopt EAF have already been written into almost all the key policy documents relating to marine environmental management (Sainsbury and Sumaila, 2003; Sissenwine and Mace, 2003; Rice, 2005).

Policy commitments are only one step towards EAF: effective implementation is also required. Ultimately, EAF will only improve sustainability if policy commitments can be turned into specific, tractable, and effective management actions (Sainsbury *et al.*, 2000; Sainsbury and Sumaila, 2003; Sissenwine and Murawski, 2004). In some cases, managers have been trying to implement EAF for many years, and many valuable lessons can be learned from their efforts. For example, management systems consistent with EAF have been operationalized by the Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR) and in parts of the North Pacific (e.g. Constable *et al.*, 2000; Witherell *et al.*, 2000).

CCAMLR adopted EAF well before the term was in popular use, and changes in gear technology played a large role in supporting implementation (Constable *et al.*, 2000; Constable, 2004). In part, CCAMLR was a response to concerns that increased krill fishing in the Southern Ocean could affect other marine life, particularly the birds, seals, and fish that depend largely on krill for food. The Convention on the Conservation of Antarctic Marine Living Resources, which CCAMLR has sought to implement, was signed in 1980 and came into force in 1982 as part of the Antarctic Treaty System. The convention's objective is the conservation of Antarctic marine living resources where "conservation" includes rational use. The convention also requires the "maintenance of the ecological relationships between harvested, dependent and related populations", and the "risk of changes in the marine ecosystem which are not potentially reversible over two or three decade" should be minimized. These objectives are typical of those adopted in many contemporary interpretations of EAF. CCAMLR did not seek to meet the convention's objectives by imposing regulations, but attempted to reach agreement on issues that signatories of the convention were then obliged to implement.

In subsequent years, CCAMLR sought to address three issues relating to the direct and indirect effects of human activities, including fishing. These issues are the incidental mortality of seabirds in fisheries, the entanglement of marine mammals in marine debris, and the impact of fishing on the seabed. In 1989, the Commission urged all Members conducting longline fishing to introduce, as soon as possible, methods to minimize the incidental mortality of seabirds (particularly albatrosses) arising from the use of longlines. In 1991, CCAMLR adopted the first conservation measure requiring vessels longlining for Patagonian toothfish in the Convention Area to use these methods, especially streamer lines to deter birds from attempting to take baits while the lines were deployed. Despite CCAMLR's long experience supporting EAF, the actual implementation has remained a significant and ongoing challenge, and there are still serious concerns about rates of seabird mortality and the status of seabird populations in the CCAMLR area.

The CCAMLR experience has shown that many of the factors that compromise the probability of meeting sustainability-related management objectives for target species also compromise the probability of meeting management objectives for the ecosystem. In a comprehensive analysis of the factors contributing to unsustainability in fisheries, FAO (2002) identified inappropriate incentives and market distortions, high demand for limited resources, poverty and lack of alternatives to fishing, complexity and inadequate knowledge, lack of governance, and interactions of the fishery sector with other sectors and the environment as factors that led to unsustainability. Their analyses showed that scientific advice on the status of fish stocks had only a small impact on a complex management and decision-making process, and often carried little weight in relation to immediate social and economic considerations. It is likely that scientific advice on the effects of fishing in the context of EAF would have a similarly small impact on the management and decision-making process (Rice, 2005), unless the fishing effect relates to issues of wider concern in society. In that case, there are a few instances where scientific advice has been the basis for successful conservation of ecosystem components. For example, the high mortality of dolphins in purse-seine fisheries and the associated collapse of populations led to public outcry and the implementation of the 1972 US Marine Mammal Protection Act. The act required that the back-down procedure should be used to release dolphins encircled in seine nets and that independent observers should record dolphin mortality. Both measures were successful in reducing bycatch mortality (Hall, 1996, 1998).

On the basis of previous observations of the performance of single-species management (OECD, 1997; FAO, 2002), many of the factors that led to ineffective single-species management will also lead to ineffective EAF. Foremost is the unwillingness of fishing industries or society to bear the high short-term costs associated with reducing fishing effort and moving towards sustainability. This is especially true as scientific advice in an ecosystem context is expected generally to lead to even higher short-term costs than single-species advice. Therefore, without very strong societal pressure to accept short-term economic hardship for long-term ecological, social, and economic benefits, there will be considerable pressure on science advisers and managers to identify win–win or neutral–win situations that allow short- and long-term objectives to be met simultaneously. Can improved gear technology create more such situations?

The effects of fishing

Within EAF, it is necessary to consider fishing effects on the ecosystem and the effects of the environment on fisheries. Here, we focus primarily on the former issue, because it is in reducing the effects of fishing on the ecosystem that developments in gear technology have the greatest potential to support EAF. However, in the final sections of the paper, we also consider how gear technologists might support the development of fisheries that are able to adapt to climate change and rising oil prices.

Studies of the effects of fishing on the ecosystem and of the indicators needed to track these effects are numerous, as evidenced by recent symposia (Gislason and Sinclair, 2000; Kaiser and de Groot, 2000; Sinclair and Valdimarsson, 2003; Daan, 2005) and reviews (Gislason, 1994; Jennings and Kaiser, 1998; Hall, 1999; NRC, 2002). Any fishing activity affects the ecosystem, but in a management context, it is necessary to identify and mitigate the effects that compromise sustainability at relevant scales. The prioritization of fishing effects has been rather overlooked in the race to describe them. Indeed, for many of the potential fishing effects that have been described, scientific understanding is too limited to establish the clear link with fishing pressure that is needed to advise on management action. In particular, this applies to the effects on a number of ecosystem processes (e.g. biogeochemical cycling) and ecosystem resilience and functioning where, in the main, the science is not well developed (Trimmer *et al.*, 2005). Despite references to adopting a precautionary principle in most policy documents relating to EAF, in practice, management has rarely acted on the precautionary principle.

Because it is impossible to give reliable and defensible advice without understanding the link between fishing pressure and the state of an ecosystem component and/or attribute, scientists can only advise on the management of a subset of known fishing effects now. Putting aside the effects of fishing on target species, these are the effects of fishing on (i) low productivity species in mixed fisheries; (ii) the genetics of exploited populations; (iii) non-target species; (iv) foodwebs; and (v) habitats. We review each of these effects below, though coverage is necessarily brief; more comprehensive reviews are available in Jennings and Kaiser (1998), Hall (1999), Gislason and Sinclair (2000), Kaiser and de Groot (2000), Sinclair and Valdimarsson (2003) and Barnes and Thomas (2005).

Low productivity species in mixed fisheries

Many fisheries are relatively non-selective and take a range of species that vary in their capacity to withstand elevated mortality. This is particularly true in mixed trawl fisheries, where sustainable mortality rates for a productive primary target species will be unsustainable for species that are less productive, such as skate and ray species (Brander, 1981; Walker and Hislop, 1998; Stevens *et al.*, 2000), and have led to widespread depletion and, in some cases, regional extinction. Conservation measures to protect unproductive species in mixed fisheries are always controversial because fishers targeting more productive species will not want to sacrifice yield to conserve the less productive species.

Genetic effects of fishing

If some part of the phenotypic variation within species is the result of genetic differences among individuals, then selective fishing will cause genetic change (Law, 2000). The selection differentials caused by fishing can be large (Law and Rowell, 1993), and several examples of trends in life history traits, such as growth and age-at-maturity, have been attributed to the genetic effects of fishing, notwithstanding the ongoing debate about the validity of some of the methods that have been used to demonstrate them (R. Law, pers. comm.). The genetic effects of fishing are increasingly seen as a management issue (Kenchington *et al.*, 2003), particularly when there are clear commitments to biodiversity conservation in the CBD (1992) and WSSD (2002), and the longer term focus of EAF provides a precedent for trying to manage the genetic effects of fishing, which may be of little consequence for annual changes in yield, but have a potentially large effect over decades. Conventional single-species fishery management will almost always create selective pressure that favours traits such as early maturity and slow growth, because fishing mortality increases with size. This selection pressure could be changed if fishing mortality on larger individuals were reduced relative to that on smaller individuals, because the faster growing individuals would have a lower risk of mortality and, potentially, contribute more to future generations.

Bycatches

Bycatches of vulnerable species are taken in many fisheries, and populations of reptiles, mammals, birds, and fish are all affected by fishing (Northridge, 1984, 1991; Tasker *et al.*, 2000). Bycatches have been the focus of considerable societal concern, often expressed in relation to the welfare of individual animals as well as the status of the population. Societal concern over mammal and bird mortalities led to bans on fishing methods and gears (e.g. Northridge, 1991; Hall, 1998). The fishing industry does not always support attempts to reduce bycatches or to rebuild populations of marine mammals, particularly if they see them as competitors for fish (Earle, 1996). Bycatch issues have placed particular pressure on fishery managers to satisfy both fishing and conservation concerns. As a result, gear technologists have been especially active developing gears and fishing methods that help fishing and conservation to coexist.

Foodwebs

Fishing affects predator–prey interactions within the fished community and interactions between fish and other species, including predators of conservation interest such as seabirds and mammals. For example, fisheries can compete for food with seabirds and mammals (Sahrhage, 1989; Wright, 1996; Anker-Nilssen *et al.*, 1997; Mangel and Switzer, 1998; Constable and Nicol, 2002) and modify patterns of predation mortality leading to effects on recruitment and productivity (Sparre, 1991; ICES, 1997; Duplisea, 2005). Fisheries also produce discards that can provide significant energy subsidies, especially for scavenging seabirds, in some cases sustaining inflated populations (Camphuysen *et al.*, 1993; Furness, 1996). In general, discarded material in the path of the net or in the water column is assumed to have fewer ecological effects than discards that are available to seabirds at the surface. Reliable predictions of fishing effects on foodwebs have rarely been possible, the main exception being in some high-latitude environments where very few species dominate the biomass and production in the system (e.g. Blindheim and Skjoldal, 1993). Foodweb issues have placed significant pressure on fishery managers to satisfy fishing and conservation concerns, but the understanding of foodwebs is often too restricted to provide consistent and reliable scientific advice.

Habitats

Many fishing gears contact benthic habitats during fishing, and habitats such as coral reefs may be affected indirectly by changes to foodwebs (Kaiser and de Groot, 2000; Barnes and Thomas, 2005). The direct impacts of fishing on habitats are patchily distributed, reflecting spatial and temporal patterns in fishing effort (Kaiser *et al.*, 2002). The patchiness of impacts and the interaction between gears and habitats are critical to understanding the significance of fishing effects on habitats; different gears have different impacts on the same habitat, and different habitats respond differently to the same gear. The magnitude of impact is usefully measured in terms of the recovery times of biomass, production, diversity, or structure. For some highly structured habitats, recovery time is so slow that no level of fishing is realistically sustainable (Koslow *et al.*, 2000; Hall-Spencer *et al.*, 2002). Information on recovery time is available from meta-analyses of experimental data and models (Collie *et al.*, 2000; Hiddink *et al.*, 2007; Kaiser *et al.*, 2006). Habitat conservation is one of the easiest issues to deal with in conceptual terms, and there are already many examples of small areas being closed to fishing to protect vulnerable habitat. However, defining acceptable impact for a large area of habitat (e.g. all biogenic habitat in a regional sea) is much more challenging.

Mitigation of fishing effects

There are a number of mitigation methods that may help to reduce the impact of fishing on low productivity species in mixed fisheries, and on the genetics of exploited populations, non-target species, foodwebs, and habitats. Here, we give some examples of these approaches and their likely use, because several authors have already reviewed the technical aspects of mitigating unwanted fishing effects (e.g. Hamley, 1975; Løkkeborg and Bjordal, 1992; Mahon and Hunte, 2001; Revill, 2003; Valdemarsen and Suuronen, 2003).

Low productivity species in mixed fisheries

Although it is often technically possible to design gear that excludes a low productivity species in a mixed fishery, some degree of loss of target species is almost always unavoidable and, therefore, the use of the gear carries an economic penalty for the fisher. This is demonstrated by recent EU efforts to protect the dwindling "iconic" cod, which are caught among many other species in the mixed fisheries of the North, Baltic, and Irish Seas. In this case, European gear technologists have developed methods that allow cod to escape from the towed gears used in most fisheries (e.g. grid, cod escape panel, modified separator trawl, and modified codends; Rihan and McDonnell, 2003; Suuronen and Tschernij, 2003, Catchpole *et al.*, 2006), but the short-term economic losses associated with their use generally made them unpopular with fishers. The Bacoma codend, Swedish sorting grid, and inclined-separator panel have all been introduced under EU law, but it is not clear whether these regulations are significantly reducing cod mortality in practice (Suuronen *et al.*, 2007).

In all mixed fisheries, some species will be able to withstand higher rates of mortality than others. If gear technology alone were used to protect the most vulnerable species, their hierarchy would likely change over time, because the target species were relatively depleted. This process could predicate a continual series of adaptive changes to the gear selectivity, and this is unlikely to be workable in practice. More realistic management options to consider, though reliant on differences in the ecology of species, might include the use of closed areas to modify overall mortality for vulnerable species, with gear selectivity set in the other areas to cater for optimal harvesting of the most prevalent species.

Genetic effects of fishing

In general, pressure for improved conservation is making fisheries more selective about target species and their sizes. Size selectivity usually focuses on the efficient capture of individuals greater than a given minimum size, consistent with the objectives of conventional fishery management that emphasize high yields rather than maintaining age structures or preventing genetic selection. However, catching fish above a minimum size increases the relative mortality on fast-growing individuals and, therefore, selects for slow growth and early maturity. In addition, this strategy prevents the accumulation of larger and older individuals in the stock and encourages the truncation of age structure, impacts that may increase the sensitivity of the population to poor recruitment events and environmental variation.

A way to reduce the genetic effects of fishing and encouraging "favourable" genetic selection might be to have lower and upper size limits. At least in some fisheries, it should be feasible to select for fish in a given size range by combining methods allowing the release of smaller fish (e.g. mesh size, square mesh panels) and large (e.g. exclusion grid). In fixed net fisheries, the selectivity curves are already dome-shaped and may encourage favourable genetic selection, although this has not been tested.

Bycatches

Gear technologists have been particularly active in developing fishing methods that reduce bycatches of vulnerable species, especially seabirds and marine mammals. These methods are reviewed by Revill (2003), Valdermarsen and Suuronen (2003), and Bull (2007), and summarized in Table 1. There has also been interest in reducing bycatches of undersized target species and species, such as most benthic invertebrates, that fishers do not wish to retain (Fonteyne and Polet, 2002; Revill and Jennings, 2005).

For widely dispersed species with low intrinsic rates of increase, typically the larger elasmobranchs, an exclusion grid could be used to exclude large adult individuals from towed gears, although this would likely lead to the loss of large target species. The behaviour of elasmobranchs in trawls is not well studied, however, and should behavioural difference between species exist, they might offer a way to influence a gear design and allow adult rays to escape. There is already some evidence that grids that have been used for other purposes may reduce elasmobranch mortality (Griffiths *et al.*, 2006). Thus, the introduction of turtle excluder devices (TEDs) in Australia's northern prawn fishery is thought to have reduced fishing impacts on a number of vulnerable elasmobranchs formerly taken as bycatch (Brewer *et al.*, 2006).

Table 1. Examples of technical innovations that may reduce the environmental impacts of fishing on bycatch species, based on the reviews of Revill (2003) and Valdermarsen and Suuronen (2003).

Reducing unwanted catches of fish and invertebrates
Larger diamond mesh
Escape panels
Square mesh codends/T90 codends
Grids
Sieve nets
Separator panels
Cutaway trawls
Blow-out panels
Headline/footrope manipulation
Sweepless trawl
Fykenet excluder
Selective longline hooks
Escape vents, traps, and pots
Benthic release panels
Magnetized gear components to repel elasmobranchs
Reducing unwanted catches of mammals
Grids
Altered float lines
Back down manoeuvre
Fykenet excluder
Pingers
Reduced unwanted catches of reptiles
Longline circle hooks
Grids (TED)
Sunken longlines
Reduce unwanted catches of birds
Streamers lines
Sinker weights
Setting tubes
Warp fixed bird scarers

Foodwebs

Managers tend to consider the effects of fishing on foodwebs if those effects are relatively strong and predictable, as for the Barents Sea cod and capelin fisheries and, in these cases, conventional controls on the fishing mortality affecting the target stocks may achieve management objectives. In most other fisheries, the understanding of fishing effects on foodwebs is not sufficient to allow us to assess how changes in gear technology might mitigate any unwanted foodweb effects. However, it is clear that modifications to gear that are intended to achieve targets that society generally perceives as desirable (e.g. to reduce discarding) will likely lead to reductions in the abundance of dependent seabird populations, many of which have previously increased in abundance as a result of the additional food provided by discarding (Tasker *et al.*, 2000).

Habitats

Recently, work on reducing the environmental effects of fishing has focused on reducing the physical and biological impacts of towed gear on the seabed. Much of this work has been thoroughly reviewed by He *et al.* (pers. comm.). In summary, alternate gears with less seabed contact, such as pelagic or semi-pelagic trawls, may be used in place of traditional bottom gears in fisheries, where the herding of target species by sand clouds is less critical. For gears that fish on the bottom, impacts can also be reduced by decreasing contact area and the weight of groundgear and doors, using trawls without groundgear, or using wheeled or rollerball groundgear to replace rock-hoppers. The extent to which these modifications will ensure that impacts are sustainable will depend on the sensitivity of the habitat where the gear is used.

All the aforementioned technical solutions are intended to reduce fishing impacts. These solutions may or may not be necessary to ensure sustainability or to meet management objectives. From the perspective of the gear technologist, guidance on priorities may be limited because (i) management objectives for fisheries are not always explicit; (ii) objectives are "high level" and not operationalized; and (iii) the extent of, and priority for, changes in gear design and use cannot be assessed without reference to the other options for changing the management system in which the gear is used. As a result, it is all too common for gear technologists to work in something of a vacuum to achieve general reductions in impacts without an indication of whether the work is really necessary and what the priorities are. As a minimum, it would be desirable to compare the investment needed to improve gear and ensure uptake by the fishing industry with the costs of alternate management options such as time and area closures or overall reductions in effort.

Environmentally responsible fishing

Gear technologists can help ensure that fisheries are environmentally responsible. In the context of EAF, we define ERF as fishing that does not compromise the sustainability of any ecosystem component or attribute and therefore does not jeopardize the benefits of a marine ecosystem's full range of goods and services for future generations. The impacts attributable to an environmentally responsible fishery, therefore, must be sustainable on the scales of time and space at which environmental impacts are managed.

The reference to scale is critical here, because local mortality or physical impact may be unsustainable when aggregate impacts (on a population or regional scale) are sustainable. Less explicit definitions of ERF and objectives for fisheries might focus on minimizing the impacts of fishing. However, minimizing impacts is almost never cost-neutral in the short-term, so any attempt to minimize will always provoke debate about which impacts actually matter. From a fish marketing perspective, standards for ERF also have to be logical, consistent, and based on science. At present, buyers competing to obtain fish from fisheries where impacts are minimized could unnecessarily place excessive pressure on fisheries without any real environmental gain.

When do fishing impacts matter?

Determining the need for gear technologists to modify existing gear requires identifying the environmental effects of fishing that "matter". In practice, this is neither a science nor a policy issue, but tends to be a sometimes uncomfortable amalgam of both. For example, the mortality of individuals or losses of small areas of habitat can become emotive political issues, even if science cannot detect the effects of these impacts at the population or regional scale. Responding to concerns about these issues would be straightforward, if there were no costs associated with limiting these impacts, but the costs are usually high.

Scientific studies of fishing impacts have tended to avoid the issue of what matters, because of the issue's impenetrability and because it is easier for some scientists to "sell" their work if they suggest that any environmental change caused by fishing does matter. Avoiding the issue may also reflect some scientists' unwillingness to engage in "policy". Perhaps the biggest weakness of many fishing impact studies is that they do not analyse carefully whether the impact matters, and they assume that readers and policy-makers can make this judgement for them. In reality, scientists are probably best equipped to make this judgement and could adopt a much stronger and more authoritative stance, at least identifying the impacts that matter in relation to a range of specified criteria.

In the existing literature on fishing impacts, it is primarily in work on "extinction" and fish population dynamics that observed population abundance is related to levels of abundance that "matter" (for example, the levels that lead to reduced reproductive capacity and/or increased risk of extinction). In this population-focused work, there are also clearly identified links between levels of abundance that matter and policy commitments to achieve sustainable yield or prevent biodiversity decline (e.g. WSSD, 2002). However, when advising on the need for changes to gear design, it is vital to provide guidance on the acceptability, or otherwise, of the impacts of different gears on low productivity species in mixed fisheries, the genetics of exploited populations, non-target species, foodwebs, and habitats. Scientists should attempt to state whether impacts are significant in relation to specified criteria, on a range of scales, to guide investment in gear technology, and help establish priorities for policy-makers.

To assess whether impacts matter and to prioritize them, an audit of impacts is required. This audit defines, on a management scale, what the impacts are, when and where they occur, and which fleet/sector/gear/métier is responsible. Ideally, there is a need to partition the relative impacts of fishing among fleet/sector/gear/métier and to be able to express them in common currencies, such as impact-per-unit-time or per-tonne-of-target-species landed. Because impacts depend on the combination of time, location, duration, and gear, it is important to recognize that rankings of gear impacts outside a specific context are rarely useful. For example, the popular view that beam trawls are more damaging than bottom otter trawls takes no account of the types of seabed on which they are likely to be used (Jennings and Kaiser, 1998).

Uptake of gear modification in real fisheries

The greatest environmental benefits from gear modification will usually be achieved when gear technologists work with those responsible for developing other technical measures and catch or effort controls to embed fully the use of new gear technology in the management system and when there are clear incentives or pressures for uptake of the new technology. The uptake of new gears on a voluntary basis can be expected to be low where no incentives are in place or disincentives exist. There are many reasons for poor uptake, but they include an unwillingness to risk losing marketable catch, the absence of uptake by all fishers and hence a commercial disadvantage to users, additional work for fishers, conservation "benefits" that do not benefit the fishers, the cost of investing in the new gear, and gear conflicts where, for example, fishers could not risk using static gears in areas where towed gear fisheries already operate.

Strong incentives and/or enforcement pressures must be in place to ensure that gears with reduced environmental impact are used and not modified by fishers. Examples of possible incentives and pressures include the allocation of spatial and temporal access rights that depend on the impact of the gears or methods used, the decommissioning of the most damaging gears and methods, grant aid to switch to gears and methods with lower impact, real-time monitoring and swift closure if target limits (e.g. for bycatch) are exceeded, ensuring homogeneity where no individual fisher is disadvantaged by adopting a new gear, processor (consumer) levies to fund the use of low impact gears, marketing and eco-labelling schemes such as market-based incentives where buyers only purchase fish from fishers using low impact gears, transitional aid to offset short-term economic losses, and the use of competitions to promote and reward the development and application of lower impact gears. Most incentives and enforcement pressures have direct and indirect costs, so before encouraging the use of gears with reduced environmental impact, it is essential to assess the benefits of any reduction in environmental impact. Therefore, in developing and introducing gears with reduced environmental impact, a key step is to assess the current and future (with the new gear) impacts of fishing in relation to the status and profitability of the fishery, the state of ecosystem components and attributes, and policy objectives for the fishery and the ecosystem. The science needed to support this step, if taken, is not always conducted as rigorously as it could be, which is unfortunate given that it would provide a basis for focusing the efforts of gear technologists on fishing impacts that really matter and ensure the greatest possible incentives for the introduction of new gears.

When gears are made more selective through technical modifications, this is typically accompanied by some loss of the target-sized fish, because knife-edge selectivity, although desirable, is rarely achieved (Cook, 2003). For the industry, this is not good, because the loss of some target-sized fish will lead to short-term economic losses. Managers, therefore, will likely pressure gear technologists to present gear design options that provide economic benefits that equal or exceed the expected losses, for example, from improving the catch quality and therefore price, or reducing fuel costs, sorting time (crew), or wear and tear on gear. In respect to the win–win or neutral–win technical-based solutions that mangers often desire, gear technology has precipitated some progress over the years. For example, Brewer *et al.* (2006) report on the use of TEDs in Northern Australian prawn fisheries and report high release rates of large species, such as elasmobranchs and turtles. Although prawn losses were reported to be around 6% with TEDs, the catch quality was improved as damaged/soft prawns were reduced by >40%. In the North Sea, many skippers used sieve nets voluntarily when targeting *Crangon crangon*, well in advance of their mandatory introduction in 2002 (van Marlen *et al.*, 1998), because of perceived benefits from improved catch quality and reduced sorting times on deck. Such devices were used despite losses of target species of up to 10% (Revill and Holst, 2004).

Conversely, the search for more selective but cost-neutral gears may stifle innovation and lead to only modest improvements in selectivity and modest reductions in environmental impact. Developing more selective gears with lower environmental impact, without the narrow constraints of the short-term win–win or win–neutral management expectation, may prove healthy for innovation and is more likely to produce new and effective gear designs in the long term. Such research should receive greater attention from gear technologists, because current constraints are likely to change in future, including fuel costs, the environmental acceptability of different impacts, the value of catch, and the willingness of markets and consumers to purchase fish from certain sources. Moreover, the significant and expected changes in the rules governing access rights, for example, may create a major incentive for the industry to adopt gears that provide more fishing opportunities.

Achieving ERF

Changes to fishing gear, without changes to other aspects of fishery and marine environmental management, are unlikely to lead to ERF in all but a relatively small proportion of circumstances. These circumstances usually relate to situations where fisheries make environmental impacts on a limited number of ecosystem components or attributes (e.g. turtle bycatches in otherwise well managed fisheries), where the objectives in relation to these impacts are quite well defined, and where monitoring of the fishery is thorough. In most other circumstances (e.g. bottom trawl fisheries), fishing has multiple impacts on ecosystem components and attributes, the objectives in relation to the impacts are not well defined, agreed, or prioritized, and monitoring of the fishery in relation to these impacts is relatively poor.

Perhaps the most significant change to fishery management that will allow gear technology to support ERF will be driven by a desire to treat fishing on par with other sectoral activities and to embed fisheries fully in marine spatial planning systems. At present, most fisheries are exempt from the requirements for environmental impact assessment (EIA) or strategic environmental assessment (SEA), even in areas where other users of the marine environment, such as the oil and gas industries, would be required to conduct them. EIA and SEA are now being considered in a fisheries context by more management bodies, and there is a precedent for this change in the FAO Code of Conduct for Responsible Fisheries (FAO, 1995).

If fisheries are managed in the context of marine spatial planning, with areas allocated to fisheries and other uses, there will be an excellent opportunity to define fishing areas where different combinations of gear and effort are environmentally acceptable. Such approaches have already been adopted in some regions, such as on the Australian Great Barrier Reef by the Great Barrier Reef Marine Park Authority, but we expect them to be used much more widely in response to increased pressure on marine resources and a growing political commitment to sustainable human impact on the marine environment. Much of the science needed to define when, where, and how frequently gears can be used sustainably has been conducted already, but the results still need to be interpreted and used to provide unambiguous management advice.

Assessing and selecting management options to support ERF

Central to assessing and selecting management options to support ERF is the need to describe the sustainability of existing fishing impacts in relation to management objectives. A typical process for achieving ERF in the context of EAF might be to (a) define management regions; (b) define objectives for fishery and environment; (c) describe spatial and temporal distribution of fishing activities by fleet and gear; (d) assess whether impacts of each fleet and gear on ecosystem components and attributes compromise objectives; (e) identify how different combinations of fleet, gear, fishing time, and location contribute to the impacts that do compromise objectives; (f) quantify the costs to the fishery, scientific funding bodies, and management authorities of using catch controls, effort controls, or technical measures (space and time closures, gear technology) to reduce impacts to levels at which the objectives are met; (g) set priorities for management action based on outcomes of step (f); (h) implement management schemes; (i) monitor impacts in relation to objectives and repeat steps (c)–(g). In theory, this is a relatively straightforward process. However, even though elements of this process contribute to many management systems, all elements in the process are rarely included, or individual elements are given cursory treatment. Particular weaknesses often include incomplete definition of operational objectives, incomplete assessment of impacts, and incomplete examination and costing of alternative combinations of management measures. In the last case, this means that management measures such as time and area closures are not considered systematically as an alternative to, or in combination with, the effects of change in gear technology.

Steps (g) and (h) are always difficult to achieve, because they frequently result in high short-term costs and therefore create strong disincentives. In this regard, many existing management systems are poorly tailored to adopt advice on methods for achieving ERF. A focus on embedding fisheries management within marine spatial planning, however, could change this situation dramatically.

Spatial management

Fishery management in a spatial planning context should help to guide the research priorities of gear technologists, both in terms of assessing the impact of the gear on ecosystem components and attributes, and developing gears with reduced impact. Such systems have already been developed in part, in some cases to support EAF (e.g. Witherell *et al.*, 2000), but often to reduce gear conflicts as much as to ensure environmental protection (Blyth *et al.*, 2002, 2004).

Within a spatial management plan, management authorities would permit fishing activities in identified areas of the marine environment. Within the areas allocated to "fishing", ERF would be achieved by allocating access rights to specific blocks (the smallest management units used in a management region), based on the need to meet objectives for target species and the ecosystem. The allocation of rights would be based on knowledge of the impacts of different fishing gears on ecosystem components and attributes, and knowledge of the components and attributes present in the blocks. For example, the use of towed bottom gears might be prevented in blocks containing sensitive habitats or in blocks where bycatches of vulnerable bottom dwelling fishes are high. Fishers would be allowed to increase the range of blocks they access if they could demonstrate that the fishing gears and methods they planned to use do not compromise management objectives. This could be achieved by an EIA or SEA type process, to test whether a new method, gear, time, and location combination had acceptable impacts. This would delegate the responsibility for achieving ERF to the fishing industry, which would have to demonstrate that the approaches they develop in conjunction with gear technologists have acceptable impact. The onus on gear technologists would be to design gears that gives fishers more opportunities for access. A management system such as that described would also centralize the resolution of gear conflicts.

In the open marine environment, fishing activities in the blocks cannot be treated as independent, and the proportion of blocks allocated to specific fishing activities in a management region would have to be based on a local (block-specific) as well as a cumulative (management region) assessment of impact. Trade-offs are likely in this process. For example, it may be acceptable to allow bottom trawler access to a large number of blocks containing low sensitivity habitat or a smaller number of blocks with highly sensitive habitat. Decisions about such trade-offs would be guided by knowledge of the expected catch rates of target species in different blocks.

Methods for assessing habitat sensitivity are increasingly well developed, although some methods rely on expert judgment and/or scoring systems and are neither repeatable nor verifiable (Zacharias and Gregr, 2005). The most useful methods probably treat sensitivity as the inverse of recovery time following a given gear impact. Hiddink *et al.* (2007), for example, have used predictions of sensitivity based on recovery time to compare the relative environmental costs of trawling in habitats with different sensitivities and to show how modifications to the existing distribution and intensity of trawling disturbance would affect the aggregate impacts of trawling. Such methods provide clear quantitative guidance to assess the outcome, in terms of costs and benefits, of different management options designed to support implementation of EAF. Rather than a fixed system of access rights, Holland and Schnier (2006) have proposed individual habitat quotas (IHQ). These are distributed to fishers with an aggregate quota set to maintain a target habitat "stock". IHQ would be relatively easy to monitor with VMS compared with species-based bycatch quotas, which require high levels of observer coverage.

To support fishery management in a marine spatial planning context requires that managers know the effects of different gears on ecosystem components (e.g. fish, benthic habitat) or attributes (e.g. abundance, diversity) in different locations (blocks) at different times, and can express them in relation to processes that can be managed, such as fishing effort, catch, or location of fishing in space or time. With this knowledge, the acceptable total impact in relation to defined objectives (what matters) can be determined. Fishing opportunities for block, gear, method, and time combinations are then allocated to meet the objectives for ecosystem impacts, consistent with and capped by acceptable impacts on target populations. If the restriction used to ensure that ERF results in a fall in target catch and fisher income, then clear drivers for improved gear technology exist, because improved gear will increase fishing opportunities once again.

Conclusions

Effectively integrating fisheries and marine environmental conservation is one of the biggest challenges facing marine scientists and policy-makers today, and has been promoted through widespread political commitment to sustainable development and EAF. We conclude that gear technologists have a key role in developing ERF and therefore in supporting it. To provide the greatest benefits, however, research on gear technology has to be prioritized and focused, taking account of the relative impacts of fishing on different ecosystem components and attributes, the extent to which these impacts compromise management objectives, the management system in which the gears are used, and the relative costs and benefits of other management measures that might support ERF. To facilitate this process, scientists must be much more proactive and assertive in defining which fishing impacts matter. Existing short-term win–win constraints can stifle the creativity of gear technologists, and more work must focus on innovation that is not constrained by the need to achieve immediate environmental benefits and maintain the short-term profitability of fisheries. In future, we expect that spatial planning, EIA, and SEA will all play much greater roles in fishery management systems, because fisheries are increasingly treated on par with other sectoral activities in the marine environment. If fisheries were managed as part of a spatial plan, the allocation of rights would be based on knowledge of the impacts of different fishing gears on ecosystem components and attributes in each of the spatial management units. Fishers would be allowed to increase the range of units they access if they demonstrate that the fishing gears and methods they planned to use do not compromise management objectives, placing an onus on gear technologists to design gears that give fishers more opportunities for access.

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