

Figure 5 Regression tree of the data for the initial response of biota to fishing disturbance. A binary partitioning algorithm recursively splits the data in each node until the node is homogeneous or contains too few observations. The vertical height of each branch indicates the importance of that split. The number under each node is the mean response for that combination of variables. Working up from the root of the regression tree permits one to predict the response of a particular taxon to a particular type of fishing disturbance under particular scenarios (adapted from Collie *et al.* 2000).

useful to develop this approach for recovery rates of fauna and habitats (see below).

Recovery rates after trawl disturbance

Soft sediment habitats

From our perspective, the short-term effects of bottom-fishing disturbance on habitats and their biota are of interest but of far less ecological importance than the issue of the potential for recovery or restoration. The short-term outcome of disturbance experiments is often counter-intuitive and open to misinterpretation. Unfortunately, relatively few studies of trawl disturbance have included a temporal component of sufficient duration to address longer term changes that occur as a result of bottom fishing disturbance. This is almost certainly a result of the conflict between financial resources, project duration, statistical and analytical considerations. Nevertheless, Collie *et al.* (2000) were able to incorporate studies that included a recovery component into their analysis. This permitted them to speculate about the level at which physical disturbance becomes unsustainable in a particular habitat. For example, their study suggested that sandy sediment communities are able to recover within 100 days which implies that they could perhaps withstand two to three incidents of physical disturbance per

year without changing markedly in character (Fig. 6). If our recovery rate estimates for sandy habitats are realistic, this would suggest that areas of the seabed that are trawled more frequently than three times per year are held in a permanently altered state by the physical disturbance associated with fishing activities. As we discuss later, such levels of fishing disturbance exist in areas such as the North Sea and this outcome has important implications for predicting the outcome of management systems that may cause changes in the spatial pattern of seabed disturbance. This expectation is supported by a recent study that links the size and species composition of North Sea benthic communities to patterns of chronic beam-trawling disturbance (Jennings *et al.* 2001a). There was minimal evidence for trawling effects on size composition or benthic production in a series of sites trawled up to 2.3 times per year. However, at another series of sites trawled up to 6.5 times per year, the most heavily trawled sites were characterized by a fauna of low biomass and low production that consisted of very small individuals. Larger bivalves and burrowing sea urchins, that can dominate the biomass in infrequently trawled areas, were effectively absent (Jennings *et al.* 2001b).

At this point, it is important to acknowledge that there are some important limitations to the data compiled by Collie *et al.* (2000). First, the small spatial

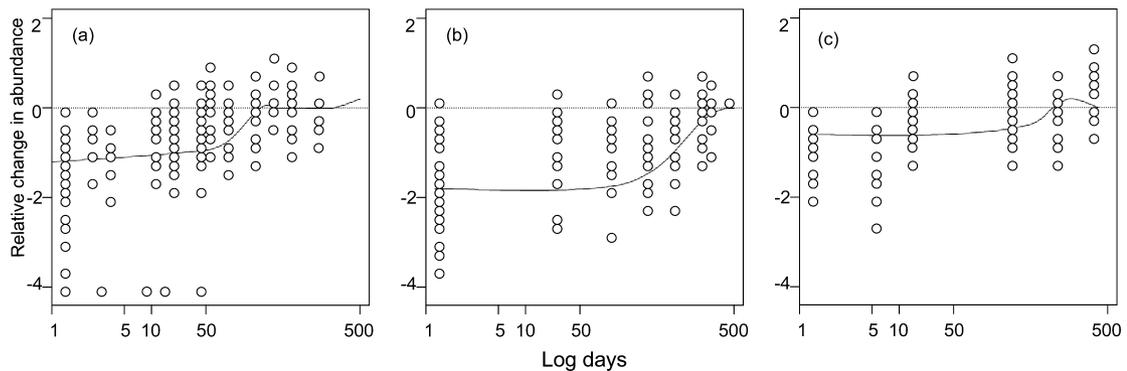


Figure 6 Results from a meta-analysis of the effects of fishing disturbance on benthic communities. The scatter plots of the relative change of all species (each datapoint represents the relative abundance of a different species on each different sampling date) in different habitats (a = sand, b = muddy sand, c = mud) at time intervals after the occurrence of a fishing disturbance. The fitted curves show the predicted time trajectory for recovery to occur. On the y -axis, 0 shows no relative change in abundance, negative values show a relative decrease in abundance (adapted from Collie *et al.* 2000).

scale of most of the trawl impact studies (the maximum width of most of the disturbed areas examined was <50 m) made it likely that much of the recolonization was via active immigration into disturbed patches rather than reproduction within patches. Second, it should be noted that while we might accurately predict the recovery rate for small-bodied taxa such as polychaetes which dominate the data set, sandy sediment communities often contain one or two long-lived and, therefore, vulnerable species. Note, for example, the occurrence of the large bivalve *Mya arenaria* in the intertidal zone of the Wadden Sea. While the majority of the benthos in this environment recovered within 6 months of lugworm dredging, the biomass of *M. arenaria* remained depleted for at least 2 years afterwards (Beukema 1995). This delayed recovery of larger-bodied organisms is, no doubt, even more important in habitats that are formed by living organisms (e.g. soft corals, sea fans, mussels), as the habitat recovery rate is directly linked to the recolonization and growth rate of these organisms. By now, there is sufficient evidence in the literature to suggest that under conditions of repeated and intense bottom-fishing disturbance a shift from communities dominated by relatively high-biomass species towards dominance by high abundance of small-sized organisms is likely to occur (e.g. Kaiser *et al.* 2000a,b).

Effects on biogenic structure

The benthic communities with which human beings identify most strongly are those that are character-

ized by a rich epifauna that provides abundant biogenic structure. Coral reefs are the exemplar, but sponge gardens, calcareous algae, or maerl beds and various hard substratum communities are all valued targets for conservation. There is little doubt that put in the path of a trawl or subjected to dynamite or 'muro-ami' fishing, these communities are at risk. It is somewhat surprising, therefore, that there have been relatively few studies that examine the effects of trawling for such biogenic habitats, or the rates of recovery. In their meta-analysis of 57 trawl impact studies, Collie *et al.* (2000) found only 10 studies that focused on biogenic habitats and of these, only four contained data suitable for analysis. Part of the reason for this lack of studies is understandable because the vast majority of trawling occurs in sandy habitats where biogenic structure is absent. It should be noted, however, that even in these sandy habitats, smaller scale patches of biogenic habitat may be present and may have been markedly impacted on trawl grounds. A good example of the magnitude of effect is provided by Hall-Spencer and Moore (2000) who showed that scallop dredges have profound effects on calcareous algae (maerl) beds, with up to 70% of thalli in dredge tracks killed through burial. Similarly, Poiner *et al.* (1998) report the results of a trawl depletion experiment in the interreef areas of the Great Barrier Reef, which showed that each trawl removed and caught between 5 and 20% of the available biomass of sessile fauna, with 70–90% removed after 13 trawls. Note that the above estimate does not include fauna that were detached from the seabed but not caught. However, video analysis of the effects

of the trawl ground rope undertaken by Sainsbury (1987) for the Australian north-west shelf, indicate that about 89% of encounters lead to dislodgement of sponges and almost certainly subsequent death.

With respect to other forms of fishing that affect habitat structure, dynamite and cyanide fishing on coral reefs are probably the most obvious, but the removal of fish themselves may also affect the nature of the available habitat. Species that act as ecosystem engineers are being increasingly recognized as playing an important role in the marine systems. In the Gulf of Mexico, for example, where unconsolidated sediment overlies hard rock substratum, fish such as the red grouper have been shown to create burrows, or dig pits, down to the rock (Coleman and Williams 2002). This seabed excavation in turn allows a rich epifaunal community to colonize. In such circumstances, depletion of the fish resource will lead to concomitant effects on the biodiversity of the benthos. The extent of such phenomena is currently unknown.

It could certainly be argued that it is by effecting changes to biogenic structure that fishing is most likely to influence the benthic communities of marine systems. Although the data are relatively sparse and well-executed studies of effects of mobile bottom-fishing gears on many biogenic habitats are difficult to find (e.g. Collie *et al.* 2000), it seems self-evident that destroying the physical integrity of reefs or other biogenic structures will have profound consequences, both for fish populations and the other taxa. Indeed, on coral reefs, some of the most complex of biogenic habitats, there are significant positive relationships between fish biomass and topographic complexity (Luckhurst and Luckhurst 1978; Roberts and Ormond 1987). What is true for coral reefs is almost certainly true for other biogenic habitats. The issue here is not only that marked and undesirable effects ensue when trawling, dynamite fishing, or other physically disruptive practices take place, but the extent of the fishing activity and the distribution of sensitive habitats. The lack of high resolution (± 100 m) maps of benthic habitats and biota is probably the biggest current impediment to effective protection of vulnerable habitat from fishing activities. Only by combining such data with microscale data on the distribution and frequency of trawling disturbance for major fishing grounds can we accurately assess the extent of impact of fishing on benthic habitats. Such data will also provide a sound basis for developing mitigation strategies.

Case history of prolonged recovery

One analysis of recovery, which also demonstrates the importance of biogenic structure provided by benthic organisms, is that of Sainsbury (1988) who studied the fishery off the north-west shelf of Australia. Research survey data available from 1960 onward has shown that while the total biomass of fish has not changed as these fisheries have developed, the composition of the fish community has altered, with Lethrinids and Lutjanids declining and Saurids and Nemipterids increasing. The available data also indicated that the benthic environment has altered over the same period. In particular, the quantity of epibenthic fauna caught in trawls (mainly sponges, alcyonarians and gorgonians) is now considerably lower than it was prior to the development of the trawl fishery (Sainsbury 1987). Using video data Sainsbury (1988) identified four habitat types on the basis of dominant benthic fauna. Fish catch data was then examined in relation to habitat type, and the results indicated that Lethrinids and Lutjanids were almost exclusively associated with habitats supporting large epibenthos. In contrast, the Saurids and Nemipterids were only found on open sand. Subsequent comparison between a closed area and one open to trawling between 1985 and 1990 shows how the area closed to fishing experienced an increase in the density of *Lethrinus* and *Lutjanus* and in the abundance of small benthos. The abundance of larger epibenthos stayed the same or perhaps increased slightly. In the area open to trawling, the abundance of fish declined along with the small and large epibenthos.

The north-west shelf is a good example of where an interaction between fisheries and the structure of benthic communities may lead to both an enhanced fishery and a less disturbed benthic community. Such mechanisms may not happen everywhere; indeed, the habitats in which they operate might be quite restricted, but we should be alert to the possibility. Unfortunately, however, in the case of the north-west shelf, it is apparent that the time scales for recovery for epifaunal benthos are slower than previously thought. Rather than taking 6–10 years for sponges to grow to 25 cm it now appears that at least 15 years are required. This slow recovery dynamic, coupled with the apparently high probability that large benthos will be removed by a trawl, means that measures to protect the habitat would need to be very effective to maintain the habitat structure required to support this high-value fishery.

What would the seabed be like without fishing disturbance?

Comparative studies

It is unlikely that we will ever unearth sufficient datasets that will provide a good picture of the manner of change in benthic communities during the period when fishing developed. Hence, if we do not see major trends in time series or marked effects from experimental trawling, might it be that fishing removed or degraded the community to a considerable degree before we even started looking? The perceived problems that might be associated with intense and prolonged bottom-fishing disturbance have only been examined with any degree of rigour in the last 20 years. However, the bottom-fishing fleets have been in operation much longer (Jennings and Kaiser 1998). For example, the whole North Sea was already accessible to otter trawlers by 1900 and the beam trawl fleet in the southern North Sea expanded dramatically through the 1960s and 1970s and reached an asymptote in the mid 1980s. Consequently, many present-day studies have been undertaken in what is already a considerably altered environment from which certain vulnerable species have been extirpated (Philippart 1998). Despite our efforts to predict the outcome of fishing activities for existing benthic communities, we are often unable to deduce the original composition of the fauna because data gathered prior to the era of intensive bottom fishing are sparse and variable in quality. This is an important caveat because recent analyses of the few existing historical datasets suggest that larger bodied benthos were more prevalent prior to intensive bottom trawling (Frid *et al.* 2000; Rumohr and Kujawski 2000). Rumohr and Kujawski (2000) noted that 25% of the bivalve fauna recorded in the North Sea in the first half of the twentieth century are no longer present, although their data require careful interpretation. Perhaps, not surprisingly, present-day comparative studies (i.e. those studies that compare areas of the seabed subjected to different regimes of chronic disturbance from none upwards) indicate that epifaunal organisms are less prevalent in areas subjected to intensive bottom fishing (Collie *et al.* 1997; Sainsbury *et al.* 1997; Kaiser *et al.* 2000a,b; Koslow *et al.* 2000; McConnaughey *et al.* 2000; Rumohr and Kujawski 2000). An important consequence of this effect is the reduction in habitat complexity (architecture) that accompanies the removal of sessile epifauna. Nevertheless, it has been hard to convincingly

demonstrate that towed bottom fishing activity has been responsible for changes in bottom fauna and habitats. Often, effort data are lacking at a scale or over a time period that is relevant to ascertain the disturbance history of a particular area of seabed. Kaiser *et al.* (2000a) were able to overcome the problems associated with verification of disturbance history by recording the frequency of trawl-induced scars in the shell of a long-lived species of bivalve mollusc *Glycymeris glycymeris*. In the few instances when such data have been available, observations have indicated consistently a shift from dominance by high-biomass organisms towards communities dominated by small-bodied opportunistic species (Engel and Kvittek 1998; Bradshaw *et al.* 2000; Kaiser *et al.* 2000a,b; McConnaughey *et al.* 2000; Jennings *et al.* 2001a,b).

Fishing effects on production in different habitats

Complex biogenic and structured habitats harbour communities of higher biomass and diversity than adjacent habitats with less complex structure (Kaiser *et al.* 1999 and others?). Since trawling disturbance reduces habitat complexity, this may reduce the total production of the associated community. However, it has also been argued that frequent trawling disturbance may lead to the proliferation of smaller benthic species with faster life histories that can withstand the mortality imposed by trawling and are favoured as food by commercially fished species. Since smaller species are more productive, trawling disturbance may 'farm the sea', with knock-on benefits for consumers, including fish populations.

There have been few empirical tests of the impact of trawling disturbance on production, but one study of trawling impacts on a soft-sediment community suggests that the effects may be negative. In this study, benthic production was assessed across quantified gradients of trawling disturbance on real fishing grounds in the North Sea (Jennings *et al.* 2001b). Biomass fell with increased levels of trawling disturbance (Fig. 7). Production was estimated from size-spectra, using an allometric relationship between body mass and the production to biomass ($P : B$). In heavily fished areas, the abundance of larger individuals was depleted more than smaller ones, as reflected by the positive relationship between the slope of the normalized size-spectra and trawling disturbance. Relative infaunal production (production per unit biomass) rose with increased trawling disturbance, and this was largely attributable to the dominance of smaller animals in the disturbed

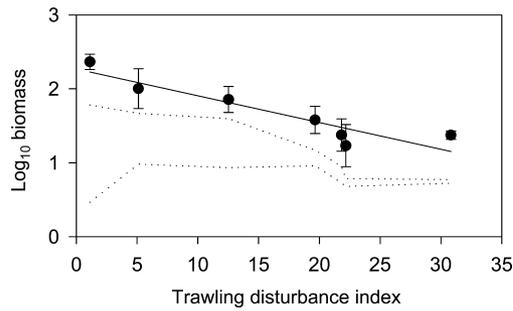


Figure 7 The relationship between trawling disturbance and the biomass of infauna in the Silver Pit region of the North Sea. The continuous line is the fitted relationship between biomass and trawling disturbance while the upper broken line shows the relationship between the biomass of bivalves/spatangoids and disturbance and the lower broken line shows the relationship between the biomass of polychaetes and disturbance. Preliminary multivariate analyses of these data showed that trawling disturbance alone accounted for more of the variance in total biomass than sediment characteristics and depth.

communities. The significant increase in relative production ($P : B$) did not compensate for the loss of total production that resulted from the depletion of large individuals (Fig. 8). Multivariate analyses have also

been used to show that bottom trawling disturbance had a dominant effect on the size-structure and production of the fauna of this soft-sediment benthic community and that the role of other environmental variables such as sediment particle size and depth was relatively weak (D. E. Duplisea *et al.* unpublished results). Given that trawling disturbance led to reductions in production in this relatively simple and unstructured habitat, it is expected that the effects may be even more profound when trawling leads to reductions in the complexity of highly structured biogenic habitats and their associated fauna.

It is also expected that trawling impacts on complex biogenic habitats will lead to changes in the trophic structure of the associated communities. One study of trawling impacts on trophic structure in a soft-sediment community demonstrated that chronic trawling disturbance led to dramatic reductions in the biomass of infauna and epifauna, but that these reductions were not reflected in changes to the mean trophic level of the community, or the relationships between the trophic levels of different size classes of epifauna. Despite order of magnitude decreases in biomass of infauna, and a shift from a community dominated by bivalves and spatangoids

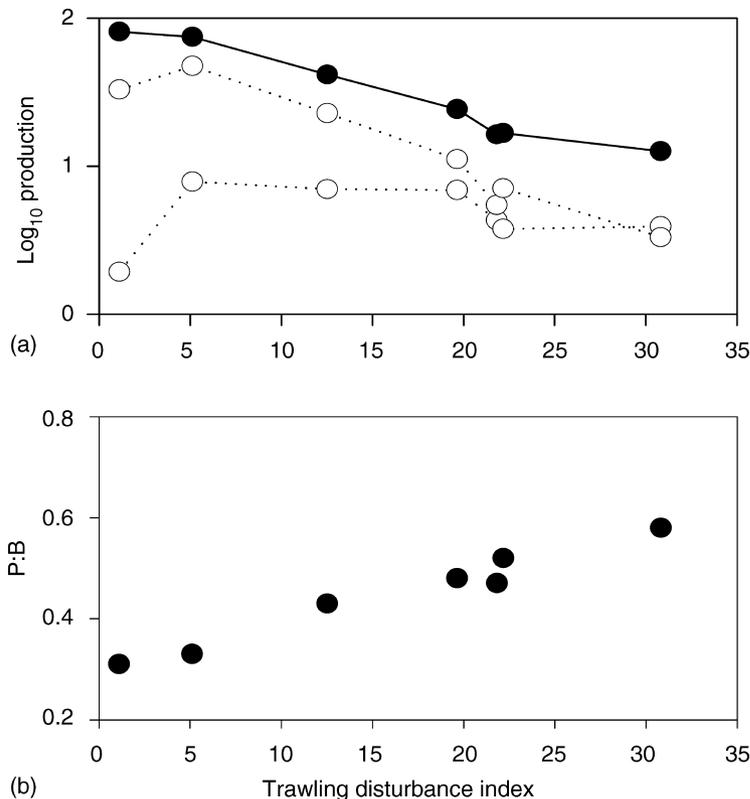


Figure 8 (a) The relationship between trawling disturbance and production for infauna in the Silver Pit region of the North Sea. The continuous line shows the relationship for the whole community, while the upper broken line shows the relationship for bivalves/spatangoids and the lower broken line shows the relationship for polychaetes (not significant). (b) The relationship between trawling disturbance and production to biomass ratios for the same infaunal community.

to one dominated by polychaetes, the mean trophic level of these communities differed by less than one trophic level between sites and differences were not linked to levels of fishing disturbance. The trophic structure of the benthic invertebrate community in this part of the North Sea may have been quite robust, thus ensuring the efficient processing of production within those animals that have sufficiently high intrinsic rates of population increase to withstand the levels of mortality imposed by trawling. The lack of changes in the trophic level of the benthos could imply that species less vulnerable to disturbance are taking the trophic roles of larger, more vulnerable species. It would be worthwhile to undertake an explicit study of whether smaller species with faster life histories begin to fill the trophic functions vacated by larger species with slower life histories because the latter cannot withstand the high mortality rates imposed by repeated trawling. Jennings *et al.* (2001a) emphasized that their results were only applicable to the free-living fauna of mobile substrates and that it was unlikely that they could be extrapolated to deeper areas with lower natural disturbance where many habitat-forming species are found (Auster *et al.* 1996). Here, loss of habitat would have important consequences for many species, and stability in trophic structure is unlikely to be observed as biomass falls.

The patchiness of trawling effects and its implications

The patchiness of trawling effort is a key determinant of the cumulative large-scale impacts of trawling disturbance on habitats. Trawling effort is patchy on a range of scales. Thus, even in the intensively fished North Sea at the scale of the ICES rectangle (areas of 0.5° latitude by 1° longitude = 3720 km^2 at 53°N used for the statistical collection of fisheries data), annual international beam and otter trawling effort ranges from 0 to over $50\,000 \text{ h year}^{-1}$ (Jennings *et al.* 1999). Half the ICES rectangles in the North Sea are beam trawled for less than 2000 h year^{-1} . Since a typical beam trawler tows two 12 m (width) beams at six knots (11.1 km h^{-1}), the trawler will impact $267\,264 \text{ m}^2 \text{ substratum hour}^{-1}$ or 534.5 km^2 in 2000 h. Thus, in rectangles subject to 2000-h beam trawling per year, and with a truly homogeneous effort distribution in the rectangle, it would take at least 7 years to trawl the entire rectangle once. This would have a limited effect on most benthic habitats, and such rectangles could be considered *de facto*

closed areas. At smaller scales, trawling effort is also very patchy. Rijnsdorp *et al.* (1998) examined effort data for their beam trawl fleet and have shown that effort is patchy at spatial scales of 30×30 , 10×10 , 3×3 and 1×1 nautical miles. Only at the smallest scale of 1×1 nautical miles was the effort distribution usually observed to be random. In practical terms, this research means that *de facto* closed areas where habitats are not impacted by fishing are likely to exist at many scales. Even in eight of the most heavily beam trawled ICES rectangles in the southern North Sea, 5% of the area is trawled less than once every 5 years (Rijnsdorp *et al.* 1998). We can only assume that the remaining presence of vulnerable habitat in many intensively fished areas is the consequence of patchiness in fishing effort. If this is the case, then management regulations that preserve such patchiness are desirable for conservation purposes.

The analysis of patterns in trawling effort shows that in the absence of radical changes in management practices, trawlers tend to target the same grounds year after year. However, there are usually seasonal (within years) changes in effort distributions. Once on the fishing grounds, many vessels will fish the same tows time after time as these tows are likely to be clear of obstructions. This means that in the short term (up to 5 years or so), the spatial distribution of effort from year to year tends to be quite consistent. However, since fishermen prefer to fish on certain types of ground, the areas that are unimpacted or lightly impacted by trawling will not necessarily be representative of all habitat types that are present.

If there are no major changes to fishery management regimes, trawlers tend to fish the same grounds year after year. This means that the same areas of the seabed are disturbed, and that areas of seabed are virtually unaffected by trawling. For most habitats that are vulnerable to fishing, a consistently patchy distribution of a given level of trawling effort from year to year is likely to have lower environmental impacts than if the same trawling effort were distributed evenly. This is because the recovery times of the vulnerable habitats are very long (Collie *et al.* 2000), and impacts by trawls at intervals of 4–5 years may be enough to cause habitat loss and structural change.

If closed areas are used as a fishery conservation tool, they will always cause changes in the spatial and temporal distribution of fishing effort. For example, the temporary closure of 40 000 square miles of

the North Sea to trawling from 14 February to 30 April 2001 (North Sea Cod Recovery Plan), led to trawlers operating in areas that were previously not fished (Rijnsdorp *et al.* 2001). As a result, while the effects of trawling on habitats may be mitigated within the closed area, the resultant changes in effort distribution may mean that the impacts of trawling are exacerbated outside the closed area. Any assessment of the potential benefits of closed area management must take into account the impacts both inside and outside the reserve. We can envisage a situation where a number of temporary closures of fishing grounds in different locations would, in the long term, result in greater overall homogeneity in trawling effort distributions than would otherwise exist. Redistribution would be a particular concern in relation to biodiversity conservation if, for example, there was a displacement of vessels from inshore fishing grounds to previously unfished continental shelves where cold-water corals and other fauna of conservation concern may be present (Roberts *et al.* 2000).

Essential Fish Habitat

Recent amendments to the U.S. Magnuson-Stevens Act require fisheries managers to address the impact of fishing gears upon fish habitat in their management plans (Benaka 1999). This will, no doubt, have a profound effect on the manner in which U.S. fisheries are managed. This legislation is one of the first measures to embrace an ecosystem perspective in fisheries management. While it is fairly simple to identify those habitats that might be considered essential to the life history of some fish, e.g. spawning and nursery areas. However, of equal relevance are the habitat quality issues that affect the acquisition of food and the avoidance of predators. Hence, there is an urgent need to identify those habitats that may have an important or 'essential' functional role for particular species or types of fish (e.g. piscivores/herbivores/omnivores or flatfish/roundfish) at other stages of their life history.

Previous studies of the relationship between fish and shellfish assemblages and their environment have focused on variables such as salinity, depth and substratum type (e.g. Overholtz and Tyler 1985; Smale *et al.* 1993). Yet, while such environmental parameters are in some cases good correlates of certain fish assemblages, they do not necessarily define the essential features of a specific habitat, rather they constitute a component of that habitat that may act as a surrogate for some other more important habitat

feature. Habitat complexity and structure (e.g. grain size composition) appear to be important physical features for some fish species (e.g. Sainsbury 1987; Gibson and Robb 1992; Auster *et al.* 1997). Many studies have already demonstrated the relationship between flatfish species and the sediment particle composition of the seabed, which may be more important than the occurrence of associated epibenthic structures or fauna that occur in that habitat (e.g. Gibson and Robb 1992; Rogers 1992). For example, plaice are better able to bury themselves in sediments that have a particular grain-size composition and hence, more effectively avoid predation. Hence, a specific particle-size composition may be essential for flatfish, whereas the presence of large sessile epifauna or rocky substrata might be considered non-essential. In contrast, there is good evidence to suggest that structural complexity can have important implications for the survival of roundfishes (e.g. Walters and Juanes 1993; Tupper and Boutilier 1995).

Habitat complexity is a product of the surface topography of the substratum and the sessile epifauna that grow upon it. Reef-forming organisms can result in habitats of very high complexity providing a multitude of refuges for a diverse range of species. More subtle features such as sand ridges and pits created by the feeding or burrowing action of benthic fauna may provide shelter for bottom-dwelling fish species (e.g. Auster *et al.* 1997). Bottom fishing activities are capable of greatly reducing habitat complexity by either direct modification of the substratum or removal of the fauna that contribute to surface topography (Jennings and Kaiser 1998; Auster and Langton 1999). Hence, degradation of habitat complexity by fishing activities may lead to changes in the associated fish assemblages (e.g. Sainsbury *et al.* 1997). Alteration of habitat features has been shown to have important consequences for freshwater fishes, and this is the caveat that underpins much of the ecological restoration projects centred on salmonid habitats that focus on the reconstruction of habitat features important for the life history of the fish (e.g. Cederholm *et al.* 1999). An initial study of habitat/fish assemblage relationships indicated that even subtle alterations in habitat characteristics are linked to changes in the dominance of certain fish species within the assemblage (Kaiser *et al.* 1999). Presumably, a good understanding of the link between fish and their habitat would enable us to predict the consequences of habitat alteration. For example, for certain species such as sole (*Solea solea*) that preferentially live in relatively uniform sandy areas,

the exclusion of towed bottom fishing gear from an area of the seabed could permit the growth of emergent sessile fauna. As sessile fauna attract decapod crustacea (Auster *et al.* 1996), this could make the sandy environment better suited to predatory flatfishes such as plaice (*Pleuronectes platessa*) and dab (*Limanda limanda*) (Kaiser *et al.* 1999). Thus, in the case of the sole fishery, the fishing activity may maintain the seabed habitat in a condition that favours the target species. Nevertheless, it is important to remember that excessive bottom disturbance will eventually result in reduced productivity.

Integrating habitat conservation into fisheries management

Fishery managers are unlikely to be concerned with habitat unless: (i) they are forced to take it into account by conservation legislation, (2), if it can be shown that the habitat is essential and that loss of habitat would cause a bottleneck in the life history that subsequently leads to a loss of yield. Fisheries management that also achieves habitat management can be realized through a number of different mechanisms. Total exclusion of all fishing effort will achieve habitat conservation provided that there are no other extrinsic factors that negatively affect the habitat (e.g. agricultural run-off from adjacent land masses). Other measures include networks of area closures at different spatial scales that are determined by the demography of the species to be protected. Temporal closures may achieve habitat

preservation if the habitat or species in question have generation times that fall within the time scale of the temporal closure.

The total exclusion of certain forms of fishing activities from areas of the seabed will often lead to opposition from the fishing industry. Nevertheless, a recent large-scale study on the north-west Atlantic coast of North America has demonstrated some potential benefits of large-scale closures. In New England, USA, seasonal closed areas have been an important component of fisheries management since the early 1970s but had little impact on the groundfish stocks that they were designed to protect. In 1994, three large areas that, in total, covered 17 000 km² of the seabed were closed all year to all fishing gears that might retain groundfish (trawls, scallop dredges, hooks, etc.). These closed areas were maintained for 5 years and were found to effectively protect the more sedentary components of the assemblage such as flatfishes, skates and scallops. Although less protection was afforded to cod (*Gadus morhua*) and haddock (*Melanogrammus aeglefinus*), limits on the number of days fished lowered stock-wide mortality rates. The closures also protected important juvenile nursery areas. Scallop dredges were excluded because they took a by-catch of groundfish species. The relaxation of fishing effort on scallops had dramatic effects and led to a 14-fold increase in scallop biomass within the closed areas during 1994–1998 (Fig. 9). A portion of the closed areas was reopened to scallop dredging in 1999 (Murawski *et al.* 2000). The returns of scallops during this period were so encouraging that

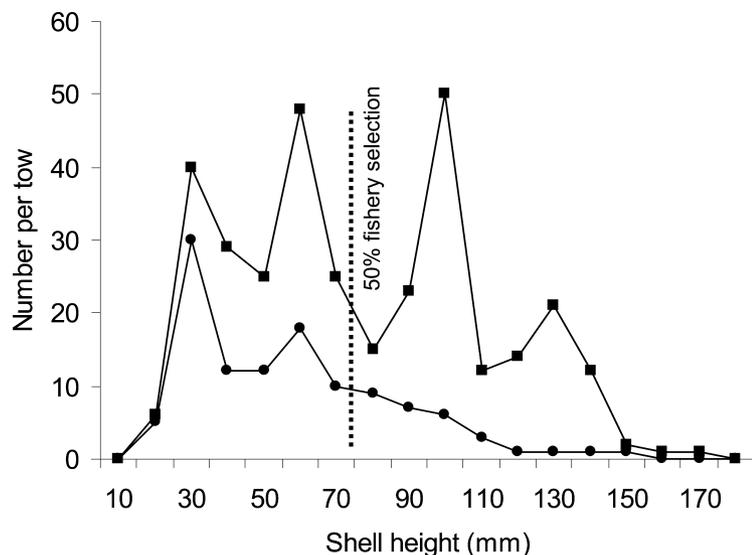


Figure 9 Standardized abundance of sea scallops (numbers per dredge tow) by shell height, taken in the July National Marine Fisheries Service dredge survey on Georges Bank. Data are presented separately for the areas closed (squares) and those open to scallop dredging (circles). Harvestable animals are indicated by the 50% selection line (from Murawski *et al.* 2000).

managers are now contemplating a formal 'area rotation' scheme for this fishery presumably on a time scale of 4–5 years.

Another approach to the protection of habitat is to partition fishing activities. In an inshore fishery off the south coast of England, two commercially important species coexist in the same habitat which has led to conflict between different sectors of the fishing industry. A good example of this situation is when fishers using towed bottom fishing gears (scallop dredges, beam trawls and otter trawls) operate in the same areas where fixed bottom gears (crab pots) are deployed. Kaiser *et al.* (2000b) examined an area subject to a voluntary agreement between these two sectors of the fishing industry such that some areas are used exclusively by fixed gear fishers, some are shared seasonally by both sectors, and others are open to all methods of fishing year round. This agreement was enacted to resolve conflict between the two sectors of the industry. An additional perceived benefit of this agreement was the possible protection of the seabed from towed bottom fishing gear. Kaiser *et al.* (2000b) undertook comparative surveys of the benthic habitat and communities within the area covered by the agreement and compared different areas subjected to a range of fishing disturbance regimes. Communities found within the areas closed to towed fishing gears were significantly different from those open to fishing either permanently or seasonally. Abundance/biomass curves plotted for the benthic fauna demonstrated that the communities within the closed areas had more large-bodied species (Fig. 10). Areas fished by towed gear were dominated by smaller bodied fauna and scavenging taxa.

While it would appear that gear restriction management regimes have the added benefit of conserving habitats, target species and benthic fauna within the management area, it is, at present, not possible to determine whether there are any wider benefits for the fishery that exploits the target species outside the management area.

With sufficient scientific information it should be possible to formulate a regime of fishing effort (i.e. physical disturbance for towed bottom fishing gear) that would be environmentally sustainable. Here, we define environmentally sustainable as the process by which the habitat and its associated biological assemblage can recover before a subsequent disturbance event. For example, in shallow sandy areas of the seabed two to three physical disturbances of the seabed every year may have little or no net effect on the habitat or resident assemblage. However, at present, the definition of sandy areas is too imprecise to allow us to select areas that would respond in the same way to a given management measure. We know, for example, that sand flats that are dominated by tube-building spionid worms take much longer to recover if these worms are removed through physical disturbance as the worms normally have a stabilizing effect on the habitat (Thrush *et al.* 1996).

It is pertinent to ask what we might expect to achieve by protecting certain 'essential' habitats from the standpoint of enhanced fisheries production. In many areas this secondary habitat is patchily distributed, and the question is whether such localized refugia are sufficiently widespread and important to make a difference for the fishery as a whole. This will often be a difficult question to answer. We know, for

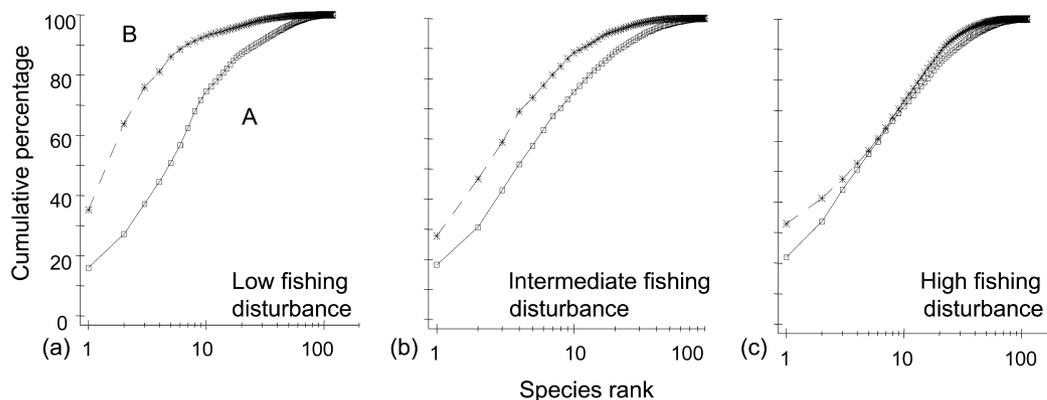


Figure 10 Abundance/biomass curves of samples collected from areas protected from towed bottom fishing gear (low disturbance), areas open seasonally to towed bottom fishing gear and those areas that are fished all year with towed bottom fishing gear (high disturbance). As the level of bottom fishing disturbance increases the biomass curve (B) converges with the abundance curve (A) which is a typical response in stressed communities (adapted from Kaiser *et al.* 2000b).

example, that juvenile cod that occupy the shallow subtidal region around the coasts of Europe and North America benefit from the shelter that algal cover can provide. Yet, the proportion of the total stock which survives and recruits into the fishery, which were afforded this protection is probably quite trivial compared to the numbers that survive from more open areas. On a *per capita* basis then, the margins may be better, but in terms of total contribution they are probably insignificant. When this is so, we might protect the habitat for other reasons, but enhancing fisheries would not be one of them.

Unfortunately, we have the additional question of whether habitats, which we now consider to be devoid of structure, used to afford protection to juveniles (the issue discussed in the previous section returns!). On the north-west shelf of Australia, it seems clear that habitats were rapidly affected by trawling and, as noted above, there is no real basis for supposing that this has not happened elsewhere. It should be recognized, however, that if benefits to a fishery can be shown if habitats are protected or restored, it is likely that those benefits will only be obtainable if alternative to trawling can be developed. Trawling and benthic habitat protection is largely incompatible. The one exception to this, of course, is if benefits accruing in an area closed to fishing spill over into trawled areas.

Future research priorities

With respect to the design of future studies, we feel that experimentalists wishing to address the fishing impacts issue will be best served by abandoning short-term, small-scale pulse experiments. Instead, the scientific community should argue for support to undertake much larger scale press and relaxation experiments. One half of the experiment has already been done because fishing activity has been providing the press for many years what we now require more carefully designed closed area contrasts. There are two principal advantages to this approach. First, the results obtained are clearly interpretable in terms of real world intensities of fishing disturbance. Second, the spatial scale of the protected areas could be relatively small (and hence, replicated to fulfil the requirements for sound experimental design) without compromising unduly the interpretation of recovery dynamics. Estimates of recovery in small protected areas in a sea of disturbance are likely to be conservative, while recovery in small deliberately disturbed patches are not. Third, the experiments

would be conducted in the very habitats (i.e. real fishing grounds) about which the question of recovery is actually being posed. The time has come to try some rotational type of closure system. This would provide the ideal 'experiment' at an appropriately large scale. In addition, we would recommend that any such management regime included a study of the changes in system productivity within these areas. At present, the only justification for funding a suitably replicated 'fishing disturbance' experiment as performed 'ad nausiam' by some of the present authors and others would be within a closure system as described above. This would demonstrate (or not) that you could drive the 'closed' system back to a state similar to areas open to continuous fishing.

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