

Impacts of trawling and scallop dredging on benthic habitats and communities



Cover photograph:

Bottom trawl equipped with rockhopper gear. Courtesy of J.W. Valdemarsen, Institute of Marine Research, Bergen, Norway.

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by
Svein Løkkeborg
Consultant
Fishing Technology Service
FAO Fisheries Department

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Preparation of this document

This study was prepared as part of the FAO Fishery Industries Division's Regular Programme 2.3.3. Fisheries Exploitation and Utilization. It presents a critical evaluation of the methodologies used in impact studies, and uses it to make conclusions about what lessons have been learned to date on how benthic communities are affected by towed-gear fishing activities.

This review focuses on the most recent studies (i.e. those of the last 15 years) to investigate the physical and biological impacts of towed fishing gears on benthic habitats and communities. It covers otter trawls, beam trawls and scallop dredges, but not hydraulic dredging because this activity is very distinctive in terms of both the way it operates (through the direct removal of sediment) and the fishing ground that it affects (the intertidal zone). The report is organized in three main sections: methodologies, physical impacts and biological impacts. Gear type and the nature of the sea bed are two factors that seem to have a great influence on the level of disturbance caused by fishing activity (Collie *et al.*, 2000). Thus, the sections on physical and biological impacts are separated into subsections on gear (otter trawl, beam trawl and scallop dredges) and bottom type (soft bottom and hard bottom with erect structures).

Abstract

Concerns about the impacts of towed fishing gears such as trawls and dredges on benthic habitats and organisms have increased over the last two decades. The reasons for this concern are that benthic habitats provide refuge for juvenile fish, and the associated fauna comprise important food sources for demersal fish. Few general conclusions have been drawn regarding benthic communities' responses to the impacts of trawling disturbances. This lack of knowledge is due to the complexity and natural variability of these communities, and to the fact that it is very difficult and demanding to conduct studies of them. This publication reviews the most recent experimental studies of the impacts of towed fishing gears (trawls and scallop dredges) on benthic communities. Generally, these studies include important caveats owing to limitations in the methodologies applied, and previous reviews have not taken these deficiencies into account. This review presents a critical evaluation of the methodological deficiencies of impact studies, and so interprets the results from these studies with caution.

Trawl impacts are investigated either by conducting experimental trawling and assessing the responses of the benthic community, or by using historical effort data and comparing fishing grounds that are subjected to low and high fishing intensities. The former approach provides exact data on the disturbance regime, but does not replicate real fisheries, whereas the latter method seldom provides suitable control sites. Ideally, the methodology applied in impact studies should have three important features: trawling disturbance at a spatial and temporal scale that is representative of commercial fishing; replicate control sites; and quantitative sampling. The most serious shortcoming in impact studies may be that of confounding effects because of a lack of replicate controls.

Otter trawls, beam trawls and scallop dredges are likely to have different physical impacts on the sea bed owing to their different catching principles. The most noticeable physical effect of otter trawling is the furrows (up to 20 cm deep) created by the doors, whereas other parts of the trawl create only faint marks. Beam trawling and scallop dredging cause a flattening of irregular bottom topography by eliminating natural features such as ripples, bioturbation mounds and faunal tubes.

The most serious biological impacts of otter trawling on hard bottom habitats that are dominated by large sessile fauna were demonstrated when erect organisms such as sponges and corals were shown to decrease considerably in abundance at the passing of the ground gear. Experimental trawling on sandy bottoms of high sea (offshore) fishing grounds caused declines in some taxa. However, such disturbances did not produce large changes in the benthic assemblages, and these habitats may be resistant to trawling owing to natural disturbances and large natural variability. Studies of the impacts of shrimp trawling on clayey-silt bottoms have not demonstrated clear and consistent effects, but potential changes may be masked by the more pronounced temporal variability in these habitats.

The long-term effects of beam trawling and scallop dredging have not been investigated, but several studies provide clear evidence of short-term effects. Intensive disturbance has been shown to cause considerable reductions in the abundance of several benthic species. Trawling disturbance caused no effects in areas exposed to natural disturbances, e.g. wave actions and fluctuations in salinity.

It can be concluded that knowledge of the impacts of towed fishing gear is still rather rudimentary. The difficulty in conducting impact studies that produce clear conclusions results mainly from the complexity and natural variability of benthic communities.

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Introduction

Until recently, concerns about the sustainable exploitation of marine resources focused mainly on proper management of the fish stocks targeted by directed fisheries. During the last two decades, however, growing concerns have been raised about the impacts on the ecosystem in general (Gislason, 1994). Questions about how towed fishing gears such as trawls and dredges may affect benthic habitats and organisms have attracted a great deal of attention, and consequently a large number of investigations addressing this issue have been conducted over the last decade. The reasons for such concern are that complex benthic habitats provide shelter and refuge for juvenile fish, and benthic organisms comprise important food sources (direct or indirect) for demersal fish (Auster *et al.*, 1996; Collie, Escanero and Valentine, 1997).

Concerns about the use of towed fishing gear were raised by fishers as early as the fourteenth century in the United Kingdom, and the sixteenth century in the Netherlands (de Groot, 1984). Complaints concerned the capture of juvenile fish and the detrimental effects on benthic life as a source of food for larger fish. The first scientific impact investigation was conducted on plaice fishing grounds in the North Sea in 1938 (Graham, 1955). Starting in the early 1970s, comprehensive projects on the impacts of towed gears have been carried out by research institutes in countries bordering the North Sea (see de Groot, 1984; Lindeboom and de Groot, 1998; Kaiser and de Groot, 2000). In addition to the North Sea region, impact studies have also concentrated on fishing grounds in the northwestern Atlantic (Grand Banks, Georges Bank), coastal Australia/New Zealand and, more sporadically, the Mediterranean, the Bering Sea/Gulf of Alaska and coastal areas of the United States of America.

Despite the growing number of studies on this issue, few if any general conclusions have yet been drawn on the responses of benthic communities to the impacts of trawling disturbances (Collie *et al.*, 2000). There are three principal reasons for the lack of knowledge in this research field. First, the structure of benthic communities is complex and shows large temporal (both seasonal and annual) and spatial variations. Anthropogenic disturbances may therefore be difficult to demonstrate because they are masked by more dominant natural factors. Second, studies to assess bottom fishing impacts show great variability in terms of gear type and design, disturbance regime, bottom type (e.g. mud versus cobble), level of natural disturbance and benthic assemblages studied. Considerable differences in the types of response to disturbances are therefore to be expected. Third, these studies show large variations in the methodology used and the scientific approach to the problem. These factors reflect the complexity of conducting impact studies,

Owing to their complexity and methodological deficiencies, individual impact studies should be interpreted with caution. This report presents an evaluation of the methodologies used in studies, and accordingly reviews current knowledge of the physical and biological impacts of otter trawls, beam trawls and scallop dredges on benthic habitats and communities.

and show that several requirements have to be met before realistic conclusions can be drawn.

Several publications review experimental impact studies to some extent (e.g. Jennings and Kaiser, 1998; Watling and Norse, 1998; Auster and Langton, 1999; Hall, 1999; Collie *et al.*, 2000), but none has taken into account the important caveats that limitations and shortcomings in the methodologies applied in these studies call for. Thus, the results from impact studies should be interpreted with caution, and the conclusions that can be drawn are often limited by methodological deficiencies.

This review presents a critical evaluation of the methodologies utilized in impact studies, and uses it to make conclusions about what lessons have been learned to date on how benthic communities are affected by towed-gear fishing activities. It shows that most studies are far from fulfilling the criteria of an “ideal study”, which requires analysis over long time scales and comparisons between fished areas and untouched control sites that do not change in other aspects.

Methodologies

EXPERIMENTAL DESIGN – TWO APPROACHES

The effects of trawl fisheries on benthic habitats and communities are investigated by determining changes in physical characteristics and community structure after applied fishing disturbance. Two approaches have been applied to demonstrate such changes. One is to conduct experimental trawling on a site and compare the physical and biological parameters at this site before and after the disturbance and/or with an undisturbed control site (Figure 1). The other approach is based on historical data on effort levels in the commercial fishery and comparison between fishing grounds that are heavily fished and areas that are lightly fished or not fished at all.

The former method (experimental trawling) provides exact data on the disturbance regime, i.e. the intensity and number of periods of trawling disturbance, and makes it possible to study a given intensity of trawling or even to design a study that determines the effects of different levels of trawling intensity (e.g. Eleftheriou and Robertson, 1992; Kaiser *et al.*, 1998; Tuck *et al.*, 1998; Prena *et al.*, 1999; Sanchez *et al.*, 2000).

This method also gives exact information on the location and width of the disturbance zone, and modern navigation and positioning systems make it possible to ensure that the benthic samples have been taken in the path of the trawl, although assigning samples to specific components of the trawl (e.g. trawl doors versus ground gear) is difficult. This is the most widely used method, and adopting this approach ensures that the benthic samples are taken from a disturbed site with a given level of disturbance.

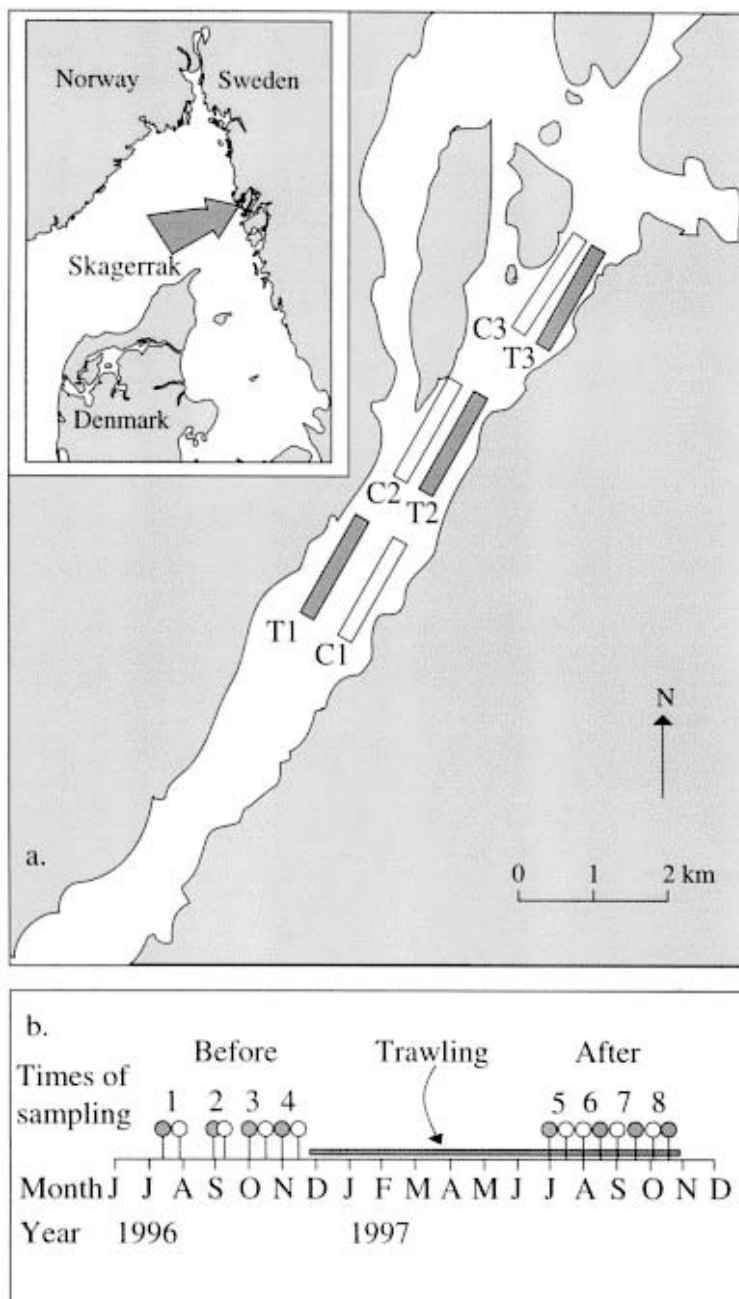
The main problem with this approach is that the temporal and spatial aspects of experimental trawling do not truly reflect the large-scale and long-term disturbances that occur in real fisheries (Kaiser *et al.*, 2000; Jennings *et al.*, 2001). In nearly all studies where this approach has been applied, the experimental trawling has been conducted along narrow corridors (but see Currie and Parry, 1996). Individuals of mobile species that are subjected to trawling disturbance may migrate into or out of the disturbed zone.

Compared with a commercial fishing ground, a narrow disturbance zone may also be more affected by scavengers that emigrate from the surrounding area to

The impacts of towed fishing gears are investigated by comparing physical and biological parameters between sites exposed to experimental trawling and undisturbed control sites, or between commercial fishing grounds that are heavily and those that are lightly fished.

Experimental trawling provides exact data on the disturbance regime and ensures that biological sampling is taken from the disturbed site. However, this approach does not replicate the spatial and temporal scale of real fisheries.

FIGURE 1
Experimental design of the trawl impact study conducted in the Gullmarsfjord (Sweden)



Three trawled and three control sites were compared (a). Samples were taken over a four-month period prior to experimental trawling and for four months after the trawling period (b).
Source: Redrawn after Lindegarth *et al.*, 2000b.

feed on prey that has been damaged or exposed on the sea bed by the trawling activity (see Kaiser and Spencer, 1994; Ramsay, Kaiser and Hughes, 1998). Furthermore, experimental trawling is normally completed within a short period of a few hours or days, and only in a few studies was the trawling operation repeated regularly over a period of several months to one year (Tuck *et al.*, 1998; Hansson *et al.*, 2000; Lindegarth *et al.*, 2000a). Although commercial trawlers may fish on a fishing ground for only a short period (as in experimental trawling), most areas fished by trawl are subjected to repeated fishing activity through successive seasons. Therefore most studies using this approach show only the immediate effects of short-term trawling. Some studies, however, also included sampling over a longer period after the trawling disturbance to assess the recovery of affected biota (Van Dolah, Wendt and Nicholson, 1987; Currie and Parry, 1996; Kaiser *et al.*, 1998; Tuck *et al.*, 1998; Kenchington *et al.*, 2001).

Impact studies based on historical data from commercial trawling effort do not have these shortcomings. Benthic samples taken from traditional fishing grounds should reflect the disturbance imposed by commercial fishing. However, effort data do not give a detailed description of the spatial distribution of trawling disturbance, because such data are grouped in blocks of relatively large statistical areas. In the North Sea for example, trawling data are collected by the International Council for the Exploration of the Sea's (ICES') statistical rectangles (0.5° latitude x 1° longitude, i.e. about 3 500 km²), and trawling effort is shown to be very patchy within these large blocks (Rijnsdorp *et al.*, 1998). The beam trawl efforts within a 1 442 km² block in the North Sea were shown to vary by a 27-fold range among smaller grids of 103 km² (Jennings *et al.*, 2001).

Thus the actual level of trawling disturbance in the areas sampled is not known in studies that use historical effort data because there will be patches of low effort within high-effort rectangles, and vice versa. In addition, various trawl types are used in commercial fisheries, and the type and configuration of the gear that may have caused trawling disturbance are therefore also unknown. For example, the impacts demonstrated in studies conducted in the Irish Sea and the Georges Bank could have been caused by disturbance from scallop dredges, beam trawls, otter trawls or a combination of these (see Auster *et al.*, 1996; Kaiser *et al.*, 1996; 2000; Collie, Escanero and Valentine, 1997; Collie *et al.*, 2000; Hill *et al.*, 1999). Another weakness of studies based on historical effort data is that neighbouring untouched areas that are suitable as control sites seldom exist (see following section) (but see Van Dolah, Wendt and Levisen., 1991; Simboura *et al.*, 1998; McConnaughey, Mier and Dew, 2000; Smith, Papadopolou and Diliberto, 2000), and comparison with reference samples taken prior to any commercial fishing activity (if available) may introduce confounding effects owing to natural long-term changes in community structure (Frid, Clark and Hall, 1999; Hill *et al.*, 1999). The properties of impact studies based on experimental trawling and historical data are summarized in Table 1.

Impact studies based on historical effort data reflect disturbances imposed by commercial fishing, but the actual intensity of disturbance is not known and suitable control sites seldom exist.

TABLE 1

Advantages and disadvantages of the experimental trawling and historical data approaches used to investigate the impacts of towed fishing gears

Properties	Experimental trawling	Historical data
Data on disturbance regime	Yes	No
Exact location and size of disturbed area	Yes	No
Description of gear type	Yes	Seldom
Reflect commercial fisheries	No	Yes
Suitable control sites	Often	Seldom
Affected by migration of mobile species	Yes	No

CONTROL SITES

Studying the effects of mobile fishing gear on benthic communities involves comparing ecological parameters before and after trawling and/or between disturbed (trawled) and undisturbed (control) sites (Figure 1). As the abundance of benthic organisms may change naturally, to test hypotheses about the impacts of fishing activities it is necessary to compare the magnitude of temporal changes in fished areas with changes in an undisturbed control area (Stewart-Oaten, Murdoch and Parker, 1986; Underwood, 1992; Lindegarth *et al.*, 2000b).

Experiments without replication at the appropriate spatial scale run the risk of overestimating the effects of trawling disturbance. The most serious shortcoming in impact studies may therefore be the confounding of effects owing to lack of replicate control sites.

Several experiments on trawling disturbance have involved comparison between a single treatment site and a single control site (e.g. Van Dolah, Wendt and Levisen, 1991; Currie and Parry, 1996; Tuck *et al.*, 1998; Frid, Clark and Hall, 1999). This experimental design lacks independent replicates of the treatments, and is therefore only suitable to demonstrate differences between locations (Hurlbert, 1984). Differences in temporal changes found between the disturbed (trawled) site and the control site during these studies

have been interpreted as the effects of trawling. Such conclusions cannot, however, be justified unless more than one control site is monitored (Underwood, 1992; Lindegarth *et al.*, 2000b).

Experiments without replication at the appropriate spatial scale are spatially confused, and run the risk of overestimating the effects of physical disturbance (Hansson *et al.*, 2000; Drabsch, Tanner and Connell, 2001). Furthermore, in order to evaluate the severity of the effects of trawling, the magnitude of the effects should be related to natural temporal and spatial variability in the ecological parameters analysed, and to the effects caused by natural disturbances such as wave action and strong currents. Such comparisons also require replicates at appropriate temporal and spatial scales.

Lindegarth *et al.* (2000b) used data from an experiment involving three pairs of disturbed and control sites to explore the problem of interpreting results from experiments using a single treatment and control site. This was achieved by comparing conclusions from analyses of the whole experiment (i.e. all six sites)

with those of analyses based on pairs of sites (see Figure 1). Analyses based on the whole experiment did not reveal changes that could be attributed to trawling disturbance, whereas analyses of pairs of sites showed a large number of significant differences, both between pairs of trawled and control sites and between pairs of control sites. The authors concluded that the impacts of trawling could not have been assessed in a useful way had this experiment involved only one trawled and one control site. They also stated that insufficient replication has potentially large consequences on the interpretation of other experiments, although experiments on the short-term effects of disturbance may be less affected by this type of confounding. The most serious and widespread shortcoming in impact studies may thus be confounding effects owing to a lack of replicate control sites.

This confounding problem is caused by natural temporal and spatial variability in benthic communities, and the control area should therefore resemble as closely as possible the disturbed area in terms of depth, current conditions, sediment type and benthic assemblage. However, potential control areas are often unfished precisely because they differ from real fishing grounds, thus interpretation may be difficult. Fortunately there are exceptions where areas have been closed to fishing for military reasons, to protect juveniles and non-target species, or to rebuild depleted stocks (Tuck *et al.*, 1998; Prena *et al.*, 1999; Lindegarth *et al.*, 2000a; Drabsch, Tanner and Connell, 2001; Kutti *et al.*, in press). Comparing disturbed and control sites within such closed areas would be the ideal situation for the experimental trawling approach.

Some studies adopted the approach of using wreck sites as control areas based on the fact that trawlers are likely to avoid fishing in the close vicinity of shipwrecks because such obstacles can cause gear damage (Hall *et al.*, 1993; Ball, Fox and Munday, 2000; Pranovi *et al.*, 2000). Although the benthic community nearest to a wreck should therefore be in a relatively undisturbed state, these sites may act as artificial reefs. The comprehensive literature on the effects of artificial reef habitats on community structures and fish assemblages clearly demonstrates that the benthic fauna of wreck sites differs from that of surrounding areas (Bohnsack and Sutherland, 1985; Seaman and Sprague, 1991).

Interpretation of results from studies using the wreck approach is therefore difficult owing to the likelihood of confounding effects associated with the wreck itself. An additional flaw in studies adopting the wreck approach is the lack of fishing effort data at a sufficiently high level of spatial resolution from the area surrounding the wreck (Hall *et al.*, 1993). Thus, when effects cannot be detected, no conclusion can be drawn about the effects of fishing and, on the other hand, when effects are demonstrated, they cannot conclusively be related to fishing disturbance.

INSTRUMENTATION FOR BOTTOM CHARACTERIZATION

In order to identify appropriate areas for an impact study and to ensure that the disturbed and control sites are of similar habitat type, proper methods and tools are needed. Many devices for bottom classification and identification are

Studies that do not use sea bed classification tools of different spatial resolution run the risk of comparing sites with natural variability in community structure, which could be misinterpreted as trawling impacts.

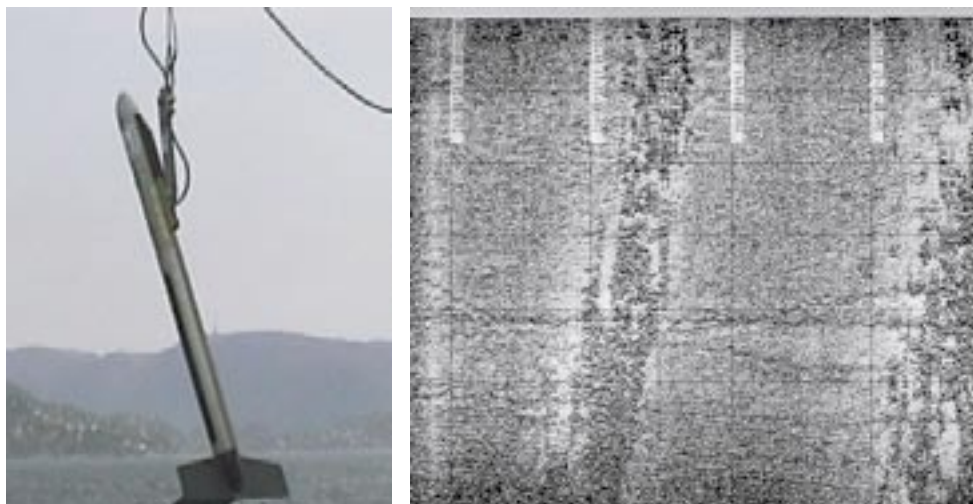
available, and the performance of several of these tools is evaluated by Humborstad *et al.*, 2004. The authors concluded that single tools, which are used in most studies, cannot provide a decisive basis for locating appropriate experimental sites. They suggest applying an acoustic sea bed classification system (e.g. RoxAnn) for broad-scale and rapid mapping, a medium-scale tool (side-scan sonar) for identifying smaller topographic relief (Figure 2) and fine-scale

observation (video camera, sledge or grab) for ground truthing and detailing the characterization of sediment type. Studies that do not use several tools for bottom characterization do not provide a proper description of the area studied, and run the risk of comparing sites with natural variability in community structure, which could be misinterpreted as trawling impacts.

This combination of observation platforms of different spatial resolution also provides valuable data for assessing the physical impacts of trawling (Humborstad *et al.*, 2004). The acoustic bottom classification system RoxAnn provides real-time characterization of the sea bed based on its hardness and roughness.

This system has been used in several impact studies (e.g. Kaiser and Spencer, 1996; Schwinghamer *et al.*, 1998; Tuck *et al.*, 1998; Humborstad *et al.*, 2004), but its performance for sea bed mapping and classification has been reported to be relatively crude (Greenstreet *et al.*, 1997; Hamilton, Mulhearn and Poeckert, 1999). Schwinghamer, Guigné and Siu (1996) used a sophisticated method based

FIGURE 2
Side-scan sonar (left) and sonogram (right) showing a sandy/gravel sea bed with two ridges of stones



on high resolution and broadband acoustics to determine trawl disturbance on the small-scale structural properties of the upper 4.5 cm of bottom sediments.

Side-scan sonars have been widely used to demonstrate physical disturbances caused by trawling (e.g. Schwinghamer *et al.*, 1998; Thrush *et al.*, 1998; Tuck *et al.*, 1998; Humborstad *et al.*, 2004). Trawl doors create furrows in muddy and sandy sediments that are readily seen on side-scan sonograms. Although marks made by ground gear have been observed by this method (Humborstad *et al.*, 2004), only relatively deep (several centimetres) furrows and marks can be recognized from side-scan recordings, owing to their limited resolution. This method is therefore suitable mainly to demonstrate the extent and longevity of the physical disturbances caused by heavy gears such as trawl doors, large dredges and beam trawls. Friedlander *et al.* (1999) demonstrated that side-scan images also present a promising independent approach for identifying the location of trawling activity and for evaluating fishing effort on a spatial scale that is consistent with commercial fishing activities.

Underwater cameras may provide more detailed observations to demonstrate physical disturbances from small trawls or the lighter parts of a gear that do not cause deep furrows. Marks on the sea bed made by trawl doors, wires, ground ropes and nets were evident from video observations in the Mediterranean (Smith, Papadopoulou and Diliberto, 2000). Fresh and older marks could be differentiated from the shape of their edges and their colour. Evidence of the resuspension of sediments, i.e. turbidity clouds, was also obtained from these observations. Freese *et al.* (1999) used video observations to quantify the proportion of boulders displaced by the ground rope. Thus, the use of underwater cameras may provide valuable observations on how different parts of the trawl interact with the sea bed.

SAMPLING TOOLS

Five different types of device have been used to sample benthic fauna for assessing the biological impacts of trawling disturbance: grab, corer, dredge, beam trawl and camera. Grabs and corers are appropriate sampling tools for bottom sediments ranging from mud and silt to coarse sand and small stones (pebbles), but not for hard-packed sandy bottoms or coarse bottoms with cobbles. Grab and core sampling is the most quantitative method, as the size of the area sampled is determined by their opening and thus can be identified very accurately. These two sampling methods have been used in most of the impact studies carried out to date. However, large numbers of samples are required, as the area sampled is small, e.g. 0.07 m² for boxcorers, 0.2 m² for van Veen grabs, and occasionally up to 0.5 m² for large grabs (Bergman and van Santbrink, 1994; Kenchington *et al.*, 2001). Consequently, these methods are not suitable for sampling benthic fauna with patchy distribution and low abundance.

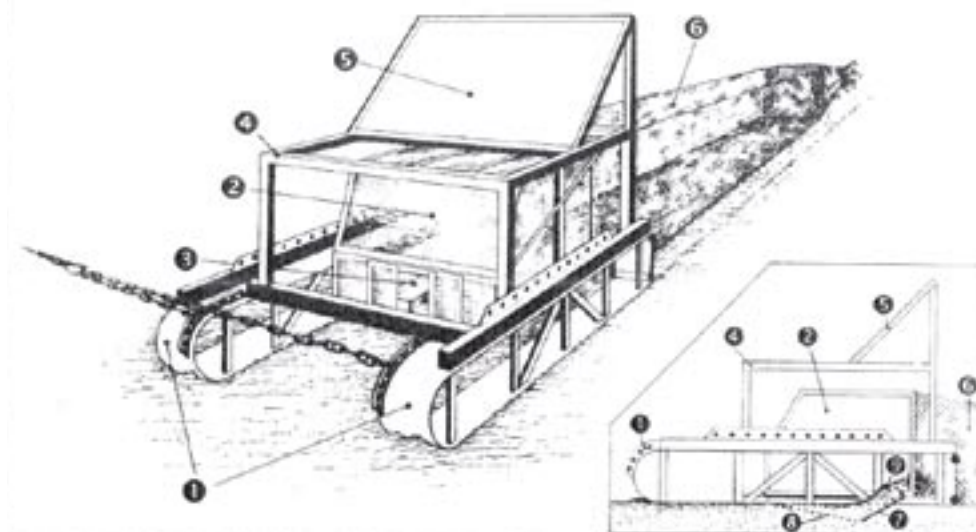
Grabs and cores provide quantitative samples, but are not suitable for patchy distributed fauna of low abundance. The semi-quantitative dredge sampling method has been improved specifically for the purposes of impact studies. Cameras are the only sampling method used on rough bottoms (cobbles, boulders).

A video-equipped hydraulic grab has been specially designed for sampling offshore dense sand beds (Schwinghamer, Guigné and Siu, 1996; Kenchington *et al.*, 2001). This grab is lowered gently to rest on the sediment, and the jaws are then closed hydraulically under video observation. In order to assess the impacts on both infaunal species and more sparsely distributed epibenthic species, grabs have been used in combination with dredges in several studies (Simboura *et al.*, 1998; Currie and Parry, 1999; Prena *et al.*, 1999; Kenchington *et al.*, 2001).

Dredges and beam trawls, which can be used on similar bottom types as grabs and corers, are more appropriate for estimating the densities of low-abundance benthic species because they cover much larger areas (up to several hundred square metres). Most types of these sampling gears are, at best, semi-quantitative owing to the problem of estimating the area sampled accurately (Holme and McIntyre, 1984).

The dredge sampling method has undergone several modifications to overcome the problem of determining the time that the gear is in contact with the bottom and the length of the tow, e.g. the odometer wheel (Prena *et al.*, 1999) and combining integrated trawl instrumentation (ITI) positioning data and video observations (Kutti *et al.*, in press). In addition, quantitative dredges have been developed for the specific purpose of trawl impact studies (Figure 3; Bergman and van Santbrink, 1994; Prena *et al.*, 1999).

FIGURE 3
Dredge for obtaining quantitative samples in trawl impact studies



1 = runners; 2 = cage; 3 = opening in the front panel to catch epifauna; 4 = steel bars to protect the cage; 5 = depressor; 6 = net; 7 = cutting blade; 8 (dotted line) = front edge of vertical strips, mounted on both sides of the cutting blade; 9 = sediment entering the net.

Source: Redrawn after Bergman and Santbrink, 1994.

Sampling by dredges can be further improved through monitoring the performance of the sledge hauls with a video camera (Prena *et al.*, 1999; Kutti *et al.*, in press). With this improvement, the sampling of rougher bottom is possible because tows of dubious quality can be aborted and repeated (Humborstad *et al.*, 2004).

Observations from video and photo cameras are the only method that has been used to sample coarse sea beds of cobbles and boulders. However, the type and size of organisms that can be studied using this method are very limited.

Only those species that are easily visible and identifiable on photographs or a video monitor (e.g. > 5 cm and > 20 cm in size, respectively) could be quantified for statistical analyses in the studies by Freese *et al.* (1999) and Moran and Stephenson (2000). Even the identification of species of large organisms (e.g. sponges) may be problematic from camera images. Quantitative analyses based on this sampling technique require reference points to determine the width of the camera image, i.e. the size of the area sampled (see Thrush *et al.*, 1998; Freese *et al.*, 1999; Moran and Stephenson, 2000). Sampling based on camera observations has the advantage that visible marks made by the gear ensure that the samples are taken within the trawl path and not in untouched corridors between adjacent paths.

Studies using grab, core, dredge or beam trawl require accurate positioning of the sampling device. In studies based on disturbance from experimental trawling, the corridors trawled are often very narrow (100 to 200 m) and there is a risk of sampling outside the disturbed area. In particular when operating in deep water and under strong currents, accurate positioning of the sampling tool is crucial. Accurate positioning of the trawl is also of great importance, because the position of the trawl relative to the vessel has been shown to vary greatly among and even within trawl hauls (Engås *et al.*, 2000).

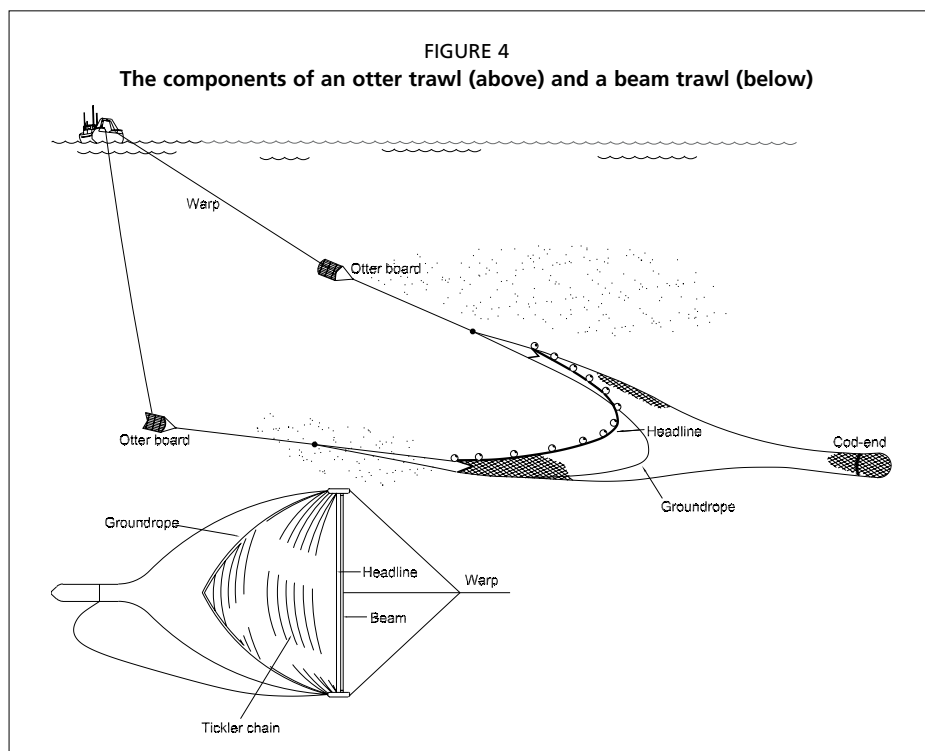
In studies where the disturbed area is trawled several times, positioning of the trawl is needed in order to determine the level of disturbance. Different types of systems have been applied to provide positioning data for sampling devices and trawls (e.g. Prena *et al.*, 1999; Humborstad *et al.*, 2004).

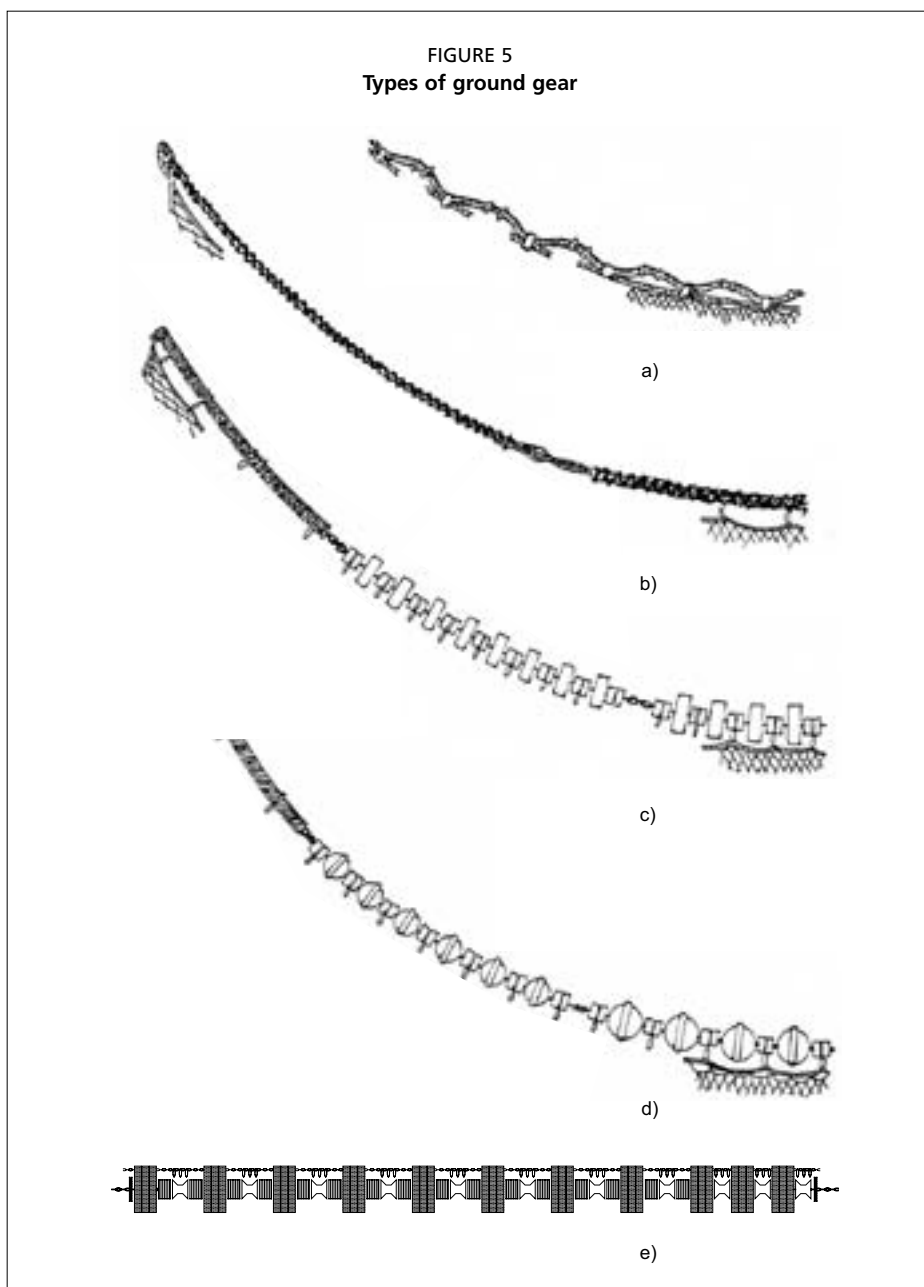
Physical impacts

THE CATCHING PRINCIPLES OF TRAWLS AND DREDGES

The catching principle of otter trawls is different from that of beam trawls and scallop dredges (Figure 4). Demersal otter trawls are designed to catch fish and shrimps that stay above the sea bed, from close to the bottom to several metres from the bottom. Beam trawls and scallop dredges, on the other hand, are used to target species that stay on the bottom or that are partly buried in the sediment. Accordingly, the tickler chains of a beam trawl and the teeth of a dredge are specifically designed to disturb the sea bed surface and penetrate the upper few centimetres of the sediment. Chains and teeth, respectively, are mounted along the whole width of the two gears (beam trawl: 4 to 12 m, scallop dredge: 0.75 to 3 m).

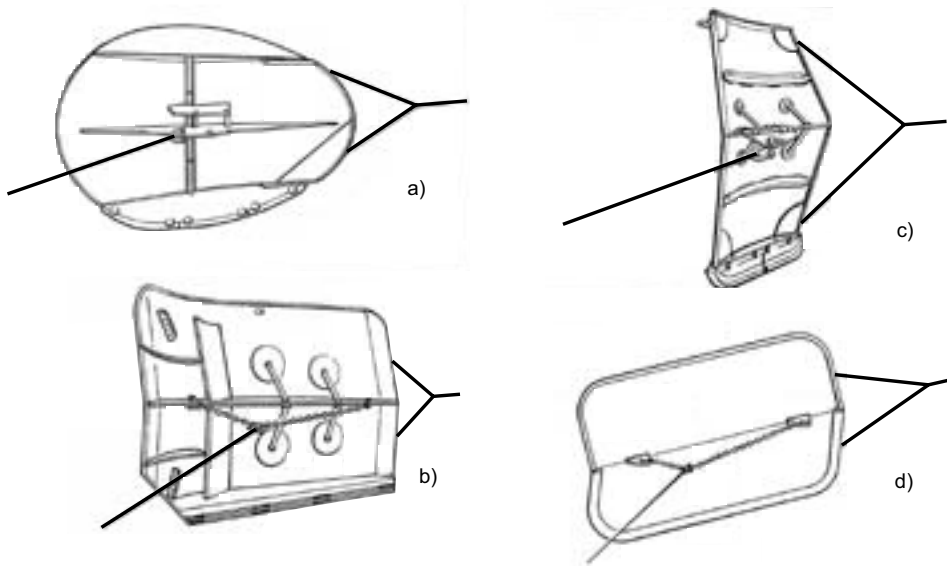
Because of their different catching principles, otter trawls, beam trawls and scallop dredges are likely to have different physical impacts on the sea bed. Unfortunately, most impact studies give an inadequate description of the gear used to impose disturbances.





Otter trawls are rigged with different types of ground gears (e.g. bobbins, rockhoppers) depending on the bottom type fished and the species targeted (Figure 5). The functions of the ground gear are to ensure close contact with the bottom and to enable fishing on rough bottoms without damage to the trawl net. When targeting flatfish, a chain may be used as ground gear to chase the fish off the bottom. The trawl doors keep the trawl mouth spread open laterally and

FIGURE 6
Types of trawl doors



a = Morgère polyvalent oval; b = Thyborøn type 2 125"; c = Morgère W vertical; d = standard V-door.

Source: Redrawn after Anonymous, 1993.

create the sand clouds that herd fish into the opening of the net (Figure 6). The creation of the sand cloud and, for some types of doors, the spreading force are the only reasons why part (i.e. the doors) of the otter trawl needs to penetrate into the sediment. Other parts, such as the warps, sweeps and net, do not normally remain in continuous contact with the sea bed. Owing to their different catching principles, otter trawls are likely to have different physical impacts on the sea bed from those of beam trawls and scallop dredges.

Furthermore, there are considerable variations in size and weight among trawls, beam trawls and scallop dredges, and their levels of impact are likely to vary according to these. It is obvious that a groundfish otter trawl with 2 300 kg doors, 140 m door spread and 53 cm diameter rockhopper gear (Kutti *et al.*, in press) will cause different disturbances from those of a shrimp trawl with 125 kg doors, 30 m door spread and 4 cm diameter ground rope with 250 g lead rings (Hansson *et al.*, 2000). The gear, in particular the parts that are in contact with the sea bed (doors, ground gear, tickler chain, sole plates, teeth), should therefore be properly described in order to interpret the effects on the sea bed and the response of the benthic assemblages studied. Unfortunately, most impact studies give poor and inadequate descriptions of the trawls used to cause the benthic disturbances.

PHYSICAL IMPACTS OF OTTER TRAWLS

Several studies on the effects of otter trawling on benthic communities describe physical disturbances of the sea bed. On a sandy bottom of the Grand Banks of Newfoundland (Canada), intensive trawling (300 to 600 percent coverage, i.e. a given site on the sea bed was trawled on average three to six times) had an immediate effect on the topography of the sediment surface owing to berms and furrows created by the trawl doors, which were readily seen by side-scan sonar and video observations (Schwinghamer *et al.*, 1998). RoxAnn data also showed changes in sediment surface characteristics in that repeated trawling over the same bottom increased surface relief or roughness, but did not affect sediment texture

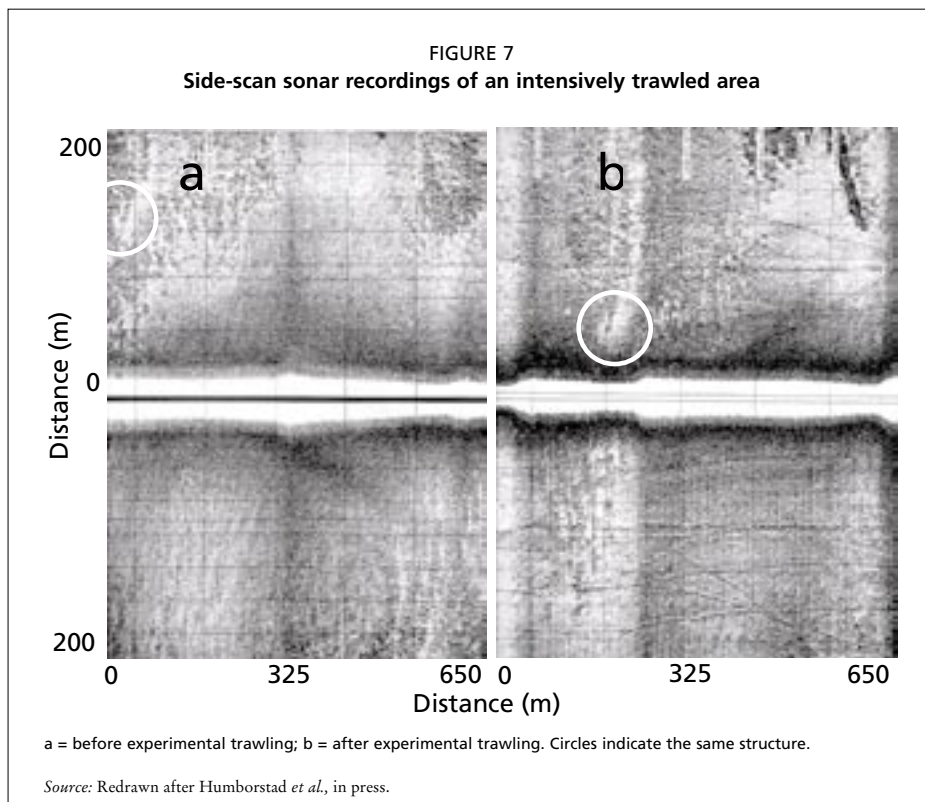
Trawl doors may cause furrows of up to 20 cm deep depending on the door weight and the hardness of the sediment. Such marks are likely to last longer in sheltered areas with fine sediments.

(hardness). Changes in the acoustic properties of the upper 4.5 cm of sediment suggested decreased habitat complexity through the destruction of biogenic structures such as tubes and burrows (Schwinghamer, Guigné and Siu, 1996). These observations indicated that the physical habitat recovered from trawling disturbance within one year. However, it is important to note that significant interannual changes were also observed in the acoustic properties of the sediment that could not be attributed to trawling disturbances.

Side-scan and video recordings of a sandy/gravel bottom in the Barents Sea also showed physical disturbance from trawling, with highly visible furrows (10 cm deep and 20 cm wide) and berms (10 cm high) caused by the doors and smaller depressions created by the rockhopper gear (Humborstad *et al.*, 2004; Figure 7). Five months later these marks had disappeared. RoxAnn data showed that intensive trawling (700 percent coverage) caused a decrease in sediment hardness and a slight increase in surface roughness, whereas moderate trawling (230 percent coverage) did not cause changes in these properties of the sediment. As was the study on the Grand Banks, this investigation was conducted on a high-seas fishing ground exposed to strong currents.

Tuck *et al.* (1998) conducted a trawl disturbance study in a sheltered Scottish loch (United Kingdom). Side-scan recordings showed clear evidence of physical disturbance from tracks left by the trawl doors. These tracks were still seen 18 months after the trawling treatment had ended, although they were very faint by this time. RoxAnn measurements also showed changes in sea bed topography, in that surface roughness increased in the trawled area. This effect of trawling had recovered after six months. The RoxAnn data showed no effect on sediment hardness.

Physical disturbances caused by flounder trawling on a macrotidal habitat in the Bay of Fundy (Nova Scotia, Canada) were assessed by eye when the trawl tracks were exposed at low tide (Brylinsky, Gibson and Gordon Jr., 1994). The trawl doors scoured furrows of 30 to 85 cm wide and 1 to 5 cm deep, which persisted for two to seven months. Less pronounced marks (10 cm wide) were made by each of the rollers of the ground rope, whereas the bridles left no visible marks. About 12 percent of the area between the outer edges of the doors was visibly disturbed, i.e. by the two doors and the ground gear.



Other experiments have also demonstrated clear marks created by the trawl doors, but do not give more detailed information on the physical disturbances than those already described. An experiment conducted on the Spanish Mediterranean coast showed evidence of marks left by the trawl doors, but no additional mark that could be attributed to the ground gear or the net (Sanchez *et al.*, 2000). Video observations from another Mediterranean study demonstrated scrape marks on the sea bed made by the trawl doors and wires, as well as a general flattening of the micro-topography caused by the nets and ground ropes (Smith, Papadopolou and Diliberto, 2000). Marks persisted throughout the closed fishing season of four months.

The physical interaction of trawl doors with the sea bed has been simulated in a test tank in order to examine closely the physical disturbance, the biological damage and the forces generated by scouring trawl doors (Gilkinson *et al.*, 1998). A full-scale door model towed at a pre-set sediment depth (2 cm) created a shallow furrow bordered by a single 55-mm high berm on the inner edge of the scour. Bivalves that were originally buried in the scour path were displaced to the berm and, in two replicates, 58 and 70 percent of displaced specimens were completely or partially exposed on the surface. Of a total of 42 specimens in the scouring zone, only two showed major damage, although all specimens had been displaced. This low incidence of damage to bivalves was explained by a buffer effect in which

small bivalves were mixed with sediment, excavated and then displaced into the berm bordering the scouring furrow. The authors stated that bivalves may suffer higher levels of damage on coarser and less smooth sea beds.

The works cited were all conducted on soft muddy or sandy bottoms. Video observations from a research submersible were used to assess trawling disturbance on a hard bottom (pebble, cobble, boulder) habitat of the continental shelf in the Gulf of Alaska (Freese *et al.*, 1999). The dominant substrate type was pebble (< 6.5 cm), averaging 93 percent of the total substrate. Observations were made in the path of the 60-cm-diameter tyre gear of an otter trawl. The path was visible as a dark band on compact substrate, and as a series of furrows on less compact substrate. The depth of the furrows caused by the tyre gear ranged from 1 to 8 cm. The trawl gear displaced 19 percent of the large boulders (> 75 cm) in its path.

In conclusion, marks on the sea bed from one or more parts of the trawl have been demonstrated in all studies using acoustic (side-scan sonar) or visual (cameras) tools for sea bed assessment. Most studies were conducted on soft or sandy bottoms. These observations show that the most noticeable marks are those caused by the doors, and only faint marks are created by other parts of the trawl. Trawl door marks have been shown to be from 1 to 5 cm deep (Brylinski, Gibson and Gordon Jr., 1994), but may reach about 20 cm in certain parts of the tracks (Krost *et al.*, 1990). The penetration depth depends on the weight and performance of the doors (type, angle of attack, speed) and on sediment grain size and hardness, being deeper in mud than in sand (Churchill, 1989; Krost *et al.*, 1990; Tuck *et al.*, 1998).

Data on the persistence of trawl marks in different environments are relatively scarce because only immediate physical effects are observed in most studies owing to their relatively short time frames. Trawl door marks were shown to disappear within less than five months in an area of strong currents in the Barents Sea (Humborstad *et al.*, 2004). In a sheltered Scottish loch, however, faint marks could still be seen 18 months after the trawling treatment (Tuck *et al.*, 1998), and the same trawl track could be identified for almost five years in a sandy mud area in Kiel Bay that is not exposed to tidal currents (Bernhard, 1989, cited in Krost *et al.*, 1990). The persistence of marks produced by trawl doors depends on their original depth, the sediment type, the current, wave action and biological activity (Tuck *et al.*, 1998; Fonteyne, 2000; Smith, Papadopoulou and Diliberto, 2000; Humborstad *et al.*, 2004). Scouring marks are likely to last longer in deep water and in sheltered areas with fine sediments (Tuck *et al.*, 1998).

PHYSICAL IMPACTS OF BEAM TRAWLS AND DREDGES

The North Sea is intensively trawled by beam trawls, and certain fishing grounds are fished many times a year (Rijnsdorp *et al.*, 1998). The physical impacts of beam trawling were studied in an area with hard, sandy sediments in the southern North Sea (Bergman and Hup, 1992). The penetration depth of the tickler chains of a heavy 12-m beam trawl was estimated by comparing the catches of the heart urchin with its length-dependent depth preference. The beam trawl was shown to

catch large individuals of heart urchin, which indicated that the tickler chains penetrated at least 6 cm into the sediment. Tracks of the beam trawl shoes were still detectable by side-scan sonar after 16 hours, but their actual penetration depth could not be established.

In another North Sea study conducted on the Flemish Banks (Belgium coast) and off the Netherlands

coast, the impacts of a 4-m beam trawl were investigated at sites consisting mainly of fine and medium sand (Fonteyne, 2000). Side-scan sonar observations showed clear marks immediately after trawling. The traces were too weak to determine the depth of penetration, indicating that this was not great. Side-scan observations were made several times during the 52 hours after trawling. Over this period the visibility of the trawl marks decreased gradually, and eventually they could be seen only as vague marks along parts of the original tracks. RoxAnn surveys showed that the sea bed roughness decreased and the hardness increased immediately after trawling owing to resuspension of the lighter sediment fraction. These sea bed characteristics returned to their original levels in less than 15 hours. The force exerted by a beam trawl on the bottom was also determined in this study, and found to be similar for heavy and light trawls. This similarity was explained by the fact that larger beam trawls have larger sole plates and are towed at higher speeds.

Boxcore sampling has been used in various sectors of the North Sea to determine the penetration depth of the tickler chains of beam trawls (Paschen, Richter and Köpnick, 2000). These observations showed a “wavy” penetration varying between 1 and 8 cm in depth. This pattern was explained by the heave motion of the vessel. The deepest penetration depth was measured in an area with softer sediments of finer muddy sand compared with the other areas studied, which were of fine to coarse sand.

The Irish Sea is also intensively trawled by beam trawls (Kaiser *et al.*, 1996) and, as in the North Sea, there are few undisturbed areas suitable as control sites for impact studies. The physical impacts of beam trawling were investigated in an area of Liverpool Bay characterized by mobile mega-ripples in one part and by stable sediments with uniform topography in another (Kaiser and Spencer, 1996). RoxAnn measurements indicated that the sediment was less hard in corridors that were experimentally trawled than in adjacent unfished areas. In the part of the area with surface ripples and sand waves, the surface roughness was lower in fished corridors, probably owing to flattening of the ripples by the beam trawl.

Divers observed the effects of scallop dredging in an exposed bay of a Scottish loch (Eleftheriou and Robertson, 1992). Examination after each of several dredge treatments showed significant physical disturbance, indicated by furrows, elimination of natural bottom features (ripples and irregular topography) and dislodgement of shell fragments and small stones. The furrows were eliminated by wave and tidal actions shortly after the dredging operations. Similar observations were made by divers on a sandy sea bed in New Zealand (Thrush *et al.*, 1995). The

The most noticeable physical effect of beam trawling and scallop dredging is a flattening of irregular bottom topography and the elimination of bioturbation mounds and faunal tubes.

dredge broke down surface features (e.g. emergent faunal tubes, ripples), and its teeth (10 cm long) created grooves 2 to 3 cm deep.

The recovery of the physical impacts of scallop dredging was determined by Currie and Parry (1996) in Port Phillip Bay, Australia. Prior to dredging, the sea bed was dominated by low-relief mounds formed by callianassids (shrimp). Observations made by divers eight days after dredging showed that the mounds were flattened. The dredge typically disturbed the top 2 cm of sediment, but could penetrate up to 6 cm. Most callianassids appeared to have survived, and their density taken in grabs did not change significantly during the three months following dredging. Dredge tracks were still visible and the sea bed remained flat one month after dredging. Six months later the tracks had disappeared and callianassid mounds were abundant. After 11 months, the topography of the dredged site appeared similar to that of the adjacent control site.

Video observations were used to determine the effects of a Rapido trawl (resembling a toothed beam trawl) on sandy sediments in the Adriatic Sea of the Mediterranean (Hall-Spencer *et al.*, 1999). The teeth of the trawl projected their full 2 cm length into the sediments and redistributed the surface layer. Observations taken one hour after trawling revealed extensive sediment redistribution with suspended particles reducing visibility 1 m above the sea bed from > 20 m (pre-trawling) to near zero. Disturbed sediment had settled 15 hours after fishing. Tracks of the Rapido trawl were seen as strips of flattened sediment that lacked evidence of bioturbation mounds or polychaete tubes, and were littered with smashed shells of crustaceans, bivalves and animal fragments.

A Rapido trawl rigged with 5 to 7 cm-long teeth caused disturbance of organic debris in the upper 6 cm of core samples (Pranovi *et al.*, 2000). Side-scan sonar observations conducted one week after trawling showed trawl tracks. Diving observations showed that the trawl did not produce a clear furrow, but rather a flattened track with a small heap of sediment along its sides. Dead and damaged organisms and active scavengers (hermit crabs, brittle stars and gastropods) were also observed.

The studies reviewed here show that the most noticeable physical effect of beam trawling and scallop dredging is a flattening of irregular bottom topography by eliminating natural features such as ripples, bioturbation mounds and faunal tubes. The penetration depth of the tickler chain of beam trawls and the teeth of scallop dredges range from a few centimetres to at least 8 cm. Because few observations have been carried out on these marks beyond a few hours after trawling disturbance, confident conclusions on their persistence cannot be drawn. However, the scarce data reported indicate that the persistence of beam trawl and dredge marks varies from a few days in tidally exposed areas of the North Sea to a few months in an Australian bay (Currie and Parry, 1996; Fonteyne, 2000).

Biological impacts

An overview of the impact studies included in this review is given in Tables 2 to 4. The following section on otter trawling on soft bottom habitats is organized as follows: high seas (offshore) fishing grounds, shrimp and *Nephrops* trawling, and studies in the Mediterranean. These three groupings represent different types of fisheries and habitats in which similar and comparable studies have been conducted.

OTTER TRAWLING ON SOFT BOTTOM HABITATS

One of the most comprehensive experiments on the impacts of otter trawling is the three-year study conducted on the Grand Banks of Newfoundland (Prena *et al.*, 1999; Kenchington *et al.*, 2001). The northeastern part of this fishing ground has a rich, diverse and homogeneous benthic community and a bottom habitat that is representative of large areas off the coast of Atlantic Canada. Fishing effort records indicate that this location had not been fished since the early 1980s, and the region was closed to all fishing activity in 1992 as a result of the collapse of the groundfish stocks (Kenchington *et al.*, 2001), so this site fulfils several important requirements of an impact study. Three experimental corridors with parallel reference corridors were established. The experimental corridors were trawled 12 times within a five-day period for three successive years starting in 1993. This trawling disturbance must be considered to be of high intensity. The effects of the experimental trawling on the mega-epibenthic community, as sampled with epibenthic sledge, are reported by Prena *et al.* (1999), and the effects on the macrofaunal community, as sampled by a large video-equipped grab, are reported by Kenchington *et al.* (2001). A before/after control/impact (BACI) design was attempted, but the intended sledge sampling programme was considerably reduced, thus the resulting mega-epibenthic samples did not allow examination of the recovery of these taxa.

The sledge samples of mega-epibenthic species demonstrated that the trawling disturbance caused an average decrease in total biomass of 24 percent in trawled corridors. This decrease was owing primarily to reductions in biomass of sand dollars, brittle stars, soft corals, sea urchins and snow crabs, whereas no significant effects were observed for mollusc species. Scavenger predation on dead or damaged organisms and change in catchability of the sampling sledge (owing to the burial of organisms by resuspended sediment) were suggested as the most likely factors

Experimental trawling on sandy bottoms of high seas fishing grounds caused short-term declines in some individual taxa, but did not produce large changes in the benthic assemblage. Natural variability was found to be considerable, and these habitats may be resistant to trawling owing to high degrees of natural disturbance.

causing lower biomass in the trawled corridors. Trawling caused significant physical damage only on the echinoderms (sand dollar, brittle star, sea urchin), with the greatest probability of impact on the sea urchin (10 percent damage). The study indicated that trawling caused decreased homogeneity and increased aggregation of mega-epibenthic organisms immediately after trawling. Although the sampling programme was not designed to determine long-term effects and recovery, available evidence indicated that the habitat and biological community recovered from the annual trawling disturbance in a year or less. Total biomass showed considerable interannual variability.

Considerable temporal variability in the community properties of reference corridors was also observed for the grab samples of the macrofauna (Kenchington *et al.*, 2001). These samples demonstrated that the total number of species and the total abundance in both reference and trawled corridors declined during the three-year experiment. The large number of species that decreased in abundance (43 taxa) and biomass (35 taxa) showed that the macrofaunal community in the reference corridors experienced considerable change through the course of the study, indicating that the benthic community at the study site is naturally dynamic and exhibits temporal changes irrespective of trawling disturbance. The mean total abundance per grab sample was lower (25 percent) immediately after trawling in one of the three years of the experiment. This decline in abundance was demonstrated for 13 taxa (mostly polychaetes), of which 11 also declined in biomass. These taxa seemed to recover within a year or less. None of the other community indices in any of the years showed an immediate significant effect of trawling, and few community indices and individual taxa showed a significant long-term effect of trawling. The authors concluded that a natural long-term decline in the macrofaunal assemblage (total numbers of species and individuals) was the most prominent feature of the study.

The impacts of experimental trawling have also been studied on a high seas (offshore) fishing ground in the Barents Sea that consisted of silt/sand/gravel mixed with shell fragments (Kutti *et al.*, in press). The research site was located within the Fishery Protection Zone around Bear Island, which was closed to commercial fishing activity in 1978 in order to protect juvenile gadoids. Five parallel transects were established, of which one was intensively trawled (700 percent coverage by the area of the door spread), one was moderately trawled (230 percent coverage) and three were used as controls. Sampling by video-equipped sledge was conducted before and immediately after trawling and every six months for 18 months after the trawling disturbance. To date, the only samples to be analysed and reported are those that were taken before and immediately after trawling in the intensively trawled transect and in one of the control transects (Kutti *et al.*, in press.).

Trawling affected the benthic assemblage mainly through resuspension of surface sediment and displacement to the surface of shallow-burrowing infaunal bivalves. Thus, significant increases in the abundance and biomass of a majority of the infaunal bivalves and some burrowing gastropods were found after trawling.

Although crustaceans as a group did not show a consistent response to trawling, the abundance of some species showed a significant reduction, probably owing to their ability to move out of the disturbed area. Diversity based on biomass data increased after trawling. Few individuals with physical damage were found in the sledge samples. It was concluded that the experimental trawling did not cause large changes in the benthic assemblage, which thus seemed to be resistant to the disturbance imposed. This resistance to trawling was explained by the high degree of natural disturbance (strong current, large temperature fluctuations) in the area.

In a study conducted in the eastern Bering Sea, previously unfished (UF) and heavily fished (HF) areas straddling a closed-area boundary were compared in order to investigate the long-term consequences for the benthos (McConnaughey, Mier and Dew, 2000). A total of 42 pairs of UF and HF sites were sampled by two trawlers using a modified otter trawl. A significant difference in biomass was found between HF and UF treatments, although the direction of this difference was not consistent for the different taxa or for the two separate sets of samples taken by the two vessels. Several taxa were considered, but a significant difference in biomass was found for only a few species. One data set showed that Actiniaria and *Neptunea* were significantly more abundant in the UF area, and the other data set showed that this area had lower abundances of empty gastropod shells, snail eggs and Porifera. Diversity was significantly lower in the HF area, as a result of greater dominance by the sea star (*Asterias amurensis*) in this area. Among sedentary organisms, niche breadth was also lower in the HF area, indicating a more patchy distribution for the attached or non-motile species in the HF area. The generalized conclusions drawn were reduced biomass (sponges and anemones), niche breadth and diversity of sedentary macrofauna in the HF area, and mixed responses within motile groups and infaunal bivalves.

In this study, the power of many of the statistical tests was extremely low; hence there was little chance of detecting a difference between the UF and HF areas. In order to decrease the probability of type II error and increase the probability of correctly rejecting the null hypothesis of no difference, the authors used a significance level of 0.10 (several p-values were in the 0.05 to 0.10 range). The sampling gear (a modified sampling trawl) used can be regarded, at best, as semi-quantitative for benthic fauna.

Owing to the lack of true control areas on the west coast of California (United States of America), the study of Engel and Kvitek (1998) used the fishing pressure gradient between two fishing grounds as a basis for comparison. The highly trawled site was trawled an average of four times per year (1987 to 1992, trawl logbook records), compared with once every three years for the lightly trawled site. Densities of epifauna (> 5 cm) were estimated from video transects conducted in 1994, and three years of grab samples were collected for infaunal analysis (1994 to 1996). Densities of epifaunal species were higher in the

Owing to a lack of true or replicate control sites, the changes in benthic assemblages demonstrated in some impact studies may reflect natural variability (spatial or temporal) and not the effects of trawling disturbance.

lightly than in the highly trawled area, and the difference was significant for sea pens (*Ptilosarcus* sp.), sea stars (*Mediaster* sp.), sea anemones (*Urticina* sp.) and sea slugs (*Pleurobranchaea californica*). The analysis of infaunal species showed significantly more polychaete species in the lightly trawled area, but no difference for crustacean species. The densities of oligochaetes and nematodes were higher in the highly than in the lightly trawled area, but the difference was significant for only one of the three years of the study. The polychaete *Chloeia pinnata* was significantly more abundant and had higher biomass in the highly trawled area in two of the years. In summary, the study indicated that intensive trawling decreased habitat heterogeneity (fewer rocks and mounds), epifauna density, number of polychaete species and favoured opportunistic species (oligochaetes and nematodes). However, the authors stated that some of these differences may have been attributable to physical differences between sites because there were no unfished control sites, no site replication and the sample sizes were small.

The study site of the investigation by Tuck *et al.* (1998) used to be a good fishing ground, but it had been closed to fishing for more than 25 years prior to the experimental trawling owing to the presence of a naval base. The treatment area was trawled on one day each month for 16 months, and ten trawl hauls were made on each trawling day. This intensive trawling activity was conducted by a trawl with no net. Faunal sampling was conducted prior to and during the trawl disturbance period (after five, ten and 16 months of disturbance) and after six, 12 and 18 months of recovery. Infauna was sampled using a grab, and epifaunal species were observed with a camera mounted on a sledge.

The study demonstrated an increased number of infaunal species and individuals in the trawled area during the period of disturbance, but no effect on biomass. Measures of diversity and evenness decreased in the trawled area. Two species of polychaetes were found to increase while two other polychaete species, although less obvious, decreased in abundance in response to trawl disturbance. Most of the changes that occurred after disturbance were reversed after trawling ceased (number of individuals, diversity, evenness), but some differences (number of species) between the treatment and reference sites remained throughout the 18-month recovery period. These measures changed over time at both sites, suggesting seasonal and annual fluctuations in the community studied.

The results of this study should be interpreted with caution because it had several deficiencies. In order not to reduce the epibenthic scavenger populations, which are potentially important mortality agents for exposed benthic fauna, their densities were preserved by using a trawl with no net. The authors claimed that this modification reduced the weight of the gear, and therefore they added extra weight (mass not given) to the ground rope. No studies have been conducted to determine the effect of removing the net of a trawl, but flume tank observations indicated that such a modification causes increased ground contact because the net lessens the weight of the ground rope during a tow (A. Engås, personal communication). Samples were taken from a single treatment and reference area, so this design is spatially confused and not suitable for demonstrating treatment

effects (see chapter on Methodologies). However, the authors argue that the effects of disturbance were examined by sampling at repeated points during a period of impact and recovery. In addition to this deficiency, it should be noted that before the experimental trawling there were significant differences between the treatment and reference sites in sediment grain size, sea bed roughness, organic carbon level and proportional abundance of the dominant phyla (polychaetes and molluscs), and there were also differences in several of the measures used to demonstrate the impacts of trawl disturbance (e.g. total number of individuals, abundance of some species, diversity and evenness).

An interesting approach was applied to evaluating the disturbances caused by flounder trawling in an intertidal habitat (Brylinsky, Gibson and Gordon Jr., 1994). The macrotidal character of the Bay of Fundy (Nova Scotia, Canada) afforded a unique sampling technique in that experimental trawling was conducted at high water, while biological samples were easily obtained at low water when the trawl tracks were exposed. The dominant groups of benthic organisms at the study site were nematodes and polychaete worms. After trawling, nematodes were less abundant in the door furrows than in the control samples, but this difference levelled out after four to six weeks. Trawling had no impact on either species composition or number of polychaetes, which were predominantly tube-dwelling or burrowing. This study indicated that the impact of flounder trawling is minor on an intertidal benthic community that is exposed to natural processes such as wave action and storms and that thus represents a heavily stressed environment.

The Gullmarsfjord on the Swedish west coast was closed to fishing for six and a half years before an experiment designed to evaluate the potential consequences of reintroducing the shrimp-trawl fishery was carried out (Hansson *et al.*, 2000; Lindegarth *et al.*, 2000a). Three pairs of treatment and control sites were arranged along the fjord. The treatment sites were trawled once a week (two hauls) over one year, giving a conservative estimate of 24 passages of the trawl over any given area within the trawled sites. The treatment sites were thus intensively trawled, but the gear used was a small and light shrimp trawl. Each site was sampled with a grab four times over a four-month period before trawling and another four times after trawling started. To date, this is the only experiment assessing the impacts of long-term trawling to be based on a comprehensive sampling programme with replicate treatment and control sites.

Biomass and the total number of individuals were shown to decrease during the experiment, but this effect could not be attributed to trawl disturbance, although the magnitude of the decreases were higher in the trawled than in the control sites (Hansson *et al.*, 2000). However, the number of echinoderms decreased consistently in the trawled sites, whereas there was no change in the control sites. This significant decrease in the number of echinoderms (30 percent) was mainly

Several studies have addressed the impacts of shrimp trawling on clayey-silt bottoms. No clear and consistent effects attributable to trawling were detected. Potential disturbance effects may be masked by the more pronounced temporal variability demonstrated in these studies.

reflected among the brittle stars (in particular the species *Amphiura chiajei*). Abundances of other phyla were also shown to change, but because changes were demonstrated to occur before trawling in the control sites and among sites within treatments, these differences could not be interpreted as the effects of trawling.

The authors discuss contradictory results between their study and previous experiments. The negative effect of trawling on echinoderm abundance was mainly owing to a decrease in the abundance of ophiuroids, which have been shown to be resistant to, or even favoured by, trawling in other studies (Lindley, Gamble and Hunt, 1995; Kaiser and Spencer, 1996; Tuck *et al.*, 1998). The hypothesis that the ratio between molluscs and polychaetes will decrease as a consequence of trawling (Thrush *et al.*, 1998) was not supported by this study. Furthermore, the results of this study differed from those of most other manipulative experiments in that fewer taxa appeared to be affected by trawling. The authors give several possible explanations for this difference, e.g. differences in experimental treatments and sensitivity to physical disturbance among assemblages (Hansson *et al.*, 2000).

Potential trawl disturbance effects in the study carried out in the Gullmarsfjord were also investigated on the basis of changes in temporal and spatial variability (Lindegarth *et al.*, 2000a), which have been proposed to be more sensitive to detecting environmental impacts than tests based on the effects on means (Underwood, 1991; Chapman, Underwood and Skilleter, 1995). These analyses showed that trawling affected small-scale temporal and spatial variability in the structure of assemblages by counteracting the decreases in variability that occurred at the untrawled sites. The authors concluded that these changes in the overall structure of the assemblages of large macrofauna were relatively subtle compared with the changes caused by natural factors, because large temporal changes in benthos were demonstrated in both trawled and untrawled areas.

The Gulf of St Vincent in South Australia had not been trawled for at least ten to 15 years before the impacts of shrimp trawling were investigated by Drabsch, Tanner and Connell (2001). Three locations, 13 to 16 km apart were chosen, and each location included a control corridor and an adjacent trawled corridor that was trawled on average twice. The before-trawl sampling was carried out two months prior to trawling, and the post-trawl samples were collected within one week after trawling. Thus, the study used a replicate BACI design including three pairs of treatment and control sites. No consistent and unambiguous effects that could be attributed to trawling were detected in the statistical analyses. Large spatial and temporal variation was demonstrated, however. The authors concluded that the lack of an effect is most likely due to the light trawl gear and the low level of trawling intensity used in this experiment, which are characteristic of the fishing grounds in the area studied.

An area of coastal Maine (United States of America) that had been closed to shrimp trawling for 20 years was used to study the effects of trawling disturbance on a muddy (clayey-silt) bottom site (Sparks-McConkey and Watling, 2001). The study area of 1.82 by 2 km was covered by nine sampling stations, of which two were trawled four times. Macrofaunal samples (grab and core) were

collected every three months for a year and a half prior to trawling and for six months after trawling. Immediately following the trawling disturbance, the total number of individuals, species richness and diversity in the trawled sites were significantly lower than in the control sites. Three months after trawling, these values for the trawled sites had returned to those of the control sites. Of the seven common polychaetes identified, four species decreased immediately after trawling and three species did not show any change in abundance. Three bivalves also showed a decrease in abundance immediately following the trawling disturbance. Nemertean abundances were significantly higher after trawling. Three months after trawling, the abundances of these common taxa, in general, were similar for trawled and control sites.

When interpreting these results it should be noted that most taxa showed large seasonal variations, and ecological parameters such as diversity and total abundance were significantly different between trawled and control sites at some stages before the trawling event. Accordingly, the most apparent feature of the multidimensional scaling analysis was changed species abundance of the common taxa, which is attributed to temporal variation and not trawling disturbance.

Two estuarine sounds in South Carolina (United States of America) were studied to evaluate the effects of commercial shrimp trawling on benthic infaunal assemblages (Van Dolah, Wendt and Levisen, 1991). In each sound, comparisons were made between an area closed to trawling and an area actively trawled during the fishing season. Grab samples were taken immediately prior to the trawling season and after five months of relatively intensive trawling. The number of species in both sounds showed a significant time effect, but no significant area effect, i.e. no difference between trawled and control areas. Species diversity, evenness and richness were similar in the trawled and control areas in one of the sounds both before and after trawling. In the other sound, species diversity increased in the control area between the two sampling periods, but not in the trawled area, which, however, still had higher diversity than the control area after five months of trawling. The total number of individuals differed considerably between control and trawled areas within each sound, between sounds and between sampling periods. Comparison of species composition and mean faunal abundance showed little evidence for trawl effects in either sound, but a significant decrease in the density of benthic infauna was observed between seasons. The authors concluded that the various community parameters assessed provided no clear evidence of trawl effects on the benthic infaunal communities. Most of the differences observed were attributed to natural seasonal variability.

Long-term impacts on the benthos were examined at two sites off the northeastern coast of England (United Kingdom), one at 80 m depth within a *Nephrops* fishing ground, and the other at 55 m located outside the main fishing area (Frid, Clark and Hall, 1999). Temporal changes of infaunal abundance and species composition were compared between the two sites over a 27-year sampling period, during which the intensity of fishing effort changed. Fluctuations in macrofaunal abundance at the site outside the main fishing ground reflected

the abundance of phytoplankton, but this relationship broke down at the site within the fishing ground during a period of increasing fishing intensity. During this period of intense fishing activity, the total abundance of individuals of taxa likely to respond positively to fishing disturbance increased significantly and then subsequently declined when fishing decreased. Numbers of individuals in taxa likely to decline in response to fishing impacts did not change significantly between time periods with different levels of fishing effort. These two taxonomic groups did not vary at the site outside the fishing area.

The difference in the dynamics of these two sites, which were fished at different intensities, provides some evidence for the effects of fishing on the abundance and composition of coastal macrofauna. However, the sites studied also differed in several other aspects, e.g. depth, community structure and sediment type, which may have affected their responses to temporal changes in, for instance, phytoplankton productivity.

The whole Irish Sea has been intensively trawled for Norway lobster, and the only unfished sites are connected to wrecks. The short-term impacts of this trawl fishery were studied by comparing grab samples taken at two sites (at 35 and 75 m depth) before and 24 hours after experimental trawling (Ball, Fox and Munday, 2000). At the shallow site, most of the polychaetes species (scavengers or opportunistic species) increased in numbers following trawling, whereas most other species showed a decrease in numbers, although few comparisons were statistically significant. There were significant decreases in number of species, biomass, species richness and diversity after trawling. The fauna at the deeper site was too scarce to make the quantitative assessment of short-term effects possible.

The long-term effects were assessed by comparing the samples taken at the fished sites with samples taken at two nearby shipwrecks. The number of individuals and the biomass showed significant decreases between the wreck and the fished ground at the shallow site, and all parameters measured showed significant decreases between the wreck and the fished ground at the deeper site. Comparisons between trawling grounds and wreck sites were based on the assumption that they differed only in fishing intensity. As discussed in Chapter 2 Methodologies, however, wrecks are artificial reefs that may have several additional effects on the benthic community in their neighbourhood. Thus, clear evidence has not been provided for the conclusion made by this study's authors that the observed differences between the fauna of the two wreck sites and the nearby fished sites would appear to reflect genuine effects of fishing.

Hall *et al.* (1993) also used a wreck as their control site, and postulated that there is a gradient of increasing trawl disturbance with increasing distance from a ship wreck. They collected grab samples along transects running outwards (5 to 350 m) from a wreck site located in an area of the northern North Sea that has been heavily fished by otter trawl. The community variables studied (abundance, number of species, diversity) showed no correlation with distance from the wreck. Total numbers of individuals were, however, significantly correlated with sediment particle size. Thus, the spatial patterns in the benthic community that

were demonstrated in this study did not appear to be consistent with an effect of fishing disturbance. The authors questioned whether studies of this kind, i.e. that use areas in close vicinity to ship wrecks as control sites, are adequate for testing the impacts of fishing disturbance. They stated that an important flaw in such studies is that there are no hard data on the distribution of disturbance, and it is simply hypothesized that a gradient exists.

The Mediterranean is markedly different from most other areas where impact studies have been conducted because of its oligotrophy, high level of salinity, high temperatures, negligible tidal currents and deep trawlable depths (Smith, Papadopoulou and Diliberto, 2000). As a result, this ecosystem may potentially be less robust and liable to disturbances. The impacts of a trawl fishery that takes place off Crete (Greece) for eight months and is then closed for four were studied by sampling at two sites in the trawled area and two control sites on either side of the trawl lane (Smith, Papadopoulou and Diliberto, 2000). Grab samples of macrofauna were taken periodically throughout the trawling and closed seasons. Towed-video operations demonstrated that trawling activity was confined to the trawl lane, and the sampling stations appeared to be consistent with the definition of trawled and control sites, although they were at different depths.

Total number of species was significantly higher on the control than on the trawled sites at some stage during the trawling season. This difference was mainly the result of higher numbers of species of echinoderms and sipunculids, which also showed greater abundances and biomass at the control sites. For crustaceans, molluscs and polychaetes the differences were rarely significant. Diversity was significantly higher and evenness significantly lower on the control than on the trawled sites. These ecological parameters showed a high degree of variability over time, and in most cases there were large differences between the two control sites, indicating temporal and spatial variability caused by factors other than trawling.

In another study conducted in the Mediterranean, experimental trawling was performed along two corridors that were swept entirely by the trawl once and twice, respectively (Sanchez *et al.*, 2000). The infauna was sampled with a grab at 16 stations in the fished and adjacent unfished areas in order to evaluate the short-term effects. Samples were collected periodically for 150 hours after trawling on the site that was trawled once, and for 72 hours after trawling on the site that was trawled twice. There were no significant differences in the diversity indices (diversity, evenness and dominance) between the fished and control sites. The total numbers of individuals and species were not significantly different between fished and control sites during the first 102 hours after trawling, but increased significantly at the site trawled once compared with the control site 150 hours after the disturbance. For the area trawled twice, the total numbers of individuals and species changed significantly through time in both the fished and unfished sites. Based on these results, the authors suggested that sporadic episodes of trawling in muddy habitats may cause relatively few changes in community composition.

In a third Mediterranean study, the structure of the benthic fauna of two neighbouring gulfs of the Aegean Sea, one open and the other closed to trawling,

The impacts of trawling have been indicated in some studies conducted on soft bottoms. However, evidence for clear and consistent changes attributable to trawling has not been provided from these experiments. The most prominent features of these studies are a lack of true and replicate control sites and pronounced temporal and spatial variability in community structures.

were assessed in relation to natural and anthropogenic factors (Simboura *et al.*, 1998). Although at the same depth and in close proximity, the two areas differed in sediment coarseness and organic content (higher percentage of sand and lower organic content in the trawling area).

The area open to trawling had higher numbers of species (three times) and individuals (four to five times), and higher community diversity and species richness. Sediment type and organic content were regarded as the controlling factors for this differentiation of the two areas. Of the many parameters estimated in the study, only the higher number of polychaetes and the dominance of opportunistic polychaete species in the trawled area indicated a degree of disturbance that could possibly be linked to trawling. This study demonstrated

considerable differences in the community structure of closely located benthic communities, which were attributed to natural parameters, and showed that trawling disturbance may be difficult to demonstrate owing to the masking of more dominant natural factors.

OTTER TRAWLING ON HARD BOTTOM HABITATS WITH ERECT STRUCTURES

Few studies of hard, rocky bottoms have been carried out, probably because sampling is difficult and expensive tools are required for visual observations. Freese *et al.* (1999) used video camera observations from a submersible to assess trawl impacts in the eastern Gulf of Alaska. A study area of hard bottom habitat (pebble, cobble, boulder) that had endured no or minimal trawling since the 1970s was identified by examining the trawling activity of the commercial fleet and by videotape recordings showing no evidence of trawling. This approach cannot confirm an undisturbed control site, but it is likely that the area had experienced low trawling activity. Shortly (from two hours to five days) after each trawl haul, the submersible made a transect along the trawl pass in the centre of marks made by the 60-cm-diameter tyre gear, which was a 5-m wide compact gear with no space between the tyres. Thus, in contrast to most other studies, all sampling was carried out in areas affected by the ground gear. A transect 50 to 70 m adjacent to each trawl path was used as a control site. Only easily visible and identifiable species were included in the analyses. These were 29 taxa greater than 5 cm in size.

The dominant substrate type was pebble (< 6.5 cm), and the trawl path was visible as a series of furrows caused by the tyre gear. The density of large sponges and anthozoans (corals) decreased significantly as a result of trawling. In the trawled transects, large proportions (55 to 67 percent) of these large erect sessile invertebrates were damaged. None of the motile invertebrates showed a significant reduction in density as a result of trawling, and only the ophiuroid *Amphiophiura ponderosa* was susceptible to damage (23 percent). In conclusion, this study

demonstrated that boulders were displaced, and large emergent sessile epifauna were removed or damaged by the ground gear after a single trawl haul.

In an investigation conducted on the continental shelf off northwestern Australia, attached benthos (> 20 cm) were counted from video transects, and comparisons were made among three sites, two that were trawled four times with demersal and semi-pelagic trawls, respectively, and one control site (Moran and Stephenson, 2000). The density of macrobenthos (mainly sponges, soft corals and gorgonians) decreased by 15.5 percent after each haul by the demersal trawl, leading to a reduction in density of about half after four trawl passes. The semi-pelagic trawl inflicted no detectable mortality on the benthos, but the catch rates of target fish species were low. Using effort data from logbooks, the annual mortality of macrobenthos was estimated to be less than 10 percent for most of the area fished by the commercial fleet.

The effects on sponges and corals of one path of a research trawl over a low-relief hard bottom habitat were studied in the South Atlantic Bight (Georgia, United States) by Van Dolah, Wendt and Nicholson (1987). The densities of individuals taller than 10 cm of three species of sponges and four species of corals (three octocorals and one stony coral) in the trawl path and in an adjacent control area were assessed by divers, and were compared before, immediately after and 12 months after trawling. The density of undamaged sponges showed a significant decrease immediately after trawling. Of the total number of sponges remaining in the trawled area, 32 percent were damaged. Most of the effected sponges were the barrel sponges *Cliona* spp., whereas the finger sponges (*Haliclona oculata*) and the vase sponges (*Ircinia campana*) were not significantly affected. Twelve months after trawling, the abundance of sponges had increased to pre-trawled densities or greater. The effects on the coral species appeared to be minimal in comparison with the sponges, as there were no significant differences between pre- and post-trawled densities for any of the species, although two species showed a non-significant decrease and some damaged corals were found immediately after trawling. The research trawl used in this study had a foot rope equipped with larger and more flexible rollers than that of the trawl used in the commercial shrimp fishery. Thus, supported by the findings of an unpublished study, the authors stated that commercial fishery is likely to cause more severe damage to the large sessile fauna of the area studied.

Considerable decreases in the abundance of large erect sessile invertebrates (e.g. sponges and corals) have been demonstrated to be a consequence of trawling. Habitats dominated by large sessile fauna may be severely affected by trawling disturbance.

BEAM TRAWLING

Most studies on the impacts of beam trawling have been conducted in the North Sea and the Irish Sea, where some areas have been intensively trawled for many decades. As hardly any areas in the North Sea have not been affected by commercial trawling (except for those in the vicinity of wrecks), few if any areas are suitable as control sites. Most studies have therefore assessed trawling impacts

Intensive disturbance by beam trawling has been shown to cause short-term changes in community structure through considerable reductions in abundance of infauna and epifauna. The long-term effects have not been studied.

by comparing samples taken before and immediately after experimental trawling on commercial fishing grounds.

One study applying this approach was conducted in the southern North Sea to determine the impacts of a heavy 12-m beam trawl (7 000 kg) (Bergman and Hup, 1992). A small quadrant was trawled three times, and samples were taken before trawling started, after the first and the third trawling events and again

two weeks later. The direct effect of this disturbance was a significant decrease in abundance (40 to 60 percent) of one echinoderm species and two species of polychaete, whereas the polychaete *Magelona papillicornis* increased in density (35 percent). No effects were found on the densities of *Ophiura* sp., molluscs (about ten species) or other species of worms (about 20 species). The decreased numbers of some species were explained by destruction during the passage of the trawl and removal by the trawl net. As the bycatch was returned to the sea after sorting on board, the effect on the benthic community depended on the survival rate of these species. The immediate effects demonstrated for some species in this study appeared to be considerable, but the authors stated that such direct effects cannot be extrapolated to the long-term effects of beam trawling on the benthic community.

In another North Sea experiment, the direct mortality of mega- and macrofauna caused by different beam trawls (12 m and 4 m wide, with tickler chains with chain mats) was also determined by the differences in densities before and after experimental trawling (Bergman and van Santbrink, 2000). The experimental corridor was trawled at an average frequency of 1.5 tows, but the mortality estimates were converted to those for a single passage of the trawl. Several taxa did not show statistically significant mortalities, but those that did were considerable. Small-sized bivalves and crustaceans showed direct mortalities of up to 22 percent, and annelid worms of up to 31 percent. In megafaunal crustaceans and bivalves, mortalities of up to 49 and 68 percent, respectively, were found. The majority of the species studied showed similar mortality caused by 4 m and 12 m beam trawls in silty and sandy areas, but there was a tendency for lower mortalities from trawls with a chain mat compared with those with tickler chains. Mortality in some infaunal species was higher in silty than in sandy areas, and small species tended in general to show low mortalities compared with larger species. The estimated direct mortality incorporated animals caught by the trawl and animals damaged or exposed in the trawl track, of which the former were insignificant owing to low catch efficiency for invertebrates. Based on different assumptions (e.g. about spatial species distribution and commercial trawling frequency), annual fishing-induced mortality in megafaunal populations was estimated to range from 5 to 39 percent on the Netherlands continental shelf, and was mainly due to the 12 m beam trawl as this is the dominant gear type, with an average trawl frequency coverage (i.e. number of tows on a given site of the fishing ground) of 1.23 (in 1994).

The Irish Sea is a heavily trawled area, particularly the northern part (Kaiser *et al.*, 1996). The effects of beam trawling on benthic infauna were determined in two costal communities in the northeastern Irish Sea, one characterized by megaripples and mobile sediments and the other by featureless and stable sediments (Kaiser and Spencer, 1996). Three corridors were fished ten or 20 times with a 4 m commercial beam trawl (3 500 kg) fitted with a chain matrix. These and adjacent unfished control areas were sampled 12 hours after trawling. The mean total number of species and the abundance of individuals were 2.4 and 5.7 times higher, respectively, in the area with stable than in the area with mobile sediments. The community of the former was affected by the trawling disturbance, with the number, abundance and diversity of taxa significantly lower in the fished than the unfished areas. The abundance of nine of the 20 most common taxa was significantly lower in the fished areas, by as much as 50 percent for the two most abundant taxa (*Urothoe* and *Ampelisca*). In the area with mobile sediments, there were no significant differences in species numbers, abundance or diversity between the fished and unfished sites. Thus, this study demonstrated the short-term effects of beam trawling on infauna taxa that live in stable sediments, but similar effects were not detected on animals inhabiting mobile sediments that are subjected to frequent natural disturbances.

As part of the same study, the effects on the megafaunal component (> 10 mm) of the community were studied immediately (approximately 24 hours) after trawling and six months later (Kaiser *et al.*, 1998). The two areas with stable and mobile sediments also differed significantly with regard to megafaunal community variables (number of species, number of individuals and diversity). As with the infauna, only the megafaunal samples taken from the area with stable sediments immediately after fishing revealed significant differences between the fished and control areas. A reduction in abundance of the polychaetes *Aphrodita aculeate* and *Nephtys* spp. contributed most of this dissimilarity, but changes in number of species, number of individuals or diversity as a result of fishing disturbance were not detected. The differences were no longer apparent six months after the trawling disturbance. However, there were marked seasonal changes in the community structure. In conclusion, this part of the study revealed that only subtle changes in community structure were caused by trawling, whereas the effects caused by seasonal fluctuations and natural disturbances were more pronounced.

Most studies have determined the impacts on the benthic community structure by recording changes in the abundance and biomass of different species, but Jennings *et al.* (2001) also investigated the effects of trawling on the trophic structure of the community studied. Trawling effort at the sites studied was determined from records of vessel sightings by fishery protection aircraft, and the authors assumed that the number of trawlers sighted per unit of searching effort was linearly proportional to the trawling disturbance. This method does not give an accurate indication of the actual level of disturbance at the site where the invertebrates were sampled, because the samples were collected at a much finer spatial scale than that of the overflight data. Two areas in the North Sea subjected

to different levels of trawling (a threefold difference) were investigated. Each area was divided into sites of 5 by 6 nautical miles, and within the two areas there were 27- and tenfold ranges, respectively, in the trawling disturbance among the sites.

The total biomass of infauna and epifauna in the most intensively trawled area decreased significantly with trawling disturbance. This decrease was most pronounced for the biomass of infauna, which showed an order of magnitude decrease when trawling disturbance increased 27-fold and was due to decreases in the biomass of bivalves and spatangoids, while there was no change in polychaetes. At the less intensively trawled area there were no significant trends in total biomass in relation to fishing disturbance, but there was a significant increase in polychaetes. No changes in the trophic structure of the community related to trawling disturbance were found. In conclusion, the study suggested that highly intensive trawling disturbance led reduced biomass of infauna and epifauna and dramatic changes in the composition of infauna, but these changes were not reflected in the mean trophic level of the community.

SCALLOP DREDGING

A comprehensive study on scallop dredging was conducted in Port Phillip Bay (Australia) on a spatial scale that is relevant to commercial fishery (Currie and Parry, 1996). A large area (600 x 600 m) was dredged over three days, until the entire site had been passed over an average of twice by the dredge. The abundances of infauna at this and an adjacent control site were determined from grab samples taken on three sampling dates before and six after (a few hours, three weeks, and three and a half, five, eight and 14 months) the experimental dredging. The dredging caused a significant decrease in the number of species on the dredge site compared with the control site (10 percent significance level was used). This difference persisted for eight months, but after 14 months the number of species was similar on both sites. The total number of individuals showed large seasonal changes, and there were no differences between the dredged and the control sites. Bray-Curtis dissimilarity measures between the sites increased significantly after dredging and persisted for 14 months, i.e. the duration of the study. In addition, the multidimensional scaling (MDS) ordination showed increased differences

between the two sites after dredging, but changes caused by seasonal and interannual variations were more pronounced.

A comprehensive study conducted on a spatial scale that is relevant to commercial dredging demonstrated a decrease in number of species and considerable reductions in abundance of several species, but dredging-induced reductions in density were small compared with temporal and spatial changes.

Of the ten most abundant species, six showed a significant decrease in abundance (28 to 79 percent) and one species increased (141 percent) after dredging. The duration of these impacts varied among species, but few lasted beyond eight months after dredging. In this study, a pronounced ecological gradient was detected between the eastern and western parts of both the dredged and the control sites. This difference was seen in the distribution of many species, and the

impacts demonstrated were not consistent between the eastern and western parts. Although impacts of scallop dredging were demonstrated in this large-scale study, the spatial heterogeneity – together with seasonal and interannual changes – makes interpretation more difficult. The authors stated that the reductions in density caused by dredging were usually small compared with annual changes in population density.

Currie and Parry (1999) report a similar study involving two additional areas in Port Phillip Bay with different soft substrates, in which the impacts on epifauna were also investigated. The dredge caught mostly scallops, with the bycatch of other epibiota being typically less than 5 percent. Damage to bycatch species was low except for spider crabs (up to 55 percent). In one of the areas, three of the ten most abundant infaunal species decreased significantly in abundance by 20 to 40 percent. Changes to community structure caused by dredging were small compared with differences between the areas studied. The authors suggested that the relatively small effects of dredging demonstrated in these two studies may be related to the low abundance of epifauna other than scallops in Port Phillip Bay.

Two experimental sites were selected for a study in New Zealand, one in an area exploited by commercial scallop fishers and the other in an unexploited area (Thrush *et al.*, 1995). A scallop dredge (2.4 m wide, with 10-cm-long teeth) was towed through half of each study site (five parallel tows) to create a dredged site and an adjacent control site. Core samples were collected by divers within two hours and again three months after dredging. The authors used a 10 percent significance level, as in their view Type II error is at least as important as Type I error when documenting impacts on the environment. In the unexploited area, the total numbers of individuals and species were significantly lower in the dredge site than the control site immediately after dredging. Reduced densities were observed for four crustacean species, three polychaetes and one bivalve. Some of these species also showed lower densities in the dredged site three months after dredging, and three species showed significant temporal changes in density during this period. In the exploited area, five species showed significant density changes over time, and patterns of density change between the dredged and the control site were less clear. Only two bivalves and one crustacean species showed consistently lower densities in the dredged site on both sampling occasions, and four species showed a marked increase in density in the dredged site after three months. The total numbers of individuals and species decreased as an effect of dredging. This experimental assessment, which was quite conservative (i.e. low intensity of disturbance in a small area), demonstrated that the macrobenthic community structure in dredged areas differed from that in undredged areas for at least three months.

Rapido trawls resemble a toothed beam trawl and are used around the coast of Italy to catch sole and scallop (see diagram and description in Hall-Spencer *et al.*, 1999). They are lightly built (3 m wide, 170 kg), and are towed at high speed (10 to 13 km/hour). As the rapido trawl has teeth and no tickler chains or chain matrix, its effects on the benthic habitat are more likely to resemble those of a scallop dredge. The impact of this gear on a commercial scallop ground in the Adriatic Sea

(Mediterranean) was studied by making seven tows along a 60-m wide corridor (Hall-Spencer *et al.*, 1999). A video sledge was towed along the corridor prior to trawling and again 15 hours after trawling, and the densities of visible organisms were determined from the video recordings. Significant reductions in abundance (> 70 percent) on the trawled track were found for several components of the macrofauna, e.g. the large bivalve *Atrina fragilis*, the sea cucumber *Holothuria forskali*, the sea anemone *Cerianthus membranaceus*, tunicates and naticid egg coils. Observations during trawling revealed that most organisms in the path of the trawl passed under or through the net, and analysis of the catch showed low total bycatch biomass (19 percent), which was dominated by tunicates, echinoderms and molluscs. Lethal mechanical damage of the taxa caught varied from < 10 percent in small, resilient taxa such as hermit crabs and gastropods to > 50 percent in large, fragile organisms such as *A. fragilis* and tunicates. The short-term effects demonstrated in this study included reductions in the structural complexity of the habitat and the selective removal of a large proportion of the benthos.

To obtain samples from an undisturbed area, experimental trawling with a rapido trawl was conducted near a wreck (Pranovi *et al.*, 2000). The disturbed line was trawled only once, and sampling by diving ensured that samples were taken exactly within the trawl track and at an adjacent control site. The track was sampled immediately after trawling and seven days later. Samples were also collected at a nearby fishing ground. The findings of this study cannot easily be interpreted, as there are several discrepancies between the text and the tables regarding whether differences were significant or not. In general, however, common macrofaunal taxa decreased in density immediately after trawling, but increased again after one week and were often higher than they were in the controls. In the comparison between the control area and the neighbouring fishing ground, biomass, numbers of individuals and taxa and numbers of many taxa were significantly lower at the fishing ground. The community in the exploited area was also less diverse and dominated by only three phyla (Mollusca, Arthropoda and Echinodermata). Analysis of the meiofauna showed that some taxa decreased after trawling while others increased. Compared with the control area, the fishing ground showed significantly higher numbers of individuals, but lower evenness. Thus, while the immediate effect of rapido trawling (one haul) was negative, the number of individuals and the total number of taxa increased after one week. These species were mainly scavengers.

The area around the Isle of Man in the Irish Sea has been heavily fished by scallop dredges. Fishing effort data from logbooks recording effort per 5 x 5 nautical mile boxes were used to compare five areas subjected to low and five areas subjected to high dredging intensity (Kaiser *et al.*, 2000). Infaunal samples were collected using an anchor dredge, and epifauna were sampled by a 2-m wide beam trawl. Both the total biomass and the abundance of epifauna differed between the areas of low and high fishing intensity, whereas the infauna samples differed in biomass only. However, the direction of these differences is not given in the paper. There were no significant differences in number of species or diversity

indices. Abundance-biomass curves (ABC) indicated that the heavily fished areas were dominated by higher abundances of smaller-bodied organisms, whereas the less intensively fished areas were dominated by fewer, larger-bodied biota. Although this study indicated that scallop dredging has led to changes in community structure, it must be noted that the study had several deficiencies, e.g. the areas compared were all disturbed, and the sampling devices used were not strictly quantitative. Furthermore, these areas were located far apart and differed in habitat type (depth and sediment type), which was shown to affect community structure. Despite these shortcomings, the authors generalized their results and stated that "... any of the large, bottom-fishing gears such as rock-hopper otter trawls and beam trawls will have similar effects".

A comparison between sites subjected to low (closed to towed gear), medium (seasonally open to towed gear) and high (open to towed gear) levels of fishing effort with scallop dredge, beam trawl and otter trawl was made on fishing grounds along the southern coast of the United Kingdom (Kaiser, Spencer and Hart, 2000). Information on the type of towed gear used or precise measures of fishing effort at the sites sampled were not available to the authors. Epifauna was sampled with a 2-m beam trawl, and infauna with an anchor dredge. Several environmental parameters (depth, grain size, mass of stones and broken shell, RoxAnn E1 and E2 values) varied significantly among the sites studied. These habitat differences had a more apparent effect on community structures (total number of individuals, number of species, diversity) than did level of fishing effort. The biomass data revealed significant differences among areas of high, medium and low fishing effort. There was a general decrease in less mobile, larger-bodied and fragile fauna and an increase in the more resilient, mobile fauna as fishing disturbance increased. Although the responses of individual taxa to fishing disturbance were not consistent for the different habitat types, the biomass of sessile fauna such as soft corals and hydroids was higher in the areas closed to towed fishing gear. The results of this study indicate the effects of trawling on benthic community structure, but this study has several limitations (e.g. lack of fishing effort data and appropriate control sites), and the habitat differences between the sites studied were shown to have the most apparent effect on community structures.

Thrush *et al.* (1998) counted large epifauna (video transects) and sampled macrofauna (grab or suction-dredge and core sampling) at 18 sites that were ranked in terms of fishing pressure from trawling, Danish seining and scallop dredging. The ranking of fishing pressure was based on fisheries legislation (e.g. closed areas) and information from fisheries managers. Dredging was considered to cause a stronger impact than trawling or seining. Such ranking should be regarded as rough, imprecise and, to some extent, subjective, so the results of the study must be interpreted with great caution. Based on results from small-scale experimental disturbance studies, *a priori* predictions about the responses of

Numerous studies have assessed the impacts of scallop dredging and, although several have important limitations, they have all indicated effects of varying degrees. Short-term reductions in species abundance and decreases in number of individuals were the most prominent features.

benthic communities to trawl disturbances were made and tested at larger scales. Fishing-pressure rank was found to account for 15 to 20 percent of the variability in community structure. Of the ten predictions tested with the core samples, fishing pressure was shown to affect significantly the density of echinoderms, polychaete/mollusc ratios (but in ways that were contrary to the prediction), the diversity index and the number of species. However, using the grab/dredge samples, fishing pressure was not a factor that affected these ecological parameters. The results from the grab/dredge samples showed significant effects on only deposit feeders, but these too were contrary to the prediction.

In this study, decreasing fishing pressure was seen to change the benthic communities in the direction predicted. However, few of the ecological parameters tested were significant, and the findings from the core samples were not supported by those from the grab/dredge samples. Given the lack of appropriate reference sites, this analysis used fishing intensity ranking based on legislation and information from fisheries managers that identified areas of different exploitation rates. One problem of this approach is that it does not identify any unambiguous cause-and-effect relationship. The study was integrated over a variety of habitat types, and the differences in community structure that were demonstrated for areas of different exploitation rate may not be a response to fishing disturbance but simply the result of fishers avoiding certain areas (e.g. because of reefs and other obstacles) and preferring other zones with different community structures.

Georges Bank (northwest Atlantic) has been dredged for scallops for decades, and the impacts on the benthic megafauna on a gravel habitat have been studied by Collie, Escanero and Valentine (1997). Two disturbed and six undisturbed sites were identified based on a combination of side-scan sonar recordings, video observations and records of dredging effort (available only for two of the six sites). Samples of benthic megafauna were obtained with a dredge and standardized per unit of sediment collected. The abundance of organisms, biomass and species diversity were significantly greater at undisturbed than disturbed sites, whereas evenness was significantly greater at disturbed sites. Although the data did not allow statistical testing of the species richness measure, they indicated that species richness was higher at undisturbed than disturbed sites. The authors stated that their study has several limitations and must be interpreted with caution. The sampling dredge was considered to be semi-quantitative, its penetration into the gravel was not constant and the estimates of the area sampled were imprecise. The benthic samples were therefore not strictly quantitative and comparable.

In this investigation, video recordings and still photographs were also taken along transects within each site (Collie, Escanero and Valentine, 2000). The still photographs showed that the percentage cover of the colonial polychaete *Filograna implexa* was significantly greater at the undisturbed sites. However, the percentage cover of low-encrusting bryozoans was significantly higher in the disturbed sites. The percentage cover of plant-like animals (bushy hydroids and bryozoans) was greater at deep undisturbed sites, but the effect of dredging was reversed at the shallow sites where the disturbed site had higher percentage cover

of these organisms. The same contradictory results between deep and shallow sites were seen in the percentage cover of emergent epifauna estimated from the videos. Similarly, there were no consistent differences between disturbance levels in terms of numerical abundance of megafauna, species diversity or evenness. Analyses of the abundance of organisms that could be identified in the videos and still photographs showed that most of these taxa were more abundant at the undisturbed sites.

Although dredging disturbance is a likely explanation for the differences in community structure demonstrated at the studied sites, the approach used in this study has some serious shortcomings. Fishing effort data (on a large scale) were available for only two of the sites, and side-scan recording is a rough and descriptive way of determining sediment type and degree of bottom disturbance. The sea bed was surveyed by video transects to identify stations for benthic sampling, and sites where epifauna were absent or present were used as disturbed and undisturbed sites, respectively. However, the presence or absence of epifauna may have other causes than dredging, e.g. differences in sediment characteristics and, thus, habitat type. In fact, the sediment distributions were patchy and differed between the disturbed and the undisturbed sites. Furthermore, the abundance of sea scallop (the target of commercial dredging) was five times higher at the disturbed (dredged) than the undisturbed sites (Collie, Escanero and Valentine, 2000; Table 3A). This difference (and possibly other changes demonstrated in the study) cannot be attributed to dredging disturbances, but simply reflects fishers' preference for areas with high densities of the target species, and thus indicates that the sites studied involved different habitat types.

The problem of finding suitable control sites among the scallop grounds in the Irish Sea was overcome by using samples collected before the initiation of intensive fishing (Hill *et al.*, 1999). Samples of epifauna and infauna collected from three sites over the period 1946 to 1952 were compared with recent samples taken from the same sites. Since the 1960s, two of these sites have been heavily dredged, while the third site has been relatively unaffected by dredging. At the heavily fished sites, the number of species, species richness and diversity were significantly greater in the recent samples compared with the historical samples, whereas the index of Simpson's dominance was significantly greater in the historical samples. Species composition was clearly different between recent and historical samples. This difference included the presence of some larger and fragile species (two echinoids and one bivalve) in the historical samples, but not in the recent samples, and a higher polychaete to mollusc ratio in the recent samples. Significant changes were also found at the site unaffected by dredging. The number of individuals and the index of Simpson's dominance decreased, and evenness increased between the historical and recent samples. The species composition also changed over this time period, and the polychaete to mollusc ratio increased. The authors believe that this study has a serious shortcoming because different types of sampling gear were used to collect the historical and recent samples. Natural long-term changes might have occurred over this time period because the community structure also

Changes attributable to dredging were not observed in areas exposed to natural stress, e.g. wave action, eutrophication and salinity fluctuation.

changed at the undisturbed site. Furthermore, some of the changes found at the heavily fished sites were the opposite of those expected to result from physical disturbance. Although this study showed that community structures had changed since 1950, the cause of the change was not clearly demonstrated.

The effects caused by a modified scallop dredge (1.2 m wide, 12-cm-long teeth separated by 8 cm, with the chain net removed) were examined in a shallow Scottish loch that is exposed to wave and tidal actions (Eleftheriou and Robertson,

TABLE 3

Studies to investigate the impacts of beam trawling on benthic habitats and communities

Study site	Depth (m)	Bottom type	Dominant species	Sampling techniques	References
North Sea	Ca. 30	Fine/medium sand	Crustacean, mollusc, echinoderm, polychaete	Grab, boxcorer, beam trawl	Bergman & Hup, 1992
North Sea	<30–50	Silt, sand	Mollusc, echinoderm, crustacean, polychaete	Grab, boxcorer, dredge	Bergman & Santbrink, 2000
North Sea	40–60 and 60–80	Sand, muddy sand	Bivalve, spatangoid, polychaete	Beam trawl, dredge	Jennings <i>et al.</i> , 2001
Irish Sea	26–34	Medium/coarse sand, gravel	Amphipod, polychaete, echinoderm	Grab, dredge, side-scan, RoxAnn	Kaiser & Spencer, 1996; Kaiser <i>et al.</i> , 1998

TABLE 4

Studies to investigate the impacts of scallop dredging on benthic habitats and communities

Gear	Study site	Depth (m)	Bottom type	Dominant species	Sampling techniques	References
Scallop dredge	Australia	12–16	Sand, silt	Crustacean, polychaete, mollusc	Grab, sledge, video, divers	Currie & Parry, 1996; 1999
Scallop dredge	New Zealand	24	Coarse sand	Polychaete, crustacean, mollusc	Core	Thrush <i>et al.</i> , 1995
Rapido trawl	Adriatic Sea	25	Sand	Bivalve, ophiuroid, sponge, tunicate, holothurian	Video	Hall-Spencer <i>et al.</i> , 1999
Rapido trawl	Adriatic Sea	24	Sand	Mollusc, polychaete, crustacean	Side-scan, divers, water-lift sampler, core	Pranovi <i>et al.</i> , 2000
Scallop dredge	Scottish bay	6	Sand	Polychaete, crustacean, mollusc, echinoderm	Grab, core, divers, photos	Eleftheriou & Robertson, 1992
Mussel dredge	Danish fjord	2–7	Not given	Porifera, anthozoa, mollusc, echinoderm	Divers	Hoffmann & Dolmer, 2000
Scallop dredge	Irish Sea	Not given	Coarse sand, gravel	Soft coral, echinoderm, mollusc	Dredge, beam trawl	Kaiser <i>et al.</i> , 2000
Scallop dredge, beam and otter trawl	Coast of Devon, UK	15–17 and 53–70	Fine, coarse-medium sand	Soft coral, hydroid, echinoderm, crustacean, mollusc	Dredge, beam trawl	Kaiser, Spencer & Hart, 2000
Trawl, seine, dredge	Hauraki Gulf, NZ	14–35	Clay, silt, shell fragments	Not given	Side-scan, camera, grab, dredge, core	Thrush <i>et al.</i> , 1998
Scallop dredge, otter trawl	Georges Bank	42–90	Pebble, cobble	Mollusc, polychaete, crustacean, echinoderm	Dredge, video, photos	Collie, Escanero & Valentine, 1997; 2000
Scallop dredge	Irish Sea	Not given	Not given	Polychaete, mollusc, echinoderm, crustacean	Dredge, grab	Hill <i>et al.</i> , 1999

1992). The dredge was towed a number of times over the same track, and after 0, two, four, 12 and 25 tows sampling (grab and diver observations) was conducted in the middle of the track and in one small control area. No significant changes in abundance, biomass, diversity or evenness of infaunal species sampled by grab that were attributable to the dredging were observed. Divers observed some damage and mortality to organisms such as *Echinocardium*, *Asterias* and *Ensis*, and high mortality of sand eel (*Ammodytes*) was observed.

Studies were made in an area of the Limfjord (Denmark) that was closed to mussel dredging ten years prior to the experiment (Hoffmann and Dolmer, 2000). The epifauna at two sites within and two sites outside the closed area was sampled by divers. The species composition differed significantly among the four sites, but these spatial differences could not be attributed to dredging disturbance. The authors suggested that other factors, such as oxygen depletion, have a much greater impact on the spatial variability in this ecosystem. This ecosystem is also subjected to large fluctuations in salinity, temperature and eutrophication.

Discussion

METHODOLOGIES

The ideal impact study should be designed with the aim of detecting benthic habitat and community changes that can be attributed unambiguously to fishing disturbance on a spatial and temporal scale that is representative of commercial fishing activity. To date it has been difficult to conduct studies that fulfil these requirements (Kaiser *et al.*, 2000), and most studies have been carried out within small experimental areas that have been trawled over a relatively short period.

The potential effects in narrowly trawled corridors can be masked by rapid recolonization by organisms from adjacent untouched areas, or on the other hand disturbance effects may be enhanced by abundant scavengers feeding in a small area of exposed benthic fauna. The time aspect is also an important factor to consider, because changes relevant to the temporal scale of commercial fishing will not have evolved in samples taken immediately after a relatively short period of experimental trawling. Potential long-term impacts that may arise in areas subjected to commercial trawling could be more serious to the function of benthic communities than immediate effects.

Sampling in replicate control sites has been raised as a crucial prerequisite for impact studies because changes in community structures demonstrated in the area trawled cannot be attributed to trawling disturbance unless more than one control site is monitored (Hurlbert, 1984; Underwood, 1992; Lindegarth *et al.*, 2000b). The potential consequences of insufficient replication on the interpretation of impact experiments are demonstrated in the study by Lindegarth *et al.* (2000b) in which significant differences between pairs of control sites were revealed. However, conclusions from studies on short-term effects may be less affected by this type of confounding because the abundance of benthic animals may not show natural variability at these temporal scales.

Strictly quantitative sampling tools have not been used in all studies on trawl impacts, and even the use of quantitative tools (corers, grabs, improved sledges) does not ensure fully comparable samples. Trawling has been shown to cause sediment resuspension and changes in surface sediment characteristics (e.g. topography and hardness; see the chapter on Physical impacts), thus such changes may affect the efficiency of benthic sampling devices (Currie and Parry, 1996; 1999; Prena *et al.*, 1999; Kutti *et al.*, in press.). Increased abundance of sedentary organisms shortly after trawling has been demonstrated (e.g. Eleftheriou and Robertson, 1992; Kaiser

Ideally, impact studies should be conducted in areas that have been subjected to trawling on a spatial and temporal scale that is representative of commercial fishing activities. Quantitative sampling in replicate control sites is also a crucial prerequisite to allow firm conclusions.

et al., 1998; Ball, Fox and Munday, 2000), and can be explained only by an increase in the efficiency of the sampling device. The catchability of a sampling sledge may also decrease owing to the burial of organisms by resuspended sediment (Prena *et al.*, 1999).

The use of semi-quantitative sampling devices and changes in sampling efficiency after experimental trawling may introduce serious artefacts that ought to be considered when the results of impact studies are being interpreted. Furthermore, inappropriate sampling may increase the variability among samples, and thus decrease statistical power to detect true effects of trawling disturbance.

This chapter addresses three important methodological requirements for studying the impacts of trawling: disturbance at a spatial and temporal scale that is representative of commercial fishing, replicate controls, and quantitative sampling. Because the resources available (e.g. vessel time and labour cost for sample analyses) are limited, compromises have to be made, and most impact studies thus fail to meet one or more of these requirements (Table 5; Figure 8).

FIGURE 8
Frequency distributions of impact studies at different spatial scales (width of trawled area), temporal scales (time between experimental trawling and sampling), numbers of control sites and types of sampling tools

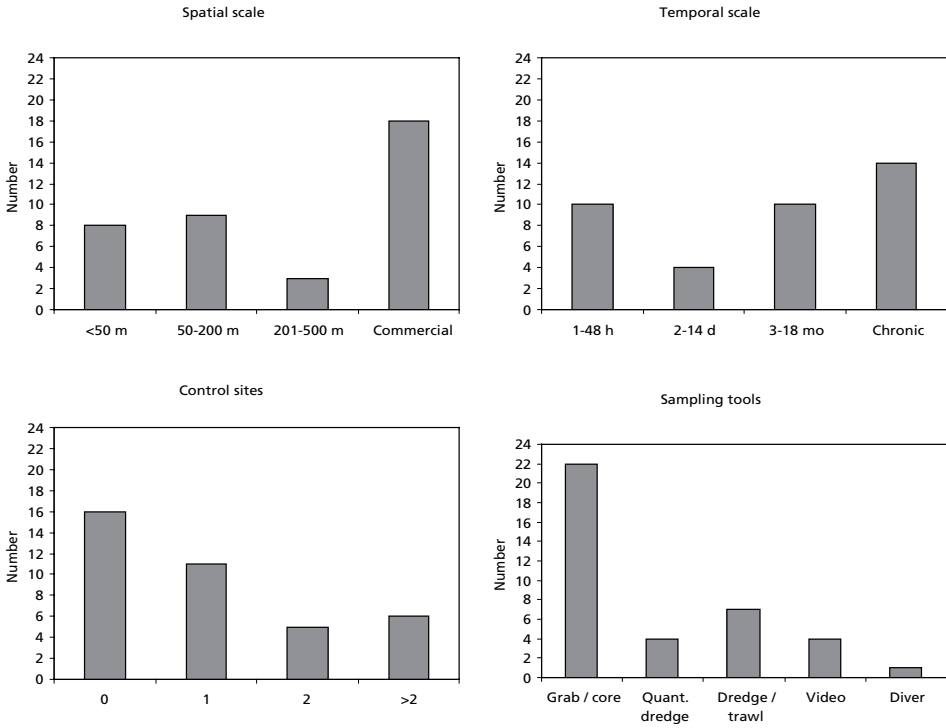


TABLE 5

Characteristics and design of studies to investigate the impacts of trawling and dredging on benthic habitats and communities

References	Spatial scale	Temporal scale	Control sites	Bottom mapping	Quantitative sampling	Trawling intensity	Gear description
Prena <i>et al.</i> , 1999	81–264 m	1–93 h	2	Yes	Yes	12 tows	Yes
Kenchington <i>et al.</i> , 2001	81–264 m	8–132 h and 1 yr	2	Yes	Yes	12 tows	Yes
Kutti <i>et al.</i> , in press.	200 m	15–29 h	No	Yes	Yes	10 tows	Yes
McConnaughey, Mier & Dew, 2000	1 nm ²	Chronic	42	No	No	No data	No
Engel & Kvitek, 1998	22 km ²	Chronic	No	No	Yes	4 times	No
Tuck <i>et al.</i> , 1998	250 m	6–18 mo	1*	Yes	Yes	16 (10 tows/ mo)	No
Hansson <i>et al.</i> , 2000	100 m	7–10 mo	3	No	Yes	40 (2 tows/ wk)	Yes
Drabsch, Tanner & Connell, 2001	200 m	1 wk	3	No	Yes	2 times	Yes
Sparks-McConkey & Watling, 2001	A few metres	0–6 mo	1	No	Yes	4 times	No
Van Dolah, Wendt & Levisen, 1991	Commercial	5 mo	1	No	Yes	No data	No
Frid, Clark & Hall, 1999	Commercial	Chronic	No	No	Yes	No data	No
Ball, Fox & Munday, 2000	40 m	24 h	No	No	Yes	2 tows	Partly
Ball, Fox & Munday, 2000	Commercial	Chronic	Wreck	No	Yes	No data	No
Hall <i>et al.</i> , 1993	Commercial	Chronic	Wreck	No	Yes	No data	No
Smith, Papadopoulou & Diliberto, 2000	500 m	8 mo	2*	No	Yes	No data	No
Sanchez <i>et al.</i> , 2000	150 m	1–150 h	2	No	Yes	1 and 2 tows	No
Simboursa <i>et al.</i> , 1998	Commercial	Chronic	1*	No	Yes	No data	No
Freese <i>et al.</i> , 1999	5 m	2 h–5 d	8	No	Video	1 tow	Yes
Moran & Stephenson, 2000	360 x 925 m	1 d	1	No	Video	4 times	No
Van Dolah, Wendt & Nicholson, 1987	30–35 m	0 and 12 mo	5	Divers	Yes	1 tow	Yes
Bergman & Hup, 1992	200 x 200 m	16 h and 2 wk	No	No	Yes	2 times	Yes
Bergman & Santbrink, 2000	60 x 2000 m	24–48 h	No	No	Yes	1.5 times	Yes
Kaiser & Spencer, 1996	30–40 m	12 h	3	Yes	Yes	10 and 20 times	Yes
Kaiser <i>et al.</i> , 1998	30–40 m	24 h and 6 mo	4	Yes	Yes	10 and 20 times	Yes
Jennings <i>et al.</i> , 2001	Commercial	Chronic	No	No	No	Rel. indices	No
Currie & Parry, 1996	600 x 600 m	0–14 mo	1	No	Yes	2 times	Yes
Currie & Parry, 1999	600 x 600 m	0–8 mo	1	No	No/Yes	2 and 4 times	Yes
Thrush <i>et al.</i> , 1995	20 x 35 m	2 h and 3 mo	1	Yes	Yes	1 time	Yes
Hall-Spencer <i>et al.</i> , 1999	60 m	15 h	No	Yes	Video	7 times	Yes
Pranovi <i>et al.</i> , 2000	3 m	1 and 7 d	1	Yes	Yes	1 tow	Yes
Eleftheriou & Robertson, 1992	A few metres	1 d	1	Yes	Yes	2–25 tows	Yes

TABLE 5 (con't.)

References	Spatial scale	Temporal scale	Control sites	Bottom mapping	Quantitative sampling	Trawling intensity	Gear description
Hoffmann & Dolmer, 2000	Commercial	Chronic	2*	No	Yes	No data	No
Kaiser <i>et al.</i> , 2000	Commercial	Chronic	No	No	No	Rel. indices	No
Kaiser, Spencer & Hart, 2000	Commercial	Chronic	No	Yes	No	No data	No
Thrush <i>et al.</i> , 1998	Commercial	Chronic	No	Yes	Yes	No data	Yes
Collie, Escanero & Valentine, 1997	Commercial	Chronic	No	Yes	No	No data	No
Collie, Escanero & Valentine, 2000	Commercial	Chronic	No	Yes	Video	No data	No
Hill <i>et al.</i> , 1999	Commercial	Chronic	No	No	No	Rel. indices	No

* Differences between the control sites or between the control site and the trawled site before the experimental trawling, i.e. not true controls.
Spatial scale: the size or width of the trawled area.
Temporal scale: the time between experimental trawling and sampling; "chronic" means that grounds subjected to commercial fishing have been investigated.
Quantitative sampling: core, grab, camera-equipped dredges and counting by divers are regarded as quantitative.
Trawling intensity: the number of tows along the experimental corridor, or the estimated number of times that the area has been touched by the trawl.

These and other potential deficiencies have to be taken into consideration before firm conclusions can be drawn. Although the investigators of these studies often recognized that their experimental designs had limitations, less caution is seen in review papers on this topic.

PHYSICAL IMPACTS

The chains of a beam trawl and the teeth of a scallop dredge are designed to penetrate the upper few centimetres of the sediment, and these parts cover the whole width of the gear. The trawl doors are the only part of an otter trawl that is rigged to penetrate into the sediment (with the exception of a few types of otter trawls rigged with chains). As a result of these differences in the rigging and catching principle, the physical impacts on the sea bed caused by otter trawling are likely to be different from those caused by beam trawling and scallop

Flattening of the bottom topography is the main physical impact of beam trawling and scallop dredging, whereas the doors of otter trawls create furrows. The consequences of these physical changes for the benthic community are poorly understood, and physical impacts should be determined at a fine scale of resolution that is relevant to benthic organisms.

dredging. As the latter two gear types penetrate into the sediment, the most conspicuous physical impact is flattening of bottom features such as ripples and irregular topography (e.g. Thrush *et al.*, 1995; Kaiser *et al.*, 1996). In addition, features such as bioturbation mounds and polychaete tubes are shown to be eliminated in the tracks of beam trawls and scallop dredges (Currie and Parry, 1996; Hall-Spencer *et al.*, 1999).

The ecological impacts of eliminating natural bottom features on the benthic community are not clear and have not been adequately addressed in the studies on trawling disturbance published to date.

Furrows and berms created by the trawl doors are the most conspicuous physical impacts from otter trawls. The trawl doors probably penetrate deeper into the sediments than scallop dredges and beam trawls, and create an irregular bottom topography rather than flattening natural features.

The area disturbed by the trawl doors comprises only a small proportion of the total area swept by the trawl, e.g. door spreads of 60 m and 140 m, respectively, for the cod trawls used in the studies by Prena *et al.* (1999) and Kutti *et al.* (in press). Because no or only faint marks are created by the other parts of an otter trawl, the physical impacts on the sea bed are likely to be marginal in most otter trawl fisheries. An exception may be intensively trawled fishing grounds in sheltered areas or in deep water, where trawl marks may last for a long time. In such areas, trawl furrows may accumulate during the fishing season and create long-lasting, irregular bottom topography.

Thus, the main physical impact of beam trawling and scallop dredging seems to be a flattening of the bottom topography, whereas the doors of otter trawls create irregular features on the sea bed. The longevity of these effects is determined by sediment type and natural disturbances (tidal current, wave actions and biological activities), and has been shown to last from a few hours to more than a year. However, data are too scarce to allow a clear relationship between persistence of trawl marks and bottom type/natural disturbance to be made. The consequences of physical disturbance of the sea bed topography for the benthic community structure are poorly understood, and have not been subject to much investigation (Gislason, 1994).

It should be noted however that the tools and methods used to determine physical impacts (RoxAnn, side-scan sonar, video) are rough and crude ways of describing sea bed characteristics. Schwinghamer, Guigné and Siu (1996), using very high-resolution acoustics, were able to determine small-scale structural changes in the upper 4.5 cm of the sediment at a scale of resolution that is relevant to the benthic biota. This is the scale at which the physical impacts of trawling should be investigated.

BIOLOGICAL IMPACTS

Several studies on the impacts of trawling on benthic communities state that trawling is the most disruptive and widespread anthropogenic disturbance on benthic habitats and may substantially alter benthic communities (e.g. Rumohr and Krost, 1991; Watling and Norse, 1998; Koslow *et al.*, 2001). This review has taken into account the fact that several studies of this topic have serious weaknesses and deficits, and has shown that the evidence for such statements is not well-documented or convincing. Other authors have stated that the impacts of trawling on benthic communities have been poorly studied and that such research has been limited to a few regions (Freese *et al.*, 1999; Smith, Papadopoulou and Diliberto, 2000). Furthermore, it has

It is difficult to conduct impact studies leading to clear and unambiguous conclusions because knowledge of the complexity and natural variability of benthic communities is rudimentary.

been concluded that few of the impacts of fishing have been well-documented (Currie and Parry, 1996), and that it has been difficult to attribute changes in the benthic community to fishing effort at a spatial scale that is representative of commercial fishing activities (Kaiser *et al.*, 2000). Benthic communities are complex and show large temporal and spatial variability. It is therefore difficult to conduct impact studies that give clear and unambiguous results, and general statements such as the one cited above should be avoided. This does not mean that trawling causes only subtle effects on benthic communities, but simply that it is difficult to demonstrate such impacts because knowledge of these complex communities is rather scarce, and effects may often be minor compared with the natural variability in space and time.

The complexity and natural variability of benthic communities raise two important issues related to the conclusions that can be drawn from trawl impact studies. Where effects have been demonstrated, caution must be taken when relating such effects to trawl disturbance, in particular in studies that lack appropriate replicate controls. Second, when effects have not been detected, it still cannot be concluded that there is no impact from fishing. The chance of detecting potential changes caused by trawling can be low because the power of the statistical tests in some studies has been shown to be very low (e.g. McConnaughey, Mier and Dew, 2000). Despite these deficiencies, and the fact that most studies have limitations, the growing literature on trawling impacts allows some conclusions to be drawn.

The comprehensive experiment conducted on the Grand Banks showed a 24 percent decrease in total biomass of megabenthic species (Prena *et al.*, 1999). This decrease in biomass was explained by predation by scavengers migrating into the narrow trawled corridors and a change in catchability of the sampling sledge after the trawling. It may therefore represent an overestimate of the real effect of the disturbance (D.C. Gordon, personal communication). For the macrofauna, total numbers of individuals decreased by 25 percent (mainly owing to declines

Habitats exposed to natural disturbances and showing large interannual variability in their benthic assemblage seem to be resistant to intensive otter trawling. The impacts demonstrated on soft bottom communities subjected to shrimp trawling were also subtle compared with natural seasonal changes. Habitats dominated by large sessile fauna may be severely affected by trawling.

in polychaetes) immediately after trawling in one of the three years of the experiment (Kenchington *et al.*, 2001). This decline seemed to recover within a year, and very few community indices or taxa showed any long-term effects from trawling. The most prominent feature of the Grand Banks study was considerable interannual variability in the mega- and macrofaunal assemblage, which indicates that the benthic community at the study site is dynamic and exhibits natural changes (Kenchington *et al.*, 2001). Similar conclusions can be drawn from the Barents Sea experiment by Kutti *et al.* (in press). This study was conducted in an area exposed to natural disturbances, and the benthic assemblage seemed to be resistant to intensive trawling.

Studies investigating the long-term effects of commercial trawling are few because comparable unfished control areas seldom exist. One exception is the study in the eastern Bering Sea by McConnaughey, Mier and Dew (2000), who showed that trawling caused reduced biomass of erect sessile organisms and mixed responses within motile groups and bivalves. Long-term effects of trawling were also indicated in the study of Engel and Kvitek (1998), but this study had serious shortcomings (lack of an unfished control site and no site replication), and should be interpreted with caution.

The four experiments on shrimp trawling provide no clear evidence of disturbance effects on benthic soft bottom communities, with the exception of a decrease in the abundance of echinoderms (mainly brittle stars) demonstrated in the Gullmarsfjord experiment (Van Dolah, Wendt and Levisen, 1991; Hansson *et al.*, 2000/Lindegarth *et al.*, 2000a; Drabsch, Tanner and Connell, 2001; Sparks-McConkey and Watling, 2001). Natural seasonal changes in community structures were demonstrated in these studies, whereas the changes that were attributed to trawling disturbances were regarded to be subtle. The two experiments on *Nephrops* trawling were also conducted on fine sediment bottoms (clay-sand), and one of them showed that trawling caused short-term effects in abundance and community composition (Frid, Clark and Hall, 1999; Ball, Fox and Munday, 2000). However, these studies lacked true control sites, and comparisons were made between sites displaying different physical characteristics. The study by Tuck *et al.* (1998) on a silty bottom also had several shortcomings, and most of the effects demonstrated were shown to recover after trawling ceased and were relatively subtle compared with the spatial and temporal variability in the area studied.

Mediterranean ecosystems may be less robust to disturbance than others owing to their special chemical and physical characteristics (oligotrophic, high salinity and temperature, negligible tidal currents). However, the three otter trawl studies conducted in the Mediterranean did not indicate that trawling disturbance caused severe changes in benthic community structures (Simboura *et al.*, 1998; Sanchez *et al.*, 2000; Smith, Papadopoulou and Diliberto, 2000). One of the studies showed a higher number of species and abundance on the control sites (Smith, Papadopoulou and Diliberto, 2000), while another showed that these figures were higher on the trawled site (Sanchez *et al.*, 2000). Furthermore, these Mediterranean studies demonstrated considerable differences in community structures that were attributed to natural variability in time and space.

Studies on the impacts of trawling on hard bottoms are few, but the three studies reviewed here all showed effects on large erect sessile invertebrates (Van Dolah, Wendt and Levisen, 1987; Freese *et al.*, 1999; Moran and Stephenson, 2000). Large proportions (15 to 67 percent) of the tall sessile fauna were damaged by one pass of the ground gear. These results were based on observations in the path of the ground gear, and the proportion of animals damaged averaged over the whole area fished by the commercial fleet will be considerably lower (see Moran and Stephenson, 2000). Reduced biomass of erect sessile organisms was also demonstrated in the eastern Bering Sea (McConnaughey, Mier and Dew, 2000).

Several studies provide clear evidence of the short-term effects of beam trawling and scallop dredging, with considerable decreases in abundance of several species. Trawling disturbance showed few effects in areas exposed to natural disturbances, and the long-term effects have not been studied.

Thus it can be concluded that tall sessile invertebrates such as sponges are damaged to a large extent when hit by the ground gear and, depending on the proportion of the fishing ground that is touched by this part of the trawl, habitats dominated by large sessile fauna may be severely affected by trawling.

Studies on the impacts of beam trawling have mainly been conducted in the North Sea and Irish Sea, and owing to the lack of appropriate control areas most of them investigated the immediate effects by comparing samples taken before and shortly after experimental trawling. These studies provide clear evidence of the short-term effects of beam trawling (Bergman and Hup, 1992; Kaiser and Spencer, 1996; Kaiser *et al.*, 1998; Bergman and Santbrink, 2000). Some species of several taxa (echinoderms, polychaetes, bivalves, crustaceans) were shown to decrease considerably in abundance (by up to 68 percent) immediately after trawling. This decrease was explained by damage from the passage of the trawl, exposure in the trawl track and removal by the trawl. The immediate effects demonstrated in these studies cannot be extrapolated to long-term effects of beam trawling on the benthic community (Bergman and Hup, 1992), and the reduction in abundances of megafaunal species observed immediately after trawling was shown to recover six months later (Kaiser *et al.*, 1998). On the other hand, a study based on fishing effort data showed that the total biomass of infauna decreased considerably with a 27-fold increase in trawling disturbance in an intensively trawled area of the North Sea (Jennings *et al.*, 2001). The two studies on beam trawling that were conducted in an area of mobile sediments subjected to natural disturbance showed no effects attributed to trawling disturbance (Kaiser and Spencer, 1996; Kaiser *et al.*, 1998).

Most of the studies on the impacts of scallop dredging are also based either on samples taken immediately after experimental trawling to demonstrate short-term effects or on comparison between areas subjected to different levels of commercial trawling. Effects demonstrated in the latter type of studies cannot be related unambiguously to dredging disturbance, as these experiments may involve the comparison of different habitat types. However, with the exception of two studies (Eleftheriou and Robertson, 1992; Hoffmann and Dolmer, 2000), effects on community structures were demonstrated in all the studies on scallop dredging reviewed here. The most common effects demonstrated were a decrease in number of species and reduced abundance for certain species (by 20 to 80 percent). These effects can be explained by mechanical damage and removal of benthos by the dredge. Recovery of the benthic community after dredging disturbance has been investigated in only one study, which showed that few effects lasted beyond eight months after dredging (Currie and Parry, 1996). Interestingly, the two studies in which no effects from dredging were observed were conducted at sites that were exposed to strong wave and tidal

actions (Eleftheriou and Robertson, 1992) or that were subjected to oxygen depletion and large fluctuations in other environmental factors (Hoffmann and Dolmer, 2000). Several of the studies on the impacts of dredging demonstrated that natural temporal and spatial variability in community structure may be more pronounced than changes caused by dredging disturbance (Currie and Parry, 1996, 1999; Thrush *et al.*, 1998; Kaiser, Spencer and Hart, 2000).

Despite the high number of impact studies conducted to date, this review has shown that few general conclusions can be drawn. As few studies incorporate factors such as habitat type, depth, level of disturbance, gear type and geographical region, the results of any single study are highly specific. In order to overcome this lack of progress, Collie *et al.* (2000) extracted results from 39 fishing impact studies and undertook an interesting meta-analysis. Although some consistent patterns and general relationships emerged from their study, the authors stated that their analyses had obvious limitations and the approach should be regarded as illustrative because of its paucity of data. Results from studies that incorporate factors such as habitat type, disturbance regime and gear type are needed before general conclusions can be drawn.

CONCLUSIONS

This review has demonstrated the importance of including evaluation and consideration of the methodology applied in studies of the impacts of trawling disturbances. Most impact studies fail to fulfil one or more of the important requirements of a proper assessment of trawl impacts. An evaluation of the impacts that trawling activities may have on benthic communities may lead to biased or even undocumented conclusions if limitations in the methodology applied are not considered.

Benthic hard bottom habitats dominated by sessile erect fauna are most severely affected by otter trawling, whereas only subtle effects have been demonstrated on soft bottoms without tall sessile invertebrates. However, most impact studies have been on sandy sea beds in relatively shallow water (at shelf depths, i.e. above the wave base), and little is known about the impacts in deep muddy habitats. Furthermore, potential damage in unique, sensitive habitats such as deep-water coral reefs is likely to be severe (Koslow *et al.*, 2001; Hall-Spencer, Allain and Fosså, 2002).

The level of impact on hard bottom communities will depend on the proportion of the habitat to be swept by the ground gear and the extent to which parts of the ground gear hit organisms. The full width or part of the ground gear may lose bottom contact, particularly on rough bottom (J.W. Valdemarsen, personal communication), and rock hopper and bobbins gear have large open spaces between the discs and bobbins (see Figure 5e). On the other hand, some fishing grounds are intensively fished and, owing to the pronounced patchiness of trawling effort, targeted fishing areas can be trawled several times per year (Rijnsdorp *et al.*, 1998; Prena *et al.*, 1999). If tall sessile fauna dominates such areas, the impacts are likely to be severe.

Documentation of the impacts of trawling in certain benthic habitats gives rise to the interesting management issue as to whether the associated fish populations and other exploited marine resources are affected by changes to habitat and benthic community structure. Although current knowledge of the linkage between benthic habitat complexity and the dynamics of fish populations is rudimentary (Auster and Langton, 1999), some effects on the fish community have been demonstrated, e.g. higher juvenile survivorship in more complex habitats (Tupper and Boutilier, 1995) and changes in the abundance of different fish genera following alteration in the abundance of epibenthic fauna (Sainsbury, 1988; Sainsbury *et al.*, 1997). The ultimate impacts of trawling on exploited marine resources cannot be fully understood until more knowledge of this linkage has been obtained.

Beam trawling and scallop dredging have also been shown to affect benthic communities, although only short-term effects have been studied. More emphasis should be given to investigations aimed at studying the long-term effects because fish populations will be affected more seriously by potential long-term effects. Several studies have demonstrated that anthropogenic impacts have a negative effect on longer-lived benthic species, but a positive effect on small opportunistic species (see Thrush *et al.*, 1998), and sole and plaice in the North Sea, which feed mainly on opportunistic species, have shown increasing growth rate over the last decades (Rijnsdorp and van Beek, 1991; Rijnsdorp and van Leeuwen, 1996). This increase in growth rate may be a result of increased productivity of suitable benthic food in heavily trawled areas of the North Sea, as these fishing grounds still provide profitable trawl catches (Rijnsdorp *et al.*, 1998).

Although an increasing number of impact studies have been conducted over the last two decades, it can be concluded that the knowledge of how towed fishing gears affect different habitat types is still rather rudimentary. The main reasons for this lack of scientifically based knowledge is that such studies are very complicated and demanding to conduct and that benthic communities show large natural variability that is not well understood. Knowledge of seasonal, annual and spatial variations in the benthic assemblage studied is therefore a prerequisite for assessing the impacts of trawling disturbances. Furthermore, there is a need to define the degree to which it is accepted that fishing activities cause changes in marine community structures. The degree of anthropogenic impacts must be evaluated in relation to the magnitude of natural disturbances (e.g. current and wave actions, fluctuations in temperature and salinity), as well as temporal and spatial variations that can be both substantial and unpredictable (Auster and Langton, 1999). Gear impacts need to be balanced against the need to harvest resources (Auster *et al.*, 1996).

References

- Anonymous.** 1993. *Trawlskovle – Håndbog om valg og justering. Kontrakt nr. TE.1.214*. Hirtshals, Denmark, DIFTA. 117 pp. (in Danish)
- Auster, P.J. & Langton, R.W.** 1999. The effects of fishing on fish habitat. *American Fisheries Society Symposium*, 22:150–187.
- Auster P.J., Malatesta, R.J., Langton, R.W., Watling, L., Valentine, P.C., Donaldson, C.L.S., Langton, E.W., Shepard, A.N. & Babb, I.G.** 1996. The impacts of mobile fishing gear on seafloor habitats in the Gulf of Maine (Northwest Atlantic): Implications for conservation of fish population. *Reviews in Fisheries Science*, 4: 185–202.
- Ball, B.J., Fox, G. & Munday, B.W.** 2000. Long- and short-term consequences of a *Nephrops* trawl fishery on the benthos and environment of the Irish Sea. *ICES Journal of Marine Science*, 57: 1315–1320.
- Bergman, M.J.N. & Hup, M.** 1992. Direct effects of beamtrawling on macrofauna in a sandy sediment in the southern North Sea. *ICES Journal of Marine Science*, 49: 5–11.
- Bergman, M.J.N. & van Santbrink, J.W.** 1994. A new benthos dredge (“Triple-D”) for quantitative sampling of infauna species of low abundance. *Netherlands Journal of Sea Research*, 33: 129–133.
- Bergman, M.J.N. & van Santbrink, J.W.** 2000. Mortality in megafaunal benthic populations caused by trawl fisheries on the Dutch continental shelf in the North Sea in 1994. *ICES Journal of Marine Science*, 57: 1321–1331.
- Bohnsack, J.A. & Sutherland, D.L.** 1985. Artificial reef research: a review with recommendations for future priorities. *Bulletin of Marine Science*, 37: 11–39.
- Brylinsky, M., Gibson, J. & Gordon Jr., D.C.** 1994. Impacts of flounder trawls on the intertidal habitat and community of the Minas Basin, Bay of Fundy. *Canadian Journal of Fisheries and Aquatic Science*, 51: 650–661.
- Chapman, M.G., Underwood, A.J. & Skilleter, G.A.** 1995. Variability at different spatial scales between a subtidal assemblage exposed to the discharge of sewage and two untrawled assemblages. *Journal of Experimental Marine Biology and Ecology*, 189: 1–2.
- Churchill, J.H.** 1989. The effect of commercial trawling on sediment resuspension and transport over the middle Atlantic Bight. *Continental Shelf Research*, 9: 841–865.
- Collie, J.S., Escanero, G.A. & Valentine, P.C.** 1997. Effects of bottom fishing on the benthic megafauna of Georges Bank. *Marine Ecology Progress Series*, 155: 159–172.
- Collie, J.S., Escanero, G.A. & Valentine, P.C.** 2000. Photographic evaluation of the impacts of bottom fishing on benthic epifauna. *ICES Journal of Marine Science*, 57: 987–1001.
- Collie, J.S., Hall, S.J., Kaiser, M.J. & Poiner, I.R.** 2000. A quantitative analysis of fishing impacts on shelf-sea benthos. *Journal of Animal Ecology*, 69: 785–798.

- Currie, D.R. & Parry, G.D. 1996. Effects of scallop dredging on a soft sediment community: a large-scale experimental study. *Marine Ecology Progress Series*, 134: 131–150.
- Currie, D.R. & Parry, G.D. 1999. Impacts and efficiency of scallop dredging on different soft substrates. *Canadian Journal of Fisheries and Aquatic Science*, 56: 539–550.
- De Groot, S.J. 1984. The impact of bottom trawling on benthic fauna of the North Sea. *Ocean Management*, 9: 177–190.
- Drabsch, S.L., Tanner, J.E. & Connell, S.D. 2001. Limited infaunal response to experimental trawling in previously untrawled areas. *ICES Journal of Marine Science*, 58: 1261–1271.
- Eleftheriou, A. & Robertson, M.R. 1992. The effects of experimental scallop dredging on the fauna and physical environment of a shallow sandy community. *Netherlands Journal of Sea Research*, 30: 289–299.
- Engås, A., Godø, O.R. & Jørgensen, T. 2000. A comparison between vessel and trawl tracks as observed by the ITI trawl instrumentation. *Fisheries Research*, 45: 297–301.
- Engel, J. & Kvitek, R. 1998. Effects of otter trawling on a benthic community in Monterey Bay National Marine Sanctuary. *Conservation Biology*, 12: 1204–1214.
- Fonteyne, R. 2000. Physical impacts of beam trawls on sea bed sediments. In M.J. Kaiser and S.J. de Groot, eds. *Effects of fishing on non-target species and habitats. Biological, conservation and socio-economic issues*. Oxford, UK, Blackwell Science. pp. 15–36.
- Freese, L., Auster, P.J., Heifetz, J. & Wing, B.L. 1999. Effects of trawling on seafloor habitat and associated invertebrate taxa in the Gulf of Alaska. *Marine Ecology Progress Series*, 182: 119–126.
- Frid, C.L.J., Clark, R.A. & Hall, J.A. 1999. Long-term changes in the benthos on a heavily fished ground off the NE coast of England. *Marine Ecology Progress Series*, 188: 13–20.
- Friedlander, A.M., Boehlert, G.W., Field, M.E., Mason, J.E., Gardner, J.V. & Dartnell, P. 1999. Sidescan-sonar mapping of benthic trawl marks on the shelf and slope off Eureka, California. *Fishery Bulletin*, 97: 786–801.
- Gilkinson, K., Paulin, M., Hurley, S. & Schwinghamer, P. 1998. Impacts of trawl door scouring on infaunal bivalves: results of a physical trawl door model/dense sand interaction. *Journal of Experimental Marine Biology and Ecology*, 224: 291–312.
- Gislason, H. 1994. Ecosystem effects of fishing activities in the North Sea. *Marine Pollution Bulletin*, 29: 520–527.
- Graham, M. 1955. Effect of trawling on animals of the sea bed. *Deep Sea Research*, Suppl. 3: 1–6.
- Greenstreet, S.P.R., Tuck, I.D., Grewar, G.N., Armstrong, E., Reid, D.G. & Wright, P.J. 1997. An assessment of the acoustic survey technique, RoxAnn, as a mean of mapping sea bed habitat. *ICES Journal of Marine Science*, 54: 939–959.
- Hall, S.J. 1999. *The effects of fishing on marine ecosystems and communities*. Oxford, UK, Blackwell Science. 274 pp.

- Hall, S.J., Robertson, M.R., Basford, D.J. & Heaney, S.D. 1993. The possible effects of fishing disturbance in the northern North Sea: an analysis of spatial patterns in community structure around a wreck. *Netherlands Journal of Sea Research*, 31: 201–208.
- Hall-Spencer, J.M., Allain, V. & Fosså, J.H. 2002. Trawling damage to Northeast Atlantic ancient coral reefs. *Proc. R. Soc. Lond. B.*, 269: 507–511.
- Hall-Spencer, J.M., Frogli, C., Atkinson, R.J.A. & Moore, P.G. 1999. The impact of Rapido trawling for scallops, *Pecten jacobaeus* (L.), on the benthos of the Gulf of Venice. *ICES Journal of Marine Science*, 56: 111–124.
- Hamilton, L.J., Mulhearn, P.J. & Poeckert, R. 1999. Comparison of RoxAnn and QTC-view acoustic bottom classification system performance for the Cairns area, Great Barrier Reef, Australia. *Continental Shelf Research*, 12: 1577–1597.
- Hansson, M., Lindegarth, M., Valentinsson, D. & Ulmestrand, M. 2000. Effects of shrimp-trawling on abundance of benthic macrofauna in Gullmarsfjorden, Sweden. *Marine Ecology Progress Series*, 198: 191–201.
- Hill, A.S., Veale, L.O., Pennington, D., Whyte, S.G., Brand, A.R. & Hartnoll, R.G. 1999. Changes in Irish Sea benthos: possible effects of 40 years of dredging. *Estuarine, Coastal and Shelf Science*, 48: 739–750.
- Hoffmann, E. & Dolmer, P. 2000. Effect of closed areas on distribution of fish and epibenthos. *ICES Journal of Marine Science*, 57: 1310–1314.
- Holme, N.A. & McIntyre, A.D. 1984. *Methods for the study of marine benthos*. Oxford, UK, Blackwell Science. 387 pp.
- Humborstad, O.-B., Nøttestad, L., Løkkeborg, S. & Rapp, H.T. 2004. RoxAnn bottom classification system, sidescan sonar and video-sledge: spatial resolution and their use in assessing trawling impacts. *ICES Journal of Marine Science*, 61:53–63.
- Hurlbert, S.H. 1984. Pseudoreplication and the design of ecological field experiments. *Ecol. Monogr.*, 54: 187–211.
- Jennings, S. & Kaiser, M.J. 1998. The effects of fishing on marine ecosystems. *Advances in Marine Biology*, 34: 201–352.
- Jennings, S., Pinnegar, J.K., Polunin, N.V.C. & Warr, K.J. 2001. Impacts of trawling disturbance on the trophic structure of benthic invertebrate communities. *Marine Ecology Progress Series*, 213: 127–142.
- Kaiser, M.J. & de Groot, S.J. 2000. *Effects of fishing on non-target species and habitats. Biological, conservation and socio-economic issues*. Oxford, UK, Blackwell Science. 399 pp.
- Kaiser, M.J. & Spencer, B.E. 1994. Fish scavenging behaviour in recently trawled areas. *Marine Ecology Progress Series*, 112: 41–49.
- Kaiser, M.J. & Spencer, B.E. 1996. The effects of beam-trawl disturbance on infaunal communities in different habitats. *Journal of Animal Ecology*, 65: 348–358.
- Kaiser, M.J., Spencer, B.E. & Hart, P.J.B. 2000. Fishing-gear restrictions and conservation of benthic habitat complexity. *Conservation Biology*, 14: 1512–1525.
- Kaiser, M.J., Hill, A.S., Ramsay, K., Spencer, B.E., Brand, A.R., Veale, L.O., Prudden, K., Rees, E.I.S., Munday, B.W., Ball, B. & Hawkins, S.J. 1996. Benthic disturbance by fishing gear in the Irish Sea: a comparison of beam trawling and scallop dredging. *Aquatic Conservation Marine and Freshwater Ecosystem*, 6: 269–295.

- Kaiser, M.J., Edwards, D.B., Armstrong, P.J., Radford, K., Lough, N.E.L., Flatt, R.P. & Jones, H.D. 1998. Changes in megafaunal benthic communities in different habitats after trawling disturbance. *Journal of Marine Science*, 55: 353–361.
- Kaiser, M.J., Ramsay, K., Richardson, C.A., Spence, F.E. & Brand, A.R. 2000. Chronic fishing disturbance has changed shelf sea benthic community structure. *Journal of Animal Ecology*, 69: 494–503.
- Kenchington, E.L.R., Prena, J., Gilkinson, K.D., Gordon Jr., D.C., Macissac, K., Bourbonnais, C., Schwinghamer, P.J., Rowell, T.W., McKeown, D.L. & Vass, W.P. 2001. Effects of experimental otter trawling on the macrofauna of a sandy bottom ecosystem on the Grand Banks of Newfoundland. *Canadian Journal of Fisheries and Aquatic Science*, 58: 1043–1057.
- Koslow, J.A., Gowlet-Holmes, K., Lowry, J.K., O'Hara, T., Poore, G.C.B. & Williams, A. 2001. Seamount benthic macrofauna off southern Tasmania: community structure and impacts of trawling. *Marine Ecology Progress Series*, 213: 111–125.
- Krost, P., Bernhard, M., Werner, F. & Hukriede, W. 1990. Otter trawl tracks in Kiel Bay (Western Baltic) mapped by side-scan sonar. *Meeresforschung*, 32: 344–353.
- Kutti, T., Høisæter, T., Rapp, H.T., Humborstad, O.-B., Løkkeborg, S. & Nøttestad, L. In press. Immediate effects of experimental otter trawling on a sub-arctic benthic assemblage inside Bear Island Fishery Protection Zone in the Barents Sea. *American Fishery Society Symposia*, in press.
- Lindeboom, H.J. & de Groot, S.J. 1998. *IMPACT-II: The effects of different types of fisheries on the North Sea and Irish Sea benthic ecosystems*. NIOZ- Report 1998-1/ RIVO-DLO Report C003/98. Den Burg, Texel, Netherlands, Netherlands Institute for Sea Research. 404 pp.
- Lindgarth, M., Valentinsson, D., Hansson, M. & Ulmestrand, M. 2000a. Effects of trawling disturbances on temporal and spatial structure of benthic soft-sediment assemblages in Gullmarsfjorden, Sweden. *ICES Journal of Marine Science*, 57: 1369–1376.
- Lindgarth, M., Valentinsson, D., Hansson, M. & Ulmestrand, M. 2000b. Interpreting large-scale experiments on effects of trawling on benthic fauna: an empirical test of the potential effects of spatial confounding in experiments without replicated control and trawled areas. *Journal of Experimental Marine Biology and Ecology*, 245: 155–169.
- Lindley, J.A., Gamble, J.C. & Hunt, H.G. 1995. A change in the zooplankton of the central North Sea (55° to 58° N): a possible consequence of changes in the benthos. *Marine Ecology Progress Series*, 115: 209–217.
- McConnaughey, R.A., Mier, K.L. & Dew, C.B. 2000. An examination of chronic trawling effects on soft-bottom benthos of the eastern Bering Sea. *ICES Journal of Marine Science*, 57: 1377–1388.
- Moran, M.J. & Stephenson, P.C. 2000. Effects of otter trawling on macrobenthos and management of demersal scalefish fisheries on the continental shelf of north-western Australia. *ICES Journal of Marine Science*, 57: 510–516.
- Paschen, M., Richter, U. & Köpnick, W. 2000. *Trapeze. Trawl penetration in the sea bed*. Contract No. 96-006. Rostock, Germany, University of Rostock.

- Pranovi, F., Raicevich, S., Franceschini, G., Farrace, M.G. & Giovanardi, O. 2000. Rapido trawling in the northern Adriatic Sea: effects on benthic communities in an experimental area. *ICES Journal of Marine Science*, 57: 517–524.
- Prena, J., Schwinghamer, P., Rowell, T.W., Gordon Jr., D.C., Gilkinson, K.D., Vass, W.P. & McKeown, D.L. 1999. Experimental otter trawling on a sandy bottom ecosystem of the Grand Banks of Newfoundland: analysis of trawl bycatch and effects on epifauna. *Marine Ecology Progress Series*, 181: 107–124.
- Ramsay, K., Kaiser, M.J. & Hughes, R.N. 1998. Responses of benthic scavengers to fishing disturbance by towed gears in different habitats. *Journal of Experimental Marine Biology and Ecology*, 224: 73–89.
- Rijnsdorp, A.D. & van Beek, F.A. 1991. Changes in growth of plaice *Pleuronectes platessa* L. and sole *Solea solea* L. in the North Sea. *Netherlands Journal of Sea Research*, 27: 433–439.
- Rijnsdorp, A.D. & van Leeuwen, P.I. 1996. Changes in growth of North Sea plaice since 1950 in relation to density, eutrophication, beam-trawl effort, and temperature. *ICES Journal of Marine Science*, 53: 1199–1213.
- Rijnsdorp, A.D., Buys, A.M., Storbeck, F. & Visser, E.G. 1998. Micro-scale distribution of beam trawl effort in the southern North Sea between 1993 and 1996 in relation to the trawling frequency of the sea bed and the impact on benthic organisms. *ICES Journal of Marine Science*, 55: 403–419.
- Rumohr, H. & Krost, P. 1991. Experimental evidence of damage to benthos by bottom trawling with special reference to *Artica islandica*. *Meeresforschung*, 33: 340–345.
- Sainsbury, K.J. 1988. The ecological basis of multispecies fisheries management of a demersal fishery in tropical Australia. In J.A. Gulland, ed. *Fish population dynamics*. Chichester, UK, John Wiley, pp. 349–382.
- Sainsbury, K.J., Campell, R.A., Lindholm, R. & Whitelaw, A.W. 1997. Experimental management of an Australian multispecies fishery: examining the possibility of trawl-induced habitat modification. In K. Pikitch, D.D. Huppert and M.P. Sissenwine, eds. *Global trends: fisheries managements*. Bethesda, Maryland, USA, American Fisheries Society. pp. 107–112.
- Sanchez, P., Demestre, M., Ramon, M. & Kaiser, M.J. 2000. The impact of otter trawling on mud communities in the northwestern Mediterranean. *ICES Journal of Marine Science*, 57: 1352–1358.
- Schwinghamer, P., Guigné, J.Y. & Siu, W.C. 1996. Quantifying the impact of trawling on benthic habitat structure using high resolution acoustics and chaos theory. *Canadian Journal of Fisheries and Aquatic Science*, 53: 288–296.
- Schwinghamer, P., Gordon Jr., D.C., Rowell, T.W., Prena, J., McKeown, D.L., Sonnichsen, G. & Guigné, J.Y. 1998. Effects of experimental otter trawling on surficial sediment properties of a sandy-bottom ecosystem on the Grand Banks of Newfoundland. *Conservation Biology*, 12: 1215–1222.
- Seaman, L.M. & Sprague, L.M. 1991. *Artificial habitats for marine and freshwater fisheries*. San Diego, California, USA, Academic Press. 285 pp.
- Simboura, N., Zenetos, A., Pancucci-Papadopoulou, M.-A., Thessalou-Legali, M. & Papaspyrou, S. 1998. A baseline study of benthic species distribution in two

- neighbouring gulfs, with and without access to bottom trawling. *Marine Ecology*, 19: 293–309.
- Smith, C.J., Papadopoulou, K.N. & Diliberto, S. 2000. Impact of otter trawling on an eastern Mediterranean commercial trawl fishing ground. *ICES Journal of Marine Science*, 57: 1340–1351.
- Sparks-McConkey, P.J. & Watling, L. 2001. Effects on the ecological integrity of a soft-bottom habitat from a trawling disturbance. *Hydrobiologia*, 456: 73–85.
- Stewart-Oaten, A., Murdoch, W.W. & Parker, K.R. 1986. Environmental impact assessment: “pseudoreplication” in time? *Ecology*, 67: 929–940.
- Thrush, S.F., Hewitt, J.E., Cummings, V.J. & Dayton, P.K. 1995. The impact of habitat disturbance by scallop dredging on marine benthic communities: what can be predicted from the results of experiments? *Marine Ecology Progress Series*, 129: 141–150.
- Thrush, S.F., Hewitt, J.E., Cummings, V.J., Dayton, P.K., Cryer, M., Turner, S.J., Funnel, G.A., Budd, R.G., Milburn, R.G. & Wilkinson, M.R. 1998. Disturbance of the marine benthic habitat by commercial fishing: Impacts at the scale of the fishery. *Ecological Applications*, 8: 866–879.
- Tuck, I.D., Hall, S.J., Robertson, M.R., Armstrong, E. & Basford, D.J. 1998. Effects of physical trawling disturbance in a previously unfished sheltered Scottish sea loch. *Marine Ecology Progress Series*, 162: 227–242.
- Tupper, M. & Boutilier, R.G. 1995. Effects of habitat on settlement, growth, and postsettlement survival of Atlantic cod (*Gadus morhua*). *Canadian Journal of Fisheries and Aquatic Science*, 52: 1834–1841.
- Underwood, A.J. 1991. Beyond BACI: experimental designs for detecting human environmental impacts on temporal variations in natural populations. *Australian Journal of Marine and Freshwater Research*, 42: 569–587.
- Underwood, A.J. 1992. Beyond BACI: the detection of environmental impacts on populations in the real, but variable, world. *Journal of Experimental Marine Biology and Ecology*, 161: 145–178.
- Van Dolah, R.F., Wendt, P.H. & Levisen, M.V. 1991. A study of the effects of shrimp trawling on benthic communities in two South Carolina sounds. *Fisheries Research*, 12: 139–156.
- Van Dolah, R.F., Wendt, P.H. & Nicholson, N. 1987. Effects of a research trawl on a hard-bottom assemblage of sponges and corals. *Fisheries Research*, 5: 39–54.
- Watling, L. & Norse, E.A. 1998. Disturbance of the sea bed by mobile fishing gear: A comparison to forest clearcutting. *Conservation Biology*, 12: 1178–1197.

Over the last two decades, concerns about the impact of towed fishing gears such as trawls and dredges on benthic habitats and organisms have increased. This publication reviews the most recent experimental studies of the impact of towed fishing gears on benthic communities. Otter trawls, beam trawls and scallop dredges are likely to have different physical impacts on the sea bed owing to their different catching techniques. The most noticeable physical effect of otter trawling is the furrow created by the doors. Beam trawling and scallop dredging cause a flattening of irregular bottom topography by eliminating natural features. The long-term effects of fishing activities have not been investigated although several studies provide clear evidence of short-term consequences. The difficulty in conducting impact studies that produce clear conclusions stems mainly from the complexity and natural variability of benthic communities.

