Fisheries and Oceans Canada / Pêches et Océans Canada
Science / Sciences

C S A S / **S C C S**

Canadian Science Advisory Secretariat / **Secrétariat canadien de consultation scientifique**

Research Document 2006/056 / **Document de recherche 2006/056**

Not to be cited without permission of the authors *

Ne pas citer sans autorisation des auteurs *

A review of Maritimes Region research on the effects of mobile fishing gear on benthic habitat and communities

Examen de la recherche menée dans la région des Maritimes sur les effets des engins de pêche mobiles sur l'habitat et les communautés benthiques

Gordon, D.C. Jr., E.L.R. Kenchington and K.D. Gilkinson[1]

Bedford Institute of Oceanography
PO Box 1006
Dartmouth, NS B2Y 4A2

[1]Northwest Atlantic Fisheries Centre
PO Box 5667
St. John's, NL A1C 5X1

ISSN 1499-3848 (Printed / Imprimé)

Canada

ABSTRACT

In collaboration with the Newfoundland & Labrador Region, the Maritimes Region has conducted an extensive field program to provide quantitative information on the effects of bottom-contacting mobile fishing gear on benthic habitat and communities. This research has included carefully designed manipulative experiments as well as observational and laboratory studies. The three major gear types used in Atlantic Canada have been studied (otter trawls, scallop dredges and hydraulic clam dredges). Impacts on both sand and gravel habitats have been investigated, but not mud habitats. Geographic areas considered include the Bay of Fundy, Northeast Channel, Western Bank, Banquereau, Laurentian Channel and the Grand Bank. The results provide information on immediate impacts (recovery < 1 y), short-term impacts (recovery 1-10 y), and long-term impacts (recovery >10 y). With just a few exceptions, the results have been subjected to peer review and published in the scientific literature (the last few reports are being drafted). They illustrate that the impacts of bottom-contacting mobile fishing gear are extremely variable and depend upon many factors including the kind of gear, how it is used, the return period of the disturbance, the kind of physical habitat and the species composition of the benthic community. Sandy habitats are easier to disturb but are faster to recover than gravel habitats. The most sensitive species are large epibenthic forms, especially those that are sessile and have slow growth rates. The results are in general agreement with the conclusions reached from recent international reviews on this issue with the exception that not all gravel habitats may be as sensitive as generally thought. The impacts of bottom-contacting mobile fishing gear is an important issue that needs to be considered as Canada moves to adopt an ecosystem approach to fisheries management. The most effective management measures are effort control, gear modification and substitution, and establishment of closed areas. The best course for action needs to be decided with input from all stakeholders (i.e. scientists, fisheries managers, habitat and ocean managers, industry, coastal communities, NGOs, etc.).

RÉSUMÉ

En collaboration avec la Région de Terre-Neuve et du Labrador, la Région des Maritimes a mené un programme exhaustif sur le terrain dans le but de recueillir des renseignements quantitatifs sur les effets des engins de pêche mobiles qui entrent en contact avec le fond sur l'habitat et les communautés benthiques. Cette recherche comportait des expériences de manipulation conçues avec minutie ainsi que des études par observation et de laboratoire. On a étudié les trois principaux types d'engins utilisés dans le Canada atlantique (chaluts à panneaux, dragues à pétoncles et dragues hydrauliques à palourdes). On a également examiné les impacts qu'ont ces engins sur les habitats sableux et graveleux, mais pas sur les habitats vaseux. Parmi les zones géographiques considérées, mentionnons la baie de Fundy, le chenal Nord-Est, le banc Western, le banc Banquereau, le chenal Laurentien et le Grand Banc. Les résultats obtenus nous renseignent sur les effets immédiats (rétablissement après moins de 1 an), à court terme (rétablissement après 1 à 10 ans) et à long terme (rétablissement après plus de 10 ans). À quelques exceptions près, les résultats ont été soumis à un examen par des pairs et ont ensuite été publiés dans des ouvrages scientifiques (les derniers rapports sont en cours de rédaction). Ils montrent que les effets des engins de pêche mobiles qui entrent en contact avec le fond sont extrêmement variables et qu'ils sont fonction d'un grand nombre de facteurs, y compris le genre d'engin utilisé et la façon dont il est employé, la période de rétablissement après la perturbation, le genre d'habitat physique dans lequel l'engin est utilisé ainsi que la composition des espèces de la communauté benthique. Les habitats sableux sont plus faciles à perturber, mais se rétablissent plus rapidement que les habitats graveleux. Les grandes espèces épibenthiques sont les plus vulnérables, particulièrement celles qui sont sessiles et qui affichent des taux de croissance lents. Les résultats correspondent généralement aux conclusions formulées à partir des récents examens internationaux portant sur le présent enjeu, si ce n'est que tous les habitats graveleux ne sont peut-être pas aussi vulnérables qu'on ne le pense en général. Les impacts des engins de pêche mobiles qui entrent en contact avec le fond constituent un enjeu important qui doit être considéré du fait que le Canada est en trains d'adopter une approche écosystémique pour la gestion des pêches. Les mesures de gestion les plus efficaces sont la gestion de l'effort de pêche, la modification et le remplacement des engins ainsi que la fermeture de zones. On doit décider de la meilleure voie à suivre de concert avec tous les intervenants (c.-à-d., les scientifiques, les gestionnaires des pêches, les gestionnaires des habitats et des océans, l'industrie, les communautés côtières, les ONG, etc.).

INTRODUCTION

The potential environmental impacts of fishing gear have long been a concern in Canada. The first known reference is Ketchen (1947) who reported observations on the impacts of an otter trawl on intertidal sediments in Departure Bay, BC. Caddy (1973) reported observations of the impacts of dredges and trawls on a scallop ground in the Bay of Chaleur, PQ. Scarratt (1973) investigated the effects of Irish moss rakes on lobster, Pringle and Semple (1987) examined the effects of rakes on Irish moss size structure, while Pringle and Jones (1980) studied the interactions of lobster, scallop and Irish moss fisheries off PEI. The impact of scallop dredging has been studied in the Gulf of St. Lawrence (Jamieson and Campbell 1985), St. Mary's Bay (Robichaud et al. 1987), and inshore Nova Scotia (Roddick and Miller 1992). The primary focus of these early studies was resolving conflicts between different coastal fisheries.

In 1990, a collaborative research program between the Maritimes and Newfoundland & Labrador Regions was established to study the potential impacts of mobile fishing gear on benthic marine ecosystems in Atlantic Canada. The long term objectives were to: 1) develop new instrumentation for viewing and sampling marine benthic habitat and communities, 2) obtain quantitative information on the impacts of mobile fishing gear on benthic habitat and communities, and 3) obtain quantitative information on the recovery rate of benthic habitat and communities after disturbance by mobile fishing gear. Funding over the years was provided from numerous sources including DFO A-Base, the Northern Cod Science Program, the Atlantic Fisheries Adjustment Program (AFAP), the Green Plan Sustainable Fisheries Program, the Environmental Science Strategic Research Fund (ESSFR), and the fishing industry.

The research conducted involved strong collaboration with the Geological Survey of Canada, Atlantic (GSCA), numerous contractors in both Nova Scotia and Newfoundland, universities, and the fishing industry. Program planning included input from fisheries biologists, fisheries and habitat managers, and the fishing industry. Contacts with European scientists, especially through ICES working groups, influenced program design. Scientists from Germany and The Netherlands participated directly in the program.

At the start of the program, a literature review of the effects of trawling, dredging and ocean dumping in Atlantic Canada was conducted by Messieh et al. (1991). In addition, an analysis of historical sidescan sonar records collected over the years by GSCA provided some information on the degree and distribution of mobile gear disturbance (Jenner et al. 1991, Harrison et al. 1991). In the Maritimes Region, less than 2% of the seabed surveyed showed any evidence of physical disturbance by mobile gear. Most was due to groundfish trawls and was restricted to areas of low sediment transport. On the Grand Banks, less than 10% of the total records showed evidence of trawling disturbance.

Considerable effort was devoted to developing new instrumentation or modifying existing equipment for observing and sampling the seabed and its biological communities. Three new tools were developed (Towcam, Campod and Videograb) (Gordon et al. 2006) and used extensively in field programs. The DRUMS™ acoustic imaging system was developed under contract by Guigné International Ltd. and integrated into the Videograb to provide information of small-scale structural properties of surficial sediments (Guigné et al. 1993, Schwinghamer et al. 1996, Schwinghamer et al. 1998). The availability of dGPS, an ORE Trackpoint acoustic positioning system, and PC-based shipboard navigation systems allowed accurate positioning of the research vessel, fishing gear and sampling equipment over the seabed (generally less than 10 m)(McKeown and Gordon 1997).

Under the lead of the Newfoundland & Labrador Region, the spatial pattern of otter trawling in Atlantic Canada was estimated using data collected in the fisheries observer program over the period from 1980 to 2000. The results indicate that trawling intensity varied widely with only relatively small areas being intensively trawled (Kulka and Pitcher 2001). This work is described in more detail in the Newfoundland & Labrador Region working paper.

Three main approaches have been used for field studies of fishing gear impacts on benthic habitat and communities: manipulative experiments, comparing different areas at the same time that have different fishing histories, and temporal studies at a single area with a well-documented fishing history. Each approach has it own strengths and weaknesses so that a combination of approaches is required for a full understanding of fishing gear impacts. Extracting unequivocal results from field data is complicated by the pronounced spatial and temporal variability inherent in benthic habitat and communities.

Over the last 15 years, DFO has been using these different approaches to investigate gear impacts in Atlantic Canada. Manipulative experiments have been conducted with otter trawls in the Minas Basin, on the Grand Banks of Newfoundland and on Western Bank. Manipulative experiments were also conducted with a hydraulic clam dredge on Banquereau and a scallop rake in the Bay of Fundy. Comparative studies, both spatial and temporal, have been conducted on the Digby scallop grounds in the Bay of Fundy. In addition, pertinent observations of gear impacts have been made during the recent DFO deep-water coral program. Some laboratory studies have also been conducted.

This working paper summarizes the results of these numerous DFO projects, most of which have already been peer-reviewed and published in the scientific literature. We then compare our results to the general conclusions of gear impacts that have come out of international reviews, as summarized in the working paper prepared by Rice. We conclude by offering recommendations for further research and how this information could be used in the management of Canadian fisheries.

SUMMARY OF FIELD AND LABORATORY PROGRAMS

Definition of Terms

Immediate Impacts

Those impacts on habitat and organisms created by the physical disturbance imparted by the fishing gear contacting the seabed. They include removal, destruction and displacement of habitat features (including structural biota), resuspension and sedimentation, creation of tracks and furrows, removal of organisms (harvest and bycatch), death and damage to organisms left behind on the seabed, displacement/redistribution of organisms, and the attraction of scavengers.

Recovery

The return of habitat and communities to conditions present before the fishing disturbance, or a new state of equilibrium. Recovery starts immediately and the rate depends upon the properties of habitat and life history traits of the organisms. Recovery processes include sediment transport, bioturbation, migration, growth and reproduction. Recovery rates can range from days to centuries, depending in part on the frequency of natural disturbance events such as storms.

Short-term Impacts

Those impacts on habitat and communities for which the recovery period is on the order of 1-10 years.

Long-term Impacts

Those impacts on both habitat and communities for which the recovery period is greater than 10 years.

Return Period

The time between fishing disturbance events which can range from weeks to many years. If shorter than the recovery period, short-term and long-term impacts are highly probable.

MANIPULATIVE EXPERIMENTS

1. Minas Basin Otter Trawling (1990-1991)

Full details are provided in Brylinsky et al. (1994).

Site

Intertidal flats (sand and silty sand) off Houston Beach and Porter Point. General area fished by small draggers for winter flounder. This is a high energy, macrotidal region with ice in winter.

Design

Trawl sets were made by commercial dragger at high water when flats were flooded with 6-8 m of water. Two types of trawls and three kinds of doors were used. Observations (samples, measurements, photos) were made at low tide when flats were exposed. Sampling was done after trawling in door furrows, roller marks and control sites outside of the trawl path.

This design allowed us to investigate immediate impacts and recovery over a few months.

Benthic community

Dominant groups were benthic diatoms, nematodes and polychaetes (*Clymenella torquata, Glyceria dibranchiata, Spiophanes bombyx, Nephytys caeca* and *Heteromastus filiformis*). Except for low densities of mud snails (*Ilyanassa obsolete*), no epibenthic organisms were present.

Gear disturbance

Single sets at high water. No repeat trawling.

Trawl catch

No large invertebrates were collected. Catch (mostly flounder and skate) was not quantified.

Natural changes

Not investigated.

Immediate impacts

The doors created parallel furrows (up to 5 cm deep and 85 cm wide) on the seabed. The rollers left marks thought to be due to compression. The bridles left no visible marks. About 12 % of the area between the outer edges of the doors was visibly disturbed. Disturbance was greater in finer sediments. The door furrows persisted for at least 2-7 months. This was surprisingly long considering the high levels of natural energy at the study site (tide, waves, ice, etc.).

Chlorophyll concentrations were lower in the furrows and roller tracks. Nematodes were markedly lower in furrows. These decreases were thought due in part to resuspension and displacement, not necessarily mortality. There was little evidence of any impacts on either the species composition or abundance of polychaetes.

Diatoms recovered rapidly, presumably because of their high division rate. In one case, chlorophyll concentrations were higher in furrows after 80 days, perhaps due to nutrient release. Nematodes recovered in 4-6 weeks.

Short-term impacts

None were evident.

Long- term impacts

None were evident.

Most affected benthic species

None, but the site was relatively depauperate, especially of epibenthic forms.

Summary

Overall impacts were minor and short-lived. No short-term or long-term impacts were evident. Those impacts observed were due primarily to the action of the doors. There was little indication that the rollers had biological impacts. The disturbance imposed by trawling seems minor compared to the natural stress imposed by tidal inundation (twice daily), storms and winter ice.

2. Grand Banks Otter Trawling Experiment (1993-1995)

Full details are provided in Paulin et al. (1995), Prena et al. (1996), Schwinghamer et al. (1996), Hurley et al. (1997), McKeown and Gordon (1997), Rowell et al. (1977), Gilkinson et al. (1998), Schwinghamer et al. (1998), Gilkinson (1999), Prena et al. (1999), Kenchington et al. (2001), Gordon et al. (2002), and Gordon et al. (2005).

Site

A 20 x 20 km experimental site was selected on the Grand Banks east of St. John's. Analysis of commercial fishing effort data indicated that the site had been subjected to commercial trawling (mostly American plaice with about 15-20% Atlantic cod) before 1980 but not since. Therefore, the benthic habitat and community at this site had at least 13 years to recover from any previous trawling disturbance. Sidescan sonar surveys indicated no visible disturbance of the seabed by trawling activity. DFO closed the site to all fishing activity for the duration of the experiment. The general moratorium on groundfisheries on the Grand Banks, established in 1992, provided an additional degree of protection from fishing disturbance.

The seabed was relatively flat, featureless (except on a micro-scale), and composed primarily of sand. Water depth averaged 137 m (range of 120 to 146 m). The seabed was relatively stable with no evidence of wave or current-induced ripples. Some iceberg scours were present but not abundant enough to interfere with the experiment.

Design

Three, 13 km long experimental corridors were established within the 20 x 20 km experimental box, each with a different heading. Each had a parallel reference corridor established 300 m to one side.   The experimental lines were trawled 12 times in 1993, 1994, and 1995 (same waypoints) by the *Templeman* using an Engel 145 otter trawl with 1250 kg polyvalent otter boards, 46 cm diameter rockhopper footgear, and wing and door spreads on the order of 20 ± 2 m and 60 ± 5 m

(the same trawl was used in the Western Bank experiment). The trawl catch was processed and species and weight determined.
Benthic sampling was done before and after trawling along both experimental and control lines by *Parizeau* using sidescan sonar, BRUTIV, an epibenthic sled and Videograb. With the exception of sidescan, due to time constraints, the benthic sampling was carried out along just two of the three transects.

This design allowed us to examine three immediate impacts, two one year recovery periods, and cumulative effects over three years.

Benthic community

A rich and diverse biological community was present at the experimental site. A total of 246 invertebrate taxa (both epifaunal and infaunal) were identified in the 200 Videograb samples, with an average of 68 taxa per sample. Mean biomass and abundance were on the order of 1 kg (wet weight) m^{-2} and 2100 individuals m^{-2}, respectively. The dominant taxonomic groups were echinoderms, polychaetes, molluscs and crustaceans. Twenty-seven taxa occurred in more than 90% of the samples and accounted for 89% of the total biomass and 87% of the numerical abundance. Being a sandy habitat, most species were free-living or burrowing. There were some tube-building species but relatively few large sessile species such as soft corals (*Gersemia* sp.) attached to shells.

The total biomass of organisms sampled by the epibenthic sled averaged 400 g (wet weight) m^{-2} and the total number of species captured was 115 (in 96 samples). The dominant epibenthic species at the study site, which comprised 95-98% of the biomass, were sand dollars (*Echinarachnius parma*), brittle stars (*Ophiura sarsi*), sea urchins (*Strongylocentrotus pallidus*), snow crabs (*Chionoecetes opilio*), soft corals (*Gersemia* sp.) and four molluscs (*Astarte borealis*, *Margarites sordidus*, *Clinocardium ciliatum*, and *Cyclocardia novangliae*). With the exception of *M. sordidus*, the molluscs were shallow infaunal species. A tube dwelling polychaete (*Nothria conchylega*) was also abundant in epibenthic sled samples but was not processed because of the extensive sorting time required (however, it was processed in the Videograb samples). Only sea urchins and snow crabs were commonly caught by both the epibenthic sled and the otter trawl while only sand dollars and brittle stars were commonly collected by both the epibenthic sled and Videograb.

Gear disturbance

The path of the trawl over the seabed was estimated using Trackpoint. The width of the disturbance zone (i.e. all trawl passes), defined by the distance between the outermost door tracks, varied considerably but averaged on the order of 120-250 m. It was greatest in 1993, when the trawler was not equipped with dGPS, and least in 1994. Since the average width of the disturbance zone was several times the spread of the otter trawl doors (60 m), the trawling disturbance was clearly not evenly distributed in this zone. Probably a very small area of the seabed was swept by all twelve sets each year. Some areas, especially near the outer boundaries, may have been swept only once. It is estimated that a given location within the disturbed zone was probably swept by the trawl on the order of 3 to 6 sets each year, with frequency being greater near the centre line.

The degree of disturbance at a particular spot will depend upon the part of the otter trawl that comes into contact with the seabed. The greatest damage is expected from the doors, which under ideal conditions are in near constant contact with the seabed. However, the tracks they create are narrow, about 1 m wide, and so they disturb only about 3% of the area swept by the trawl (i.e. 60 m between the doors in this experiment). The next most damaging component of the otter trawl is probably the rockhopper footgear, also in constant contact with the seabed, which has a width on the order 20 m or about 33% of area swept by the trawl. The net follows behind the footgear and therefore can potentially affect the same area. More than 60% of the area swept by the trawl is affected only by the ground warps which can contact the seabed periodically.

The general level of trawling effort, twelve sets along the same line once a year, was much higher than usually occurred on the Grand Banks before the groundfish moratorium in 1992. Most areas in the disturbed zones were probably swept by 3 to 6 sets of the otter trawl each year (i.e. 300-600% per year). Analysis of the offshore trawler observer database, collected between 1980 and 1998 and scaled up to total effort, indicated that the detailed distribution of effort was very patchy (Kulka and Pitcher 2001). Most trawling was concentrated in specific regions, and large areas appear to be untrawled. The area of seabed swept by otter trawls at an intensity greater than 100% (i.e. more than once a year) was generally less than 1.5% of the total shelf area. Presumably, these are the preferred areas where fish are most abundant and the bottom is fishable. The maximum trawling intensity estimated from this database ranged from 141% to 644 % per year (i.e. the seabed was swept by a trawl 1 to 6 times a year) which is comparable to the intensity applied in this experiment. Therefore, the intensity of trawling used in our experiment (twelve sets once a year over the same bottom) is high, at the upper end of the range of effort applied by the commercial fleet in recent years. However, it should be kept in mind that this effort was concentrated into just a few days each year while commercial effort is generally spread out over the entire year. This difference could have implications for recovery potential.

Trawl catch

The fish catch in the otter trawl was extremely low and averaged just 18 kg (wet weight) for a 13 km long set over the entire experiment. The dominant species caught were American plaice (*Hippoglossoides platessoides*) and thorny skate (*Raja radiata*). Other species captured in smaller quantities were capelin (*Mallotus villosus*), Arctic cod (*Boreogadus saida*), sand lance (*Ammodytes dubius*) and Atlantic cod (*Gadus morhua*).

The invertebrate bycatch was very low and averaged 10 kg (wet weight) for a 13 km long set. Dominant species were snow crabs (*Chionoecetes opilio*), basket stars (*Gorgonocephalus arcticus*) and sea urchins (*Strongylocentrotus pallidus*). Other species included soft corals (*Gersemia* sp.), whelks (*Buccinum* sp.), and hermit crabs (*Pagurus* sp.). Iceland scallops (*Chlamys islandica*) were only occasionally caught on the sandy bottom since their preferred habitat is gravel. These are all large surface dwelling species and most have some degree of mobility.

Natural changes

The biomass of epibenthic organisms in reference corridors showed considerable interannual variability. The most pronounced natural changes were observed in the Videograb data. There was a clear trend of decreasing total abundance with time in the macrobenthic communities in the reference corridors, dropping about 50% between 1993 and 1995. The number of species per sample also decreased significantly during the experiment. Approximately 20% of the species tested showed significant date effects for both abundance and biomass in the reference corridors. These combined results demonstrate that the habitat and biological community at the study site are naturally dynamic and exhibit marked changes irrespective of trawling activity. This natural variability makes it more difficult to detect the effects of otter trawling.

The average biomass of fish catch in the trawl decreased each year of the experiment but it can not be determined with certainty whether this trend was due to natural variability or the continuing effects of overfishing before the groundfish moratorium initiated in 1992. The effects of dramatically reduced groundfish populations on benthic community structure on the Grand Banks is unknown but potentially significant because of the importance of benthic invertebrates in the diet of demersal fish.

Immediate impacts

The experimental otter trawling had no apparent effect on the grain size of surficial sediments. The trawling did not appear to affect organic carbon and nitrogen in surficial sediments in the first two years while, in 1995, concentrations were significantly lower after trawling. Otter door tracks, and in some cases disturbance from footgear, were readily visible on sidescan sonar records immediately after trawling and ten weeks later.

Video observations made with BRUTIV revealed that the seabed in freshly trawled corridors was lighter in colour than reference corridors, and that organisms and shell hash tended to be organized into linear features parallel to the direction of trawling. Door tracks and damaged organisms were also visible on occasion. High-resolution video observations with the Videograb indicated that untrawled seabed had a hummocky, mottled appearance with abundant organic detritus, while recently trawled seabed was generally smoother and cleaner. While some new structural features were created by the doors (i.e. furrows and berms), the visual observations showed a generally smooth sediment surface with an overall decrease in habitat complexity.

There was a significant increase in the RoxAnn™ E2 signal after trawling in 1995. The E2 signal is considered to be a proxy for sediment hardness. DRUMS™ acoustic data indicated that trawling caused significant changes in small-scale subsurface sediment structure down to depths of 4.5 cm. These results were interpreted to indicate that the trawling destroyed biogenic structures such as mounds, tubes and burrows and thereby reduced habitat complexity.

Immediately after trawling each year, the total biomass of organisms sampled with the epibenthic sled was significantly lower in trawled corridors than in reference corridors. This difference was greatest after the third trawling event in 1995, and averaged 24% over the entire experiment. At the species level, this biomass reduction immediately after trawling was significant for snow crabs, sand dollars, brittle stars, sea urchins and soft corals. Actual impacts on snow crabs were probably greater than the analyses showed because of their rapid migration into trawled corridors (i.e. some of the snow crabs sampled after trawling were not present before). Judging by their capture rate in the otter trawl, there probably was a similar reduction in the biomass of basket stars but this was not detected in the epibenthic sled data, probably because this species was poorly sampled. The homogeneity (variance in species mean abundances) of epibenthic organisms collected by epibenthic sled was lower (i.e. greater variance) in trawled corridors immediately after trawling than in nearby reference corridors. This presumably reflects the realignment of organisms into rows as seen in the BRUTIV video footage. Sand dollars, brittle stars and sea urchins demonstrated significant levels of damage from trawling. In addition, the mean individual biomass of epibenthic organisms was lower in trawled corridors suggesting size specific impacts of trawling, especially for sand dollars. However, no significant effects of trawling were observed on the four mollusc species commonly captured by the epibenthic sled. The reduced biomass of epibenthic organisms in trawled corridors immediately after trawling is presumably due to several factors including direct removal by the trawl, displacement, predation and possibly migration of non-captured organisms.

The immediate effects of trawling on macrofauna were examined by comparing community properties determined from the Videograb data before and after trawling each year in the trawled corridors. Few significant effects were observed in 1993 and 1995. However, in 1994 there was a significant drop in total community abundance immediately after trawling, with polychaetes being the most affected taxonomic group. In the same year, there was no significant drop in the total community biomass but sand dollars and several species of polychaetes were negatively affected. No significant immediate effects of trawling were detected on the number of species present, species diversity or evenness. No significant damage to sand dollars or brittle stars could be detected in the Videograb samples. Multivariate analysis indicated changes in community structure only in 1994. It may have been easier to detect immediate impacts in 1994 because that year the trawling disturbance was more concentrated along the centre line of trawled corridors and there was a longer delay between the cessation of trawling and Videograb sampling which provided more time for predators to feed on dead, damaged or exposed organisms.

The annual trawling had no significant effect on the abundance of adult or juvenile mollusks, as sampled by Videograb, in any year. Recruitment rates of bivalves were similar in both reference and trawled corridors. There was no evidence that trawling affected either the size structure or species composition of molluscs. In addition, there was no detectable difference in mollusc damage between reference and trawled corridors.

Short-term impacts

The 1993 tracks were not visible a year later but the 1994 tracks were faintly visible in 1995. There was no visible difference in seabed surface structures of trawled and reference corridors before retrawling in 1994 and 1995, suggesting habitat recovery over the intervening twelve months.

The short-term effects of trawling on organisms were examined by comparing community properties in trawled corridors before trawling with reference corridors. Few significant effects on macrofauna abundance and biomass were observed. These were restricted primarily to eight species of polycheates in 1994 which decreased in abundance. It is not clear whether these apparent effects were due to otter trawling or the natural spatial and temporal variability in the benthic communities. However, there was a significant increase in the frequency of damaged sand dollars in trawled corridors, especially for the larger organisms. There was no evidence of any cumulative effect of trawling disturbance on community structure over the three-year experiment. Ten dominant species were remarkably stable during the experiment and showed no effect of either natural or trawling disturbance.

Since it was not possible to collect epibenthic sled samples before retrawling in 1994 and 1995, there are no direct data on the recovery rates of epibenthic organisms in the trawled corridors. However, the fact that most of the affected species have some degree of mobility and that the biomass of epibenthic species in the trawled corridors was relatively constant over the three year experiment suggests that recovery time for most affected species is on the order of a year or less.

Long-term impacts

None were evident.

Laboratory experiments

The results of the laboratory experiments conducted at Memorial University indicated that small and medium size bivalves living on or near the surface of a sandy seabed were displaced in fluidized sediment ahead of the trawl doors and thereby escaped direct hits. Only 2 out of 42 recovered bivalves which had originally been buried in the scour path of the door were damaged. Two large near-surface bivalves, which are not common at the study site, were not displaced and were destroyed by direct hits from the trawl door. These results are consistent with the observations of no significant detectable impacts of otter trawling on molluscs in the field experiment. Burrowing experiments indicated that the majority of bivalve taxa (70%) at the study site were shallow burrowers and that most of the species tested were slow to very slow burrowers.

Most affected benthic species

Snow crab (*Chionoecetes opilio*)
Sand dollar (*Echinarachnius parma*)
Brittle star (*Ophiura sarsi*)
Sea urchin (*Strongylocentrotus pallidus*)
Soft coral (*Gersemia* sp.)
Several species of polychaetes.

Summary

Immediate physical impacts of the experimental trawling on seabed habitat were readily visible and tended to decrease habitat complexity, but it appears that recovery from the disturbance occurred within a year. Significant immediate effects of the experimental trawling were detected on some species of large epibenthic organisms as sampled by the epibenthic sled, in particular snow crabs, sand dollars, brittle stars, sea urchins and soft corals. Indirect evidence suggests that recovery of these species took place within a year, most likely through migration and transport from undisturbed areas immediately outside the narrow trawled corridors.

The immediate effects of experimental otter trawling on the abundant and diverse macrobenthic organisms present at the study site, as sampled by the Videograb, are relatively minor and restricted primarily to sand dollars and some species of polychaetes. Some of the observed drop in polychaete abundance is most likely due to predation but some could also be due to displacement outside the trawled corridors. Echinoderms (except sand dollars), molluscs and crustaceans showed little or no effect. The major signal observed in the data was a natural temporal trend over the three-year experiment. The minor impacts observed appear to have shifted the benthic community in the same direction as the natural changes. The macrobenthic community appears to have recovered fully from the trawling disturbance within a year. Therefore, some impacts could be judged short-term but there was no evidence of long-term impacts from the annual trawling disturbance.

3. Western Bank Otter Trawling Experiment (1997-1999)

Full details are provided in Kenchington et al. (2005), Henry et al. (2005), Kenchington et al. (2006), and Gordon et al. 2006.

Site

A 2 x 2 km experimental site was selected inside the haddock nursery area which has been closed to trawling since 1987. This site remains open to scalloping but analysis of effort data indicated no fishing at the site before or during the experiment. Therefore, the site had not been disturbed by mobile fishing gear for at least 10 years. The seabed is composed of gravel lag, mostly pebble and cobble, but some boulders. It was relatively flat with a mean depth of 70 m.

Design

The experiment was set up as an asymmetrical BACI (Before-After-Control-Impact) design to compare temporal changes on a single trawled line with those on three control lines. The trawled and control lines were just 2 km long (compared to 13 km in the Grand Banks experiment). The single experimental line was trawled 12-14 times in 1997, 1998, and 1999 (same waypoints) using an Engel 145 otter trawl with 1250 kg polyvalent otter boards, 46 cm diameter rockhopper footgear and wing and door spreads on the order of 20 ± 2 m and 60 ± 5 m (same trawl used in the Grand Banks experiment). Trawling was done by either the *Needler* or *Teleost*. The trawl catch was processed to determine species, weight, and the stomach contents of fish. Habitat and benthic communities were sampled before and after trawling along experimental and control lines by either the *Parizeau* or *Hudson* using sidecan sonar, BRUTIV/Towcam, Campod and Videograb.

This design allowed us to examine three immediate impacts, two one year recovery periods, and cumulative effects over three years.

Benthic community

A total of 341 taxa were identified representing 12 phyla. Polychaetes, amphipods and molluscs dominated. Shannon-Weiner diversity was 1.5 ± 0.18 (average ± standard deviation), while species richness was 14.6 ± 2 and evenness 0.77. Mean biomass and abundance per sample (0.5 m^2) were 300 g and 600 individuals, or 600 g m^{-2} and 1200 individuals m^{-2}, respectively. Biomass was dominated by the horse mussel *Modiolus modiolus*, a long-lived bivalve, while the tube-building amphipod *Ericthonius fasciatus* was the most abundant species. The majority of species were epifaunal (60%). Carnivory was the most common adult feeding mode. The largest predator in the data set was the snow crab. There was a rich colonial epifauna containing at least 53 taxa, the majority of which were hydroids.

Gear disturbance

The path of the trawl over the seabed was determined with a high degree of accuracy in 1997 and 1998 using Trackpoint and found to be quite variable. Essentially all of the trawled corridor (100 m wide) had been swept at least once by the entire trawl (60 m wide between the doors) while 71-83% of the area had been swept at least once by the rockhopper footgear and net (20 m wide). The locations of individual Campod and Videograb samples were exposed to varying levels of disturbance which ranged from 1 to 12 passes of the entire trawl and from 0 to 9 passes of the rockhopper footgear and net. The level of disturbance applied was similar to that in the Grand Banks experiment which was judged to be near the high end of the range applied by commercial fishing.

Trawl catch and stomach contents

Twenty-two species of fish and five invertebrate species were captured in the trawl. Atlantic cod, haddock and winter flounder, all visual predators, increased in the trawl catch with successive sets suggesting scavenging behaviour. Detailed analysis of the stomach contents of Atlantic cod, haddock, American plaice, yellowtail and winter flounder showed changes in diet attributed to trawling. Two classes of impacts were documented: (1) quantitative changes (+/-) to the proportion of species consumed, and (2) qualitative changes through opportunistic feeding on novel food items. All species investigated demonstrated statistically significant proportional changes in their diets following trawling disturbance. Qualitative changes in diet were seen in Atlantic cod, American plaice and yellowtail flounder. All of these fish species increased consumption of the horse mussel, *Modiolus modiolus*, with American plaice and yellowtail flounder found feeding on the mussels only after trawling commenced. Abundance of the tube-building polychaete *Thelepus cincinnatus* in fish stomachs increased as trawling progressed.

Natural changes

No natural changes in habitat were visible along the control lines. The abundance of 24 individual taxa (polychaetes, amphipods, echinoderms and molluscs) changed significantly over time on the control lines during the experiment, with the majority of these increasing. A significant change in relative biomass amongst the taxa was also observed. The number of taxa, total biomass, and hydroid biomass increased over the study period, with associated changes in community composition.

Immediate impacts

Physical disturbance to the seabed was evident in the sidescan sonograms due to re-orientation of the gravel clasts and the digging of shallow furrows. Also detected was a linear depression made by dragging a boulder back and forth with the trawl (which damaged the net). No changes in habitat were detected by QTC, multibeam bathymetry or backscatter, or DRUMS. Little physical disturbance was evident in the video. However, small-scale disturbance was apparent in some photos taken at 58% of the Campod stations in the trawled corridor immediately after trawling compared to 15% along control lines. This disturbance was categorized as scraping/scouring, sedimentation, displacement, and digging of furrows. The observed disturbance was well predicted by the number of passes by the footgear and net over the sampling site. The probability of not observing small-scale physical damage in at least one of the five photos at a given station after two passes of the footgear and net was effectively zero. A non-significant difference in the volume of Videograb samples before and after trawling was observed suggesting that trawling may have increased the packing of sediment clasts.

Trawling had few detectable immediate effects on the abundance or biomass of individual taxa and none on community composition. A few taxa, primarily a mixture of polychaetes and amphipods, decreased significantly after trawling and data from fish stomachs collected during the experiment showed that some of these were scavenged by demersal fish.

Immediate effects of the trawling on colonial epifauna were detected as decreases in the number of taxa per sample, total biomass and total hydroid biomass across the trawling events, although those trends were non-significant after Bonferroni adjustment.

Analysis of the photographs showed that the three top-ranking species in terms of biomass, the horse mussel *Modiolus modiolus*, the tube-building polychaete *Thelepus cincinnatus*, and the brachiopod *Terebratulina septentrionalis*, were visibly damaged more than other species by the trawl. Observed damage was significantly related to the number of passes by the trawl. As noted above, the abundance of both *Modiolus* and *Thelepus* increased in fish stomachs as trawling progressed.

Short-term impacts

The recovery of the habitat from physical disturbance appeared to be slow. Some lineations in sidescan sonograms were still evident in 2001, two years after the third trawling. While some trawl-induced disturbance was observed, except for an apparent increase in the packing of sediment clasts, no significant changes in the structure or complexity of the gravel lag seabed were observed, even after three years of repetitive trawling.   Conclusions could have been different if large, structuring-forming epibenthic organisms had been present.

At the conclusion of the experiment, the relative abundance (but not biomass) of taxa on the experimental line were significantly different from controls, in most cases decreases were observed. Fifteen taxa showed significant decreases. As in the analyses of individual years, the species affected were primarily high turn-over species such as polychaetes and amphipods. A marked decrease in the biomass of the horse mussel *Modiolus modiolus* was observed over time. The proportion of epifaunal biomass also declined significantly from 90% to 77% on the trawled line by the conclusion of the experiment. These changes are in part due to trawl-induced damage and subsequent predation by demersal fish. No cumulative effects were detected on the assemblages of colonial epifauna. While some of the tests for trawling effects were statistically weak, it is certain that any effects were small relative to natural inter-annual change.

Long-term impacts

The observed impacts of the annual trawling on horse mussels over three years are judged to be long-term because of their slow growth rate.

Most affected benthic species

Horse mussel (*Modiolus modiolus*)
Tube-building polychaete (*Thelepus cincinnatus*)
Brachiopod (*Terebratulina septentrionalis*)

Summary

Minor impacts were observed on the gravel lag habitat but recovery appeared to be slow. Therefore habitat impacts are judged to be at least short-term in nature. Significant natural changes with time were observed in the benthic communities. Immediate impacts on organisms were relatively minor. The most impacted organisms were large and attached epibenthic forms. No significant impacts were observed on the colonial epifauna. Both quantitative and qualitative changes to the diet of demersal fish were observed, presumably caused by changes in prey availability brought about by trawl disturbance. The proportion of epifaunal biomass declined significantly from 90% to 77% over the three-year experiment indicating a significant short-term impact. Because of their slow growth rate, the impacts on horse mussels are judged to be long-term.

4. Banquereau Hydraulic Clam Dredge Experiment (1998-2000)

This experiment was conducted under a Joint Project Agreement with Clearwater Fine Foods Incorporated. Full details are provided in Gilkinson et al (2002), Gilkinson et al. (2003), Gilkinson et al. (2005a), and Gilkinson et al. (2005b).

Site

The experimental site was located on Banquereau, an expansive sandy bank on the Scotian Shelf off eastern Canada. Selection criteria included the presence of Arctic surfclams *(Mactromeris polynyma)*, the major target species in the dredge fishery, spatial uniformity of both sediments and topography (to reduce natural spatial variability), and the absence of previous disturbance from dredging/trawling activity. The seabed was relatively flat and featureless with an average water depth of about 75 m (range of 70-80 m. These depths are near the deeper end of the depth range generally fished in the offshore clam fishery. Sediments were relatively homogenous and consisted of well-sorted fine-grained sand. Empty mollusc shells were abundant, many of which were worn and covered with epifauna and detritus. These commonly formed circular-shaped shell patches (about 5-10 m in diameter). No evidence of previous dredging or trawling disturbance was visible.

Design

The experiment was designed as an asymmetrical BACI approach with multiple reference areas and temporal replication in both treatment and reference areas. This design is well suited to detecting impacts from pulse disturbances, and it reduces the chances of confounding treatment and location effects. Three experimental treatment boxes (each 100 m by 500 m) were established inside an experimental frame measuring 1.5 km by 2 km. Box X (dredged-only) was dredged but the bycatch was retained on board and discarded later in Box Z (discard-only). Box Y was also dredged but, according to standard commercial procedures, the bycatch was released immediately within the same box. Therefore, observations in Box Y (dredged + discard) examined the combined effects of dredging and discarding while those in Box X examined the effects of dredging only, and those in Box Z examined the effects of discarding only. Two reference boxes (W1 and W2) were also situated within the experimental frame and both were separated from the treatment boxes by at least 500 m.

Benthic sampling was conducted by the *Hudson* before experimental dredging, immediately after dredging, two weeks after dredging, and one and two years after dredging. Sampling tools included sidescan, RoxAnn, QTC, multibeam, BRUTIV/Towcam, Campod, and Videograb with DRUMS. Some opportunistic sampling was also carried out in 2001 and 2003 using sidescan sonar and Campod.

This design allowed us to examine a single disturbance plus recovery over two years.

Benthic community

A total of 270 taxa were observed in the 180 Videograb samples. Nine invertebrate phyla were identified, dominated by arthropods (mostly amphipods), annelids (mostly polychaetes), and molluscs. A total of 19 species occurred in more than 90% of the samples, while 140 species were found in less than 10% of the samples. The total abundance per Videograb sample (0.5 m^2)

ranged from 59 to 5,767 individuals with an overall average of 1,141, or 2282 individuals m^{-2}. Three species comprised 65% of total mean species abundance. These were the polychaete, *Spiophanes bombyx,* and the amphipods *Priscillina armata* and *Ampelisca macrocephala*. The total biomass per Videograb sample (0.5 m^2) ranged from 8 g to 2.5 kg with an overall average of 955 g, or 1910 g m^{-2}. The propellerclam, *Cyrtodaria siliqua*, dominated, comprising 77% of the total biomass. The second most dominant species, the sand dollar *Echinarachnius parma*, comprised only 8% of the total biomass.

A total of 52 epifaunal taxa were observed. Most common were sand dollars (*Echinarachnius parma*), sea cucumbers (*Cucumaria frondosa*), brittlestars (*Ophiura sarsi*) and sea urchins (*Strongylocentrotus droebachiensis*). Soft corals (likely *Gersemia rubiformis*) were the largest and most common structure-forming epibenthic organism at the experimental site. Most appeared to be attached to empty shells.

Gear disturbance

The dredging disturbance followed standard commercial fishing practices as closely as possible. The experimental dredging was conducted by the *Atlantic Pursuit*, a commercial offshore clam vessel owed and operated by Clearwater. Following standard practice, paired dredges were used. Each dredge was 4 m wide and the cutting blade was set at a depth of 20 cm. The experimental dredging boxes were set up on the ship's plotter screen to aid in keeping the tows within the box boundaries and to try to distribute them evenly across the 100 m wide box. A total of 12 successive tows were made in alternating directions with sufficient lead-ins and exits to ensure that the dredges were on-bottom for the entire length of the box (500 m). After each tow, the dredges were retrieved and the contents dumped on board for processing before the dredges were re-deployed.

Dredge catch

A total of 35 taxa (33 invertebrates and two fish) were collected by the dredges (bar spacing was 3-4 cm). Propellerclams, sea cucumbers, and sand dollars constituted greater than 80% of the total biomass. Non-target molluscs (primarily Buccinidae), tunicates, anemones, polycheates, hydrozoans, soft corals and fish (grey sole and sculpins) comprised approximately 1% of the total biomass. Most of the soft corals (*Gersemia rubiformis*) were attached to shells. It is estimated that the dredges removed 5-13% of the propellerclams, 17-34% of the Arctic surfclams (*Mactromeris polynyma*), and 36-63% of the Greenland cockles (*Serripes groenlandicus*). For a number of reasons these are considered underestimates. No estimates could be made for ocean quahogs (*Arctica islandica*).

Natural changes

Over time, there was a progressive decline in densities of burrows and a steady increase in densities of polychaete tubes in the reference boxes. There were consistent differences in community structure and biomass between the two reference boxes over the three year period. The average abundance of many species increased over time, particularly polychaetes and small crustaceans. Three arthropods (*Ampelisca macrocephala, Unciola spp,* and *Corophium crassic*orne) and two polychaetes (*Spiophanes bombyx* and *Euchre papillosa*) showed marked increases in abundance in the reference boxes and Box X over the 3-year period.

Immediate impacts

As expected, there was considerable seabed disturbance. The dredges created distinct, curvilinear furrows (on the order of 4 m wide and 20 cm deep) with considerable overlap which, based on analysis of sidescan sonograms, covered 53% and 68% of the area inside the two dredged boxes. Berms were created immediately adjacent to the furrows. Edges of furrows were straight-sided. The seabed within the furrows appeared to be flat, lighter in colour, and relatively smooth with an absence of empty shells, detritus and burrows which were common before dredging and in the reference boxes. There were signs of sedimentation throughout the dredged boxes. There was a loss of small-scale structural complexity due to removal of biogenic features by the dredge or through burial from resuspended sediment. There were dramatic declines in all micro-habitat variables immediately after dredging. Large numbers of whole exposed propeller clams lay scattered on the seabed throughout the dredged boxes, many showing signs of damage.

The DRUMS acoustic data indicated that dredging had a measurable effect on sediment microstructure. All reference samples, and samples collected before dredging in both boxes, were classified as undisturbed. However, 26-42% of the Videograb samples from the dredged boxes were collected from areas classified by DRUMS as disturbed. The dredging disturbance was also detected in the RoxAnn data collected by the *Atlantic Pursuit* during the experimental dredging, in the QTC data collected by *Hudson* immediately after dredging, and in the multibeam data collected by the *Creed* two months later.

The experimental dredging affected a large number of macrofaunal species. On the order of 42-45 non-target species declined in average abundance by about 46%. Most of these were polychaetes and crustaceans but also some molluscs and echinoderms (e.g. sea cucumbers). No effect of dredging on the mean densities of sand dollars and brittlestars could be detected. Mean abundance of the four target bivalve species declined by 22-42% while mean biomass declined by 26-64% (mostly due to propellerclams).

Although soft corals were removed by the dredges, no significant immediate impact on their abundance was detected (however the power of the analysis was low). The capture efficiency of the dredges was calculated to be quite low (2-19%) suggesting that water turbulence generated by the dredges may displace soft corals away from the dredge path. Other large epibenthic species, such as sand dollars, may have been displaced as well.

Large numbers of damaged and dead propellerclams were observed on the seabed immediately after dredging. It was estimated that 50-60% of the propeller clams had potentially lethal injuries compared to just 11-17% before dredging (presumably due to damage during sampling). There was little change in the abundance of exposed propellerclams after two weeks which indicated they were unable to re-burrow and most likely would die. Consumption by scavengers (which include whelks, moon snails, sea stars, crustaceans, brittlestars, sea urchins and various fish) over this two week year period was surprisingly low.

Shell and tissue damage was assessed for 32 taxa (24 molluscs, 6 echinoderms and 2 crustaceans) and was found to be significantly increased by the dredging. The propellerclam is most susceptible to damage because of its large size, abundance and life position in the sediment.

The number of flatfish increased immediately after dredging, presumably to feed on damaged organisms. Yellowtail flounder (*Limanda ferruginea*) is one of two species common on Banquereau, and polychaetes and crustaceans form an important part of the diet. There was also a trend of a greater number of whelks in both dredged boxes. The brittle star *Ophiura sarsi* was observed feeding on the tissue of exposed damaged propellerclams two weeks after dredging.

There was very little evidence of any discard material (live organisms, dead organisms, tissue, etc.) inside the discard box.

A related experiment on the survival of juvenile surfclams passing through the hydraulic dredge was conducted on Banquereau (distant from the experimental site) in May 1999 under the supervision of Dale Roddick (DFO Maritimes). The *Atlantic Vigour* towed a hydraulic dredge over a clam bed and, immediately after, juvenile clams from within the furrows and from nearby undisturbed areas were collected using the Videograb deployed from the *Hudson*. Levels of damage were accessed and the survival of juvenile clams was monitored for 11 days while holding them in native sediment and running seawater on board the *Hudson*. The results indicated that the mortality of juvenile clams that passed through the bars on the dredge and were left behind on the seabed was relatively low, on the order of 6-15%.

Short-term impacts

After one year, furrows were no longer visible in video. Nevertheless, the seabed still appeared disturbed and large numbers of empty, articulated propeller clam valves were evident. After two years, the DRUMS acoustic data indicated a decrease in the number of Videograb samples classified as disturbed, but habitat in the dredged boxes was still visibly different. Dredge furrows were still clearly visible in sidescan sonograms after three years indicating persistent changes to sediment structure and/or compaction inside furrows. Burrow openings remained rare and empty articulated propeller clam valves were still abundant. Over time, although low relief, the degraded dredge furrows act as traps for empty shells.

Effects on sediment microstructure were still visible after two years, but the differences between dredged and reference boxes were less, indicating partial recovery. However, virtually no recovery in the abundance of large burrows was evident three years after dredging due to the high mortalities of propellerclams which function as important ecosystem engineers.

One year after dredging, there was no longer a significant difference in the abundance of sea cucumbers between dredged and reference boxes. Most of the whole propellerclams observed lying on the seabed in both dredged boxes immediately after dredging appear to have died leaving their empty articulated shells (cluckers) behind. These represent an extensive source of hard substratum that can be used by sessile epibenthos such as sea cucumbers and soft corals. After one year, the number of non-target species in dredged boxes was less than in the combined reference boxes. Individual species showed different patterns of change. A total of 39-43 species showed an increase in average abundance compared to predredging levels which averaged 284-419%. Most of these were polychaetes and crustaceans although the brittle star also increased in abundance by 63%. On the other hand, 14-15 species, mostly polychaetes, decreased in abundance by 48-56%. Average biomass showed no significant changes while average body weight was lower.

Two years after dredging, the average body weight of non-target species remained depressed but the number of species increased. The total abundance of non-target species continued to increase on the order of 70-133%, due largely to dramatic increases in the abundance of the spionid polychaete *Spiophanes bombyx*. Similar trends were evident in the reference boxes. A total of 35-39 individual species increased in abundance on an average of 600-916% while a total 14-16 species decreased on an average of 54-57%. Before dredging, *Spiophanes bombyx* accounted for 16% of the total abundance and 20 other species combined to make up 80% of the abundance while two years after dredging *Spiophanes bombyx* accounted for 49% of total abundance and 80% of the total abundance was attributable to just seven species. Again, similar trends were seen in the reference boxes. No long term declines in soft corals could be detected.

The average abundance of the four target species declined further during the first year after dredging. Average abundance and biomass in 1999 were 41-58% compared with before dredging levels. After two years, average abundance and biomass of the four target species remained depressed and averaged 46-67% of pre-trawl levels. After one year, the dead or damaged propeller clams seen on the seabed had transformed into empty shells. Recruitment of target bivalve species was uniformly low throughout the experimental area over the three year study period.

Non-target species showed considerable recovery during the experiment. Sea cucumbers appeared to have recovered within one year. Some species showed large increases in abundance (>100%) over two years, in particular two species of sedentary tube-dwelling polychaetes (*Spiophanes bombyx* and *Euchone papillosa*). Other species of polychaetes and crustaceans showed increases in abundance after just one year. The brittle star *Ophiura sarsi* increased over two years. However, four species of polychaetes decreased in abundance during the experiment. Despite the recovery observed, it is clear that two years after dredging the community of non-target species is still in the colonizing phase.

Long-term impacts

No recovery was observed over two years in the target bivalve species. Because of their variable recruitment and slow growth rates, these impacts are clearly long-term. Some habitat impacts may also be long-term.

Most affected benthic species

Sea cucumber (*Cucumaria frondosa*)
Propellerclam (*Cyrtodaria siliqua*)
Arctic surfclam (*Mactromeris polynyma*)
Greenland cockle (*Serripes groenlandicus*)
Ocean quahog (*Arctica islandica*)

Summary

Dredging effects were readily detectable against a background of natural temporal and large-scale spatial variability. The most obvious effect on habitat was a dramatic change in seabed topography due to the numerous overlapping curvilinear furrows made by the dredges. The loss of burrows, tubes, and shells created a smooth surface within the furrows. Furrows gradually degraded with time through the combined actions of slumping, sediment transport and bioturbation. While not visible in video after one year, the sidescan data indicate that they last for at least three years and act as traps for empty shells. Differences in patterns of acoustic reflectance between dredge furrows and the surrounding seabed indicate long-lasting effects on sediment structure and/or compaction. Densities of clam burrows within the furrows were reduced by up to 90% with no signs of recovery after three years due to the high mortalities of their architects.

Immediately after dredging, most macrofaunal species decreased in abundance with the greatest declines inside dredge furrows (which covered 53-68% of the area of dredged boxes). Large numbers of propellerclams were excavated to the seabed surface while there were few signs of discards on the seabed. Following initial declines in abundance and biomass of most taxa, there were marked increases in abundance of polychaetes and amphipods one year later. Two years after dredging, abundances of opportunistic species were generally elevated by more than 100% relative to pre-dredging levels. Dredging resulted in pronounced, sustained reductions in biomass (up to 67%) of the target bivalves with no signs of recovery after two years. Short-term and long-term impacts are clearly evident.

5. Bay of Fundy Scallop Dredge Experiment (1993)

Full details are provided in Robinson et al. (2001).

Site

Two study sites were chosen based on preliminary dive surveys, one off Grand Manan Island at the mouth of the Bay of Fundy and the other off Ministers Island in Passamaquoddy Bay. The depth range was 4-12 m at mean low water and bottom type comprised of boulders and rock ledge.

Design

This study was designed to investigate the impacts of using scallop dredges to harvest green sea urchins (*Strongylocentrotus droebachiensis*). Each study site was divided into two rectangular plots (50 x 100 m), one as control and other for experimental dredging. The experimental plots were dredged by commercial fishermen using standard gear to create what was considered to be a moderate dredging disturbance. Diver surveys were run in both plots before, during and immediately after the experimental dredging, as well as 3 and 6 months later. All epifaunal macroinvertebrates were counted. In addition, the percentage of bottom covered by macrophytes and bottom characteristics was recorded.

This design allowed the examination of immediate impacts and recovery over six months.

Benthic community

A total of 26 readily visible taxa were observed by divers over the course of the experiment at both sites. Most taxa occurred in low abundance so data analysis only considered the most common species which were green sea urchins (*Strongylocentrotus droebachiensis*), kelp (*Laminaria longicrurus*), lobster (*Homarus americanus*), rock crab (*Cancer irroratus*), sea cucumber (*Cucumaria frondosa*), sea peach (*Halocynthia pyriformis*), northern whelk (*Buccinum undatum*), starfish (*Asterias vulgaris*) and sculpin (*Myoxocephalus octodecemspinosus*).

Gear disturbance

Multiple sets were made with standard scallop dredges deployed by commercial fishermen over the same bottom to create what was considered to be a moderate fishing disturbance.

Dredge catch

Not processed.

Natural changes

Few natural changes were documented in the control plots but the experiment was only six months in duration.

Immediate impacts

Dredging dislodged rocks. Signs of displaced rocks were still visible six months after the disturbance.

As expected, dredging caused a significant reduction in the abundance of sea urchins. It also caused an increase in the frequency of broken sea urchin tests (resulting in mortality). Other taxa that showed a negative effect of dredging were kelp and lobster. Broken kelp stipes were readily visible. Lobsters were probably not damaged but migrated out of the experimental plots. Taxa showing no significant effect included rock crabs, sea cucumbers, sea peaches, and starfish. However, diver observations indicate that some impacts must have occurred because detached or crushed organisms were common in the experimental plots. Whelks and sculpins increased in abundance after dredging. Such a response is not surprising since both species are predators and probably moved into the experimental plots to feed on dead or damaged organisms. Sea urchin abundance appear to have recovered after six months, presumably through inward migration.

Short-term impacts

None were evident. However, habitat recovery will probably take longer than six months after rock dislodgement.

Long-term impacts

None were evident.

Most affected benthic species

Sea urchin (*Strongylocentrotus droebachiensis*)
Kelp (*Laminaria longicrurus*)

Summary

Experimental scallop dredging caused immediate impacts on the habitat and some benthic species, in particular, the target species (sea urchins), and kelp. However, only a small fraction of the benthos was monitored. Those impacts observed were generally short-lived and differences between the control and experimental plots were not observed after six months.

OBSERVATIONAL AND LABORATORY STUDIES

6. Temporal changes on the Digby scallop grounds (1966/67 versus 1997)

Full details are provided in Caddy (1970), Fuller et al. (1998) and Kenchington et al. (2006).

Site

This study was done in the Lower Bay of Fundy off Digby, NS in an area known as the 'Inside Zone' (approximately 800 km^2). Average depth was 70 m. The bottom was a gravel lag with sand patches. Strong tidal currents prevail. The site has a long history of fishing with bottom contacting mobile gear. Scallop dredging began in 1921 and otter trawling in 1945. Fishing effort, while variable from year to year, has continued. The site is not a pristine habitat but has been subjected to chronic fishing disturbance.

Design

The approach of this study was to compare bycatch data sets collected in 1966/67 (Caddy 1970) and 1997 (Fuller et al. 1998) and look for changes in the composition of the megafauna community over 30 years that might be attributable to fishing gear. Similar sampling and processing methods were used in both surveys. Digby drags were used to collect scallops and bycatch in both surveys. Tows in 1966/67 were of 15 min duration while those in 1997 were of 8 min duration. Presence and absence data were analyzed. A conservative approach was taken in preparing the two data sets to avoid creating false differences. Both data sets were trimmed to those stations that fell into a common area (92 stations from each survey). The final combined data set contained 35 megafauna taxa, most at the species or genus level. Data analysis included a biological traits analysis (mobility, attachment, habitat, etc.).

This design allowed us to examine the effects of chronic fishing disturbance over 30 years on an entire fishing ground.

Benthic community

A rich epibenthic community was present at the time of both surveys; 132 megafauna taxa in 1966/67 and 150 megafauna taxa in 1997. Dominant groups were sponges, cnidarians, brachiopods, molluscs, polychaetes, crustaceans, echinoderms and tunicates. The strong tidal currents provide a rich food supply.

Gear disturbance

No experimental gear disturbance was applied.

Dredge catch

The data presented are the bycatch from scallop dredges. No sampling of seabed habitat or communities was conducted before or after fishing.

Natural changes

Since there were no adequate control sites, it was not possible to single out natural changes but they may have contributed to some of the temporal changes observed.

Immediate impacts

Not investigated.

Short-term impacts

Not investigated.

Long-term impacts

Significant changes in the composition of the megafaunal community, as represented in the available data sets, were observed over the 30 year period. The mean number of taxa per station increased from 14.1 to 17.4 while the standard deviation decreased from 4.9 to 3.0. In 1966/67, the average similarity among samples was 54.4% but this increased in 1997 to 69.0% indicating that the megafauna community became more homogeneous with time. The frequencies of occurrence of dominant taxa changed markedly. Some of those that were most widely-distributed in 1966-67 suffered declines in frequency of occurrence as much as 61%, while a number of other species increased by a similar amount, forming a new group of principal taxa which largely replaced the formerly-dominant group. Taxa that decreased in frequency of occurrence were the polychaete *Pseudopotamilla reniformis*, the tunicate *Boltenia ovifera*, the sponge *Cleona* sp. and the horse mussel *Modiolus modiolus*. Those that increased were the whelks *Neptunea decemcostata* and *Buccinum undatum*, the sunstar *Crossaster papposus*, the starfish *Henricia* spp., the robust-shelled, burrowing clams *Astarte* spp., the hermit crabs *Pagurus* spp. (often living in whelk shells), and various brittlestars (Ophiuroidea). However, nothing in the data sets indicated that any species were lost from the area.

Biological traits analysis indicated that mobility, degree of attachment, habitat, feeding mode, body flexibility and regenerative powers could explain some of the change observed in the frequency of occurrence. Over the 30-year period, there was a relative decline in fragile, sessile, permanently-attached and colonial taxa, particularly deposit and filter feeders, and an increase in robust, mobile grazers and scavengers. Taxa with a low ability to regenerate declined while those with an intermediate ability increased. There also appeared to be a corresponding shift towards smaller taxa.

Because of the nature of the data set, it is not possible to draw firm conclusions on the reasons for the observed changes in megafauna community structure which could be due to numerous factors working singly or in combination. The slight differences in sampling protocols are thought to have had a minor influence. Changes in the oceanographic environment and pollution are also though to have been of minor influence. However, the changes observed in the biological traits analysis are the kind of changes that would be expected to result from physical impacts on the seabed and benthos. At this study site, such physical impacts are being applied on a regular basis by both scallop dredges and otter trawls. Therefore, we suggest that the primary cause of the observed changes in the megabenthic community structure, over three decades, was the physical impacts of mobile fishing gears, with discarding as a likely contributing cause.

Whatever the nature of the changes between the two surveys, they did not include the initial effects of fishing on previously-pristine bottom since scallop dredging dates back to 1921 and otter trawling to 1945. Any consequences of the "first pass" of mobile gear over this seabed were long concluded. While we have no information on the responses of the benthic community to the initial towing of mobile gear, our results demonstrate that on-going changes in the megabenthos under on-going fishing can continue for decades.

Most affected benthic species

Sabelid polycheate (*Pseudopotamilla reniformis*)
Tunicate (*Boltenia ovifera*)
Sponge (*Cliona* spp.)
Horse mussel (*Modiolus modiolus*)

Summary

Despite the inevitable limitations of the data sets which are confined to a single area and lack adequate controls, because of the use of biological traits analysis, it is concluded that the observed changes in the frequency of occurrence of dominant taxa over 30 years are due primarily to the chronic physical disturbance applied by frequent scallop dredging and otter trawling. In general, there was a relative decline in fragile, sessile, permanently-attached and colonial taxa, particularly deposit and filter feeders, and an increase in robust, motile grazers and scavengers. These changes are clearly long-term.

7. Spatial differences in the Digby scallop grounds (2000)

Full details are provided in Henry and Kenchington (2004a and b).

Site

Heavily fished scallop grounds in the Bay of Fundy off Digby, NS. Gravel bottom which ranged in depth from 38 to 108 m. The site has been fished on a continuous basis for 80 years.

Design

This study compared the structure of hydroid communities found on cobbles and live adult sea scallops (*Placopecten magellanicus*) as sampled with a standard scallop dredge during the 2000 annual DFO inshore survey. It is assumed that large scallops have escaped previous contact with scallop dredges and represent pseudo-controls for fishing disturbance, while cobbles may have experienced repeated abrasion, displacement, or burying by scallop dredges and may have even been subjected to processing on board fishing vessels. In total, 136 cobbles and 104 scallops were examined. These were collected on 39 tows spread over a large area. Most tows sampled both cobbles and scallops. In a companion study, the genetic diversity of a hydroid species was examined between the two substrates.

This design allowed us to examine the effects of chronic fishing disturbance over an entire fishing ground.

Benthic community

Only the hydroid community attached to cobbles and scallops as collected by scallop dredge was examined. In total, 51 hydroid taxa from 24 genera were observed. No attempt was made to sample other components of the benthic community.

Gear disturbance

No experimental gear disturbance was applied.

Dredge catch

Looked only at attached hydroids, not total bycatch from scallop dredges. No sampling of seabed habitat or communities before or after fishing.

Natural changes

Not investigated.

Immediate impacts

Not investigated.

Short-term impacts

Not investigated.

Long-term impacts

The mean number of hydroid taxa was lower on cobbles than scallops. The hydroid assemblages on cobbles and scallops were significantly different at all taxonomic levels. The differences between the two assemblages were mostly explained by 25 of the 51 taxa. The life history traits of these 25 taxa were also significantly different between cobbles and scallops. Taxa on cobbles were characterized by low-lying runner-like growth forms and mixed growth forms. These taxa tended to be smaller with less branching and possessed medusa life stages. Hydroid taxa on scallops were more typically erect tree-shaped phalanx growth forms with larger and more heavily branched colonies and planula larvae life stages. Differences between the two assemblages were also related to estimates of fishing effort, the higher the effort the greater the difference. Natural factors that might have caused the observed differences were examined but did not seem to be important. Colonies of the hydroid *Sertularia cupressina* on scallop valves were sexually-derived whereas those on cobbles had greater injuries and were more often clonally-derived. It was concluded that chronic fishing disturbance was the major factor responsible for these differences.

Most affected benthic species

Large, slow-growing and erect hydroids such as *Calycella syringe*, *Obelia dichotoma* and *Sertularia cupressina*.

Summary

This novel approach provides strong circumstantial evidence that chronic scallop dredging can change the taxonomic structure of hydroid assemblages on gravel seabeds. Erect tree-shaped phalanx growth forms with larger and more heavily branched colonies and planula larvae life stages are replaced by taxa with low-lying runner-like growth forms and mixed growth forms which tend to be smaller with less branching and possess medusa life stages. These changes are clearly long-term because of the short return period of the disturbance.

8. Lab studies with soft corals (2002)

Full details are provided in Henry et al. (2003).

Site

Colonies of the soft coral *Gersemia rubiformis* were collected by divers in the Bay of Fundy and brought to the Fish Laboratory at BIO for experiments.

Design

Soft coral colonies, attached to cobbles, were placed in individual aquaria. Half were rolled over and crushed ten times, once every two weeks, for two months. The other half were left undisturbed. Changes in colony and polyp physiognomy were noted. Genetic observations were also made.

This design allowed an assessment of the immediate impacts from disturbance.

Benthic community

Not investigated.

Gear disturbance

Artificial disturbance in the lab.

Dredge catch

Not investigated.

Natural changes

Not investigated.

Immediate impacts

Proportions of colonies in different states did not differ between treatments over time. Crushing immediately induced complete colony retraction and daughter colonies were produced in crushed corals. Randomly amplified polymorphic DNA genetic markers demonstrated that daughter colonies were sexually derived. Despite initial fast growth, daughter colonies experienced high mortality. Premature larval expulsion may have been intrinsically initiated to dispose of resource-costly planulae during colony repair. Corals regenerated well from acute localized injuries.

Short-term impacts

Not investigated.

Long-term impacts

Not investigated.

Most affected benthic species

None

Summary

The soft coral *Gersemia rubiformis* was not significantly affected by disturbance in the lab. It has the ability to temporally retract and survive repeated crushings and also recovers well from acute localized injuries.

9. Deep-water corals (2000-2003)

These observations were collected during the DFO deep-water coral program funded in part by the ESRF (Environmental Studies Research Fund) which is funded by the oil and gas industry. Full details are provided in Mortensen and Buhl-Mortensen (2005), Mortensen et al. (2005), Mortensen et al. (2006a), and Mortensen et al. (2006b).

Sites

Several deep-water coral habitat sites off Nova Scotia including the Northeast Channel, the Scotian Slope, the Gully and the Stone Fence at the mouth of the Laurentian Channel. Water depths were in the range of 200 to 500 m. Bottom type was variable but all sites had some stable substrate to support corals (i.e. cobble, boulder, bedrock). All sites had been exposed to fishing activity.

Design

Analysis of video footage of deep-water coral communities collected by Campod deployed from *Hudson*.

Benthic community

A wide variety of epibenthic organisms were observed at all sites but in most cases were not quantified.

Gear disturbance

The general level of gear disturbance in the study areas could be estimated from effort data. The fishing gear most commonly used in deep-water coral habitats is otter trawls and longlines.

Trawl catch

Not investigated.

Natural changes

Not investigated.

Immediate impacts

While some of the damage observed may have occurred a few days before the video was collected, it is assumed that all impacts can be classified as long-term because of the very slow recovery period for corals.

Short-term impacts

While some of the damage observed may have occurred a few years before the video was collected, it is assumed that all impacts can be classified as long-term because of the very slow recovery period.

Long-term impacts

In the Northeast Channel, signs of fishing impact were visible as broken live corals, tilted corals and scattered skeletons. Broken or tilted corals were observed on 29% of the transects and were not concentrated in any particular area. In total, 4% of the observed colonies were damaged. A higher percentage of *Paragorgia arborea* colonies was damaged compared to *Primnoa resedaeformis* (7.9% versus 3.4%). This is most likely due to their generally larger size and less flexible skeletons. It appears that damage may make corals more susceptible to parasites since a parasitic anemone was more common on damaged colonies of *P. resedaeformis* than intact ones. Lost longlines were observed loose on the seabed or entangled in corals on 37% of the transects. Tracks on the seabed, either from longline anchors or parts of otter trawl gear, were present along three transects, while lost gillnets were observed along two transects. With one exception, longlines were only found on transects where coral were present.

No signs of damage to corals were observed in the video footage collected along the transects surveyed on the Scotian Shelf. This is probably because the dominant species are small, free-living cup corals which are less prone to damage from fishing gear than the large, attached gorgonians and *Lophelia* reefs.

Only a few signs of fisheries damage to corals were observed in the Gully, just a few trawl tracks and one corroded lost wire from a trawl. However, tilted seapens and seapen skeletons were quite common on the sides of the outer part of the Gully.

The *Lophelia pertusa* reef at the Stone Fence clearly showed an accumulated impact from fishing gear. All live colonies were either small or clearly broken in an unnatural way. Furrows caused by trawl doors were visible. The rubble zone surrounding the reef was larger than observed at similar sized reefs off Norway. There was an unusual number of pale grey skeletons in the rubble zone. Gorgonians showed signs of disturbance in the form of their small size and unnatural occurrence on the sides of and underneath boulders. Many cobbles and boulders showed signs of being overturned (i.e. clean surface atop and fouling underneath). A fragment of a trawl net was also found.

Recovery of organisms

Not investigated. However, the growth rate of deep-water corals is very slow so complete recovery can take a century or more.

Most affected benthic species

Gorgonian *Paragorgia arborea*
Gorgonian *Primnoa resedaeformis*
Stony coral *Lophelia pertusa*

Summary

Large deepwater gorgonian and stony corals can be significantly impacted by all types of bottom tending fishing gear, including longlines and gillnets. Because of the very slow recovery period, these impacts are clearly long-term.

SUMMARY OF DFO FIELD PROGRAMS

As summarized in Table 1, our research has considered the three most widely used types of bottom-contacting mobile fishing gears in Atlantic Canada; otter trawls, scallop dredges and hydraulic clam dredges. We have worked on both sand and gravel habitats but have not been able to consider muddy habitats. Five manipulative experiments with control sites have been conducted. In most cases, we were able to conduct these experiments at locations that had not been disturbed by fishing in recent years. These experiments allowed us to look at immediate impacts and in some cases long term impacts over three years. Three observational studies have also been conducted that provide information on the impacts of chronic fishing disturbance. Several laboratory experiments were also conducted. We have investigated the direct impacts of gear on both habitats and benthic communities, and have used a wide variety of seabed observation and sampling tools which collect information over a broad range of spatial scales. The otter trawling experiments on the Grand Banks and Western Bank and the hydraulic clam dredging experiment on Banquereau are the most detailed. In fact, Løkkeborg (2005) states that the three-year otter trawling experiment on the Grand Banks is one of the most comprehensive ever conducted.

With few exceptions, the results have been published, or are in press, in the scientific literature after peer review (see references). The results of the Minas Basin and Grand Banks experiments were available when the reviews considered in the Rice working paper were prepared and are widely cited. The results of the other experiments have been published more recently. A few remaining publications are in the drafting stage. The results of our research have also been presented at numerous national and international conferences and workshops.

Our major results are summarized as follows, organized by habitat, benthic communities and gear type:

Habitat

Sandy seabeds are easily disturbed. The doors and footgear of otter trawls create distinct tracks on the seabed which are readily detected by sidescan sonar and at times by imagery. Hydraulic clam dredges leave distinct furrows. Both these gears destroy biogenic structures in the seabed (i.e. mounds, tubes and burrows) and reduce habitat complexity. Recovery of habitat depends upon the level of natural energy, in general the deeper the water the slower the rate of recovery. Recovery of sandy seabed from otter trawling appears to take on the order of a year or less, while recovery from hydraulic clam dredging takes more than three years.

Gravel seabeds are more difficult to disturb since individual clasts are larger and often packed together in a gravel lag deposit. Therefore, impacts seem to be less. Nevertheless, door tracks can be seen in sidescan sonar sonograms and displaced clasts in imagery. However, there was no evidence of decreased habitat complexity. While disturbance to gravel habitats seems to be less than sand habitats, the recovery period is longer. For example, the door tracks on Western Bank lasted at least two years.

No observations have been made on muddy seabeds which are widely distributed in Atlantic Canada in basins and slope water. These are most likely very easy to disturb and recovery is probably very slow because such sediment is only found in low energy habitats.

Biogenic habitat provided by large attached epifauna such as corals and sponges is easily disturbed and takes a long time to recover.

Communities

The immediate impacts of the Minas Basin otter trawling experiment were minor. The most affected taxa were benthic diatoms and nematodes which recovered rapidly. Impacts would probably have been greater if more epibenthic organisms were present.

There was a significant drop in the biomass of large epibenthic organisms immediately after trawling in the Grand Banks otter trawling experiment. However, recovery seemed to be complete in a year, most likely due to inward migration from undisturbed areas just outside the trawl corridors. These same organisms showed an increase in visible damage. In one year out of three, there was a significant drop in total community abundance immediately after trawling with polychaetes being the most affected group but there was no detectable effect on the number of species, diversity or evenness. No effect was observed on molluscs, including recruitment. Few significant long term effects were observed on macrofauna abundance and biomass, and these were restricted primarily to eight species of polychaetes in just one year. There was no evidence of any cumulative effect of trawling on community structure over the three year experiment.

Immediate impacts of otter trawling on benthic organisms in the Western Bank experiment were observed but less than detected in the Grand Banks experiment. There were just a few effects on the abundance or biomass of individual taxa and none on community composition. Those taxa that decreased, primarily polychaetes and amphipods, were found to increase in the stomachs of demersal fish that moved into the trawled corridors to feed on damaged organisms. Three large common epibenthic taxa were visibly damaged and the degree of damage was related to number of passes by the trawl. In contrast, the long term effects of the Western Bank experiment appear to be greater than seen on the Grand Banks. At the conclusion of the experiment, the relative abundance of taxa had changed, with fifteen taxa (mostly polychaetes and amphipods) showing a decrease. Over the three year experiment, the proportion of epifaunal biomass (mostly horse mussel) decreased significantly. However, no cumulative effects were detected on the assemblages of colonial epifauna which is of particular concern as it has the potential to alter trophic structure and function.

The hydraulic clam dredging experiment had the greatest impacts on benthic organisms. Numerous species of polycheates, crustaceans, molluscs and echinoderms declined sharply immediately after dredging. Surprisingly, no significant effect could be detected on soft corals, even though some were removed by the dredge. Large numbers of damaged organisms were left behind on the seabed, especially propellerclams. Most of these appeared to die, leaving their articulated shells as new habitat for other species. Some increases in scavengers was observed, in particular flat fish and whelks. While some recovery occurred, the benthic community was still highly altered after two years. Some taxa increased, in particular some polychaete species, while others decreased. There was no sign of recovery in the four target bivalve species.

The Bay of Fundy scallop dredge experiment had an immediate impact on sea urchins, kelp and lobsters. An increase was noted in the abundance of whelks and sculpins which are presumably migrating into the disturbed zone to feed on damaged organisms.

The observational studies in the Bay of Fundy provide strong evidence of cumulative effects over decades of commercial fishing disturbance. The megafauna community appears to have become more homogeneous and the frequency of occurrence of dominant taxa has changed. However, no taxa have disappeared. There was a decline in fragile, sessile, permanently-attached and colonial taxa and an increase in robust, mobile grazers and scavengers. These are the changes expected from chronic fishing disturbance. Differences in hydroid assemblages on scallops and cobbles also indicate chronic effects. There is also evidence that chronic fishing disturbance is affecting the genetic diversity of at least one hydroid species.

Lab experiments indicate that soft corals attached to cobbles are not adversely affected by physical disturbance. However, the observations made on deep-water corals indicate their high vulnerability to fishing gear impacts.

The benthic organisms most susceptible to the fishing disturbance studied in our field projects are summarized in Table 2. The majority are relatively large epibenthic forms that live at the sediment water interface. Some are attached while others are free-living. The only exceptions are some of the polychaetes which are small and live within the sediment and the deep-dwelling molluscs which were only affected by the hydraulic clam dredge. The recovery rates for these organisms are quite variable and depend on recruitment, growth rate, and degree of mobility. In the case of polychaetes, this can be less than a year. Large molluscs will require ten years or more, while deep-water corals will require on the order of a century.

All our study sites had diverse benthic communities with hundreds of taxa. The majority of taxa showed no effects, especially the infauna living within the seabed. While there was evidence of significant changes in the relative abundance of benthic taxa under some conditions, there was no evidence of any taxa disappearing.

Gears

The three gear types are compared in Table 3.

Otter trawls are widely used in Atlantic Canada over a broad range of bottom types; mud, sand and gravel. Most of the disturbance is caused by the doors and footgear. Since they are generally designed to glide over the seabed with minimal penetration, the impacts of a single pass are likely minor, except where large structure forming organisms like sponges and deep-water corals are present. However, fishermen tend to return to the same fishing spots year after year so some areas are subjected to almost continuous fishing disturbance which does not give benthic communities much chance to recover. Because of the large area affected, collectively otter trawls probably have the greatest effect on benthic habitat and communities of any gear type in Atlantic Canada. Except for removing fish from the ecosystem, the major impacts are on non-target organisms.

Scallop rakes are used primarily on gravel bottoms where scallops are most abundant. They are designed to penetrate the seabed to some degree and therefore impart considerable disturbance. However, their use is more restricted than otter trawling so the area of seabed affected each year is much smaller. The use of multibeam bathymetry backscatter by the industry in recent years to locate scallops beds has significantly reduced the area of seabed disturbed. Except for removing scallops from the ecosystem, the major impacts are on non-target organisms.

Hydraulic clam dredges are restricted to sandy seabeds where the target species are found. Of the three gear types, it is the most destructive since it is designed to penetrated the seabed to a depth on the order of 20 cm. However, there are relatively few commercial vessels using this gear (three at the moment), so the annual footprint is quite small. In addition, due to the slow growth rate of the target species, it is common industry practice to let dredged areas lie fallow for at least ten years to let stocks recover. Industry has used acoustic tools to map the distribution of clam beds so effort is focused on areas with highest potential catch. Taking all these factors into consideration, the overall impact of hydraulic clam dredges is probably less than the other two gear types. In contrast to otter trawls and scallop rakes, the major and longest lasting impacts are on the target species themselves. This encourages the industry to follow sound conservation practices that benefit benthic habitat and communities.

Obtaining quantitative information on the impacts of mobile fishing gear on benthic habitat and communities is expensive and time consuming, especially when taking into account the inherent natural spatial and temporal variability that exists. Our experiments have their faults. For example, the trawling disturbance applied in the Grand Banks and Western Banks otter trawling experiments was different from that usually applied by commercial fisheries (a single disturbance per year along a narrow corridor). The immediate impacts are probably realistic. However, given that the time interval between samplings was one year, the recovery periods may have been over-estimated, especially for mobile organisms that can move in from nearby undisturbed areas. On the other hand, the observational studies in the Bay of Fundy were more realistic since they were conducted on a commercial fishing ground but they lacked adequate controls making it difficult to separate gear impacts from natural changes. Therefore caution should be used in applying the results. The fact that we used a wide variety of sampling tools in most of our experiments reduces the chances that we missed some major impacts. Some direct effects were probably missed because of low statistical power in the data but these were probably minor. Our experiments focussed on the direct effects of fishing gear and did not address potential indirect effects on important processes such the spawning and survival of juvenile demersal fish, biogeochemical exchanges between the seabed and water column, and benthic production.

COMPARISON OF RESULTS TO INTERNATIONAL REVIEWS

We now compare the results of our field projects summarized above with the major conclusions about impacts and mitigation measures extracted from recent reviews in the Rice working paper. The numbers in parentheses refer to the experiments as listed in the text and Table 1.

Impacts of Bottom Gears on Habitat

1. Mobile bottom gears can damage/reduce structural biota

Support. Damage to horse mussels (3, 6), kelp (5) and deep-water corals (9) has been observed.

2. Mobile bottom gears can damage/reduce habitat complexity

Support. A reduction in the habitat complexity of sandy seabed was observed for both otter trawling (2) and hydraulic clam dredging (4). No reduction in habitat complexity was observed on gravel seabeds (clasts are more difficult to move). However, in some cases, habitat complexity was increased. For example, hydraulic clam dredging increased the abundance of shells that provide attachment sites for other species (4).

3. Mobile bottom gears can reduce/remove major habitat features (boulders etc)

Little support for this on sandy and gravel seabeds. Sediment clasts (i.e. cobbles and boulders) can be dislodged but are generally not removed from the seabed. However, there is strong evidence that *Lophelia* reefs can be heavily damaged by otter trawls (9).

4. Mobile bottom gears can alter seafloor structure

Strong support. Otter trawl doors can create furrows in the seabed (1, 2, 3). Footgear can also modify the seabed. Hydraulic clam dredges create large furrows (4).

5. There is a gradient of impacts, with greatest impacts on hard, complex bottoms and least impact on sandy bottoms

Limited support. In the case of otter trawling, which is used over a variety of seabed types, our results show that immediate habitat impacts were greater on sandy (2) than gravel seabeds (3). However, it took longer for gravel seabeds (3) to recover than sandy seabeds (2) so impacts last longer. This presumably reflects the greater mobility of sand.

6. There is a gradient of impacts, with greatest impacts on low energy environments and least (often negligible) impact on high-energy environments

Strong support. The greatest immediate impacts of otter trawling on seabed habitat were observed at 120-146 m (2) and the least in the intertidal zone (1). Impacts at 70 m were immediate (3).

7. Trawls and mobile dredges are the most damaging of the gears considered

Support.

Impacts of Bottom Gears on Benthic Species and Communities

8. Mobile bottom gears can change the relative abundance of species

Strong support. Otter trawling changed the relative abundance of benthic species on the Grand Banks (2) and Western Bank (3). Hydraulic clam dredging did the same on Banquereau (4) as did scallop dredging in the Bay of Fundy (5, 6, 7).

9. Mobile bottom gears can decrease the abundance of long-lived species with low turnover rates

Support. Horse mussels decreased in abundance after three years of otter trawling (3) and 30 years of scallop dredging/otter trawling (6). Hydraulic clam dredging reduced the abundance of large, infaunal molluscs (4) and no evidence of recovery was seen after two years.

10. Mobile bottom gears can increase the abundance of short-lived species with high turnover rates

Support. There was a large increase in certain species of polychaetes and amphipods after hydraulic clam dredging.

11. Mobile bottom gears affect populations of surface-living species more often and to greater extents than populations of burrowing species

Strong support. As shown in Table 2, with the exception of commercial molluscs and some polychaetes, the most affected organisms are epibenthic.

12. Impacts of mobile bottom gears are less in high-energy / frequent natural disturbance environments than in low energy environments where natural disturbances are uncommon

Support. The greatest immediate impacts of otter trawling on organisms were observed at 120-146 m (2) and the least in the intertidal zone (1). Impacts at 70 m were immediate (3). In addition, deep-water corals are only found in relatively low energy environments (except for relatively strong currents that bring food particles)(9). However, significant effects of chronic fishing where observed in the high-energy Bay of Fundy (6, 7).

13. Mobile bottom gears affect populations of structurally fragile species more often and to greater extents than populations of "robust" species

Some support. Many of the sensitive species listed in Table 2 are structurally fragile (e.g. deep-water corals, echinoderms, brachiopods, etc.). However, the horse mussel is usually considered a robust species because of its thick shell and habit of living in crevices between sediment clasts but it clearly can be impacted by repeated disturbance (3 and 6).

14. Abundance of scavengers increases temporarily in areas where bottom trawls have been used

Strong support. Numerous organisms were observed to move into disturbed areas, These included snow crabs (2), cod (3), haddock (3), winter flounder (3), yellow tail flounder (4), whelks (4, 5), and sculpin (5). The Western Bank otter trawling experiment clearly demonstrated changes in the diet of demersal fish (3).

15. **Rates of nutrient cycling and/or sedimentation are increased in areas where bottom trawls have been used**

Some support. No new evidence to present with regard to nutrient cycling. Otter trawling did cause some sediment resuspension but effects seemed to minor and short-lived (2, 3). However, hydraulic clam dredging did cause a major resuspension and subsequent sedimentation of sand.

Considerations in the Application or Adoption of Measures to Reduce Impacts

16. **The impact of mobile fishing gears on benthic habitats and communities is not uniform. It depends on:**
    a. **the features of the seafloor habitats, including the natural disturbance regime**
    b. **the species present**
    c. **the type of gear used and methods of deployment**
    d. **the history of human activities (particularly past fishing) in the area of concern**

Support

17. **Given the above considerations, the impact of mobile bottom gears has a monotonic relationship with fish effort, and the greatest impacts are caused by the first few fishing events**

Inconclusive. We did not observe changes in the benthic communities during the first year of trawling at either the Grand Banks or Western Bank experiments where both sites had been closed to fishing for a number of years. We do have evidence that damage to benthic organisms occurs with the first few fishing events but that is a function of distribution and sensitivity of the sampling design. Intuitively this statement might be true when referring to areas with upright, fragile epifauna such as corals.

18. **Recovery time from trawl-induced disturbance can take from days to centuries, and depends on the same factors as listed in Conclusion 16.**

Support

19. **Application of measures to reduce impacts requires case specific analyses and planning; there are no universally appropriate fixes. The effects of mobile bottom gears on seafloor habitats and communities are consistent enough with well-established ecological theory, and across studies, that cautious extrapolation of information across sites is legitimate.**

Agree to some extent. Ecological theory for deep-sea benthic communities is not as well developed as for intertidal and shallow subtidal communities. The former fits well into our observations but the latter does not.

20. **Conclusions regarding the potential synergy of technical mitigation measures, and the value of economic incentives in facilitating implementation and compliance were only discussed in the ICES review and the NMFS panel report. However, nothing in the other reviews directly contradicts these conclusions.**

No comments

21. The same is the case for the ICES admonition that in cases where benthic communities or habitats have recovered due to application of some mitigation measures, the benefits of the recovery can be quickly dissipated unless either the measures are continued in the long term or the fishery is otherwise managed in ways the prevent a resumption of the detrimental impacts.

Agree

In summary, there is excellent agreement between the results of our DFO research and the general conclusions from international reviews. The differences are minor and due to experiments which are just getting into the scientific literature, in particular the Western Bank otter trawling experiment. This concurrence gives further confidence in providing scientific advice to fisheries, habitat and ocean managers.

There are some additional general conclusions that have come out of our research and that are also supported by international experience.

Understanding natural variation

Benthic habitat and communities are subject to considerable natural spatial and temporal variation. There is a general understanding of the spatial variation in benthic habitat and communities that is relatively well understood in Atlantic Canada, but we have a poor understanding of temporal variation because of limited long-term data sets. This variability must be factored into the design of experiments, both manipulative and observational. Many published results are flawed since natural variability was not taken into account. Our experience indicates that in some cases gear impacts are less than natural variation and difficult to separate.

Spatial scale

Impacts of mobile fishing gear on benthic habitat and communities can occur over a wide range of spatial scales (hundreds of meters down to centimetres). It is important to use observation tools that cover this entire range or else some important impacts may go undetected.

Temporal scale

Immediate impacts are relatively well known and we are gradually obtaining a good understanding of recovery times for both benthic habitat and organisms. However, the most significant impacts that we need to understand are the long-term ones. It is particularly important to understand the relationship between the recovery of habitat and organisms and the return period of fishing disturbance. Long-term changes are most likely to occur when the disturbance return period is shorter than the recovery period, as appears to the case in the Digby scallop grounds and deep-water coral habitats.

RECOMMENDATIONS FOR MANAGEMENT

The issue of fishing gear impacts on benthic habitat and communities is clearly one of legitimate concern which is appropriate to address in the management of all benthic fisheries, both existing and new. As described above, the impacts of fishing gear on benthic habitat and communities depend upon numerous factors including the kind of gear, how it is used, the return period of the disturbance, the type of habitat, and the composition of benthic communities. The severity of impacts for different scenarios is likely to vary over a considerable range from minor to major.

In order to maintain the long-term integrity, biodiversity and productivity of benthic habitat and communities, as well as the sustainability of the commercial fisheries that they support, it is essential to incorporate our newly acquired knowledge of gear impacts into management regimes.

Fisheries management procedures in the past were based solely on the population dynamics of exploited fish populations and did not take into account environmental information. This shortcoming is now recognized and steps are underway to develop more ecosystem-oriented approaches to fisheries management which need to include the impact of fishing gear on benthic habitat and communities. We need to develop a system of ecosystem-based management where the benefits of fishing can be evaluated against its side effects which may include impacts on benthic ecosystems and the valuable functions they provide. In particular, we must determine the kinds, levels and spatial patterns of fishing disturbance that different habitats can withstand without altering them to the point where recovery is retarded or they are shifted to an alternative, less desirable state. Habitat conservation should become one of the primary operational principles of fisheries management.

Despite our incomplete knowledge of benthic ecosystems, we have enough information in hand to move ahead and make intelligent decisions. For example, as reviewed above, we have a good understanding of the relative impacts of different gears as well as the relative sensitivity, and recovery, of different habitats and communities. Fisheries managers, industry, conservation organizations, and scientists must work together to find the best means for incorporating this information into new management regimes. In doing so, it is important to realize that is impossible to generalize the results of a few experiments to the wide variety of benthic habitats and communities found on the continental shelf of Atlantic Canada. Each habitat will have to be considered on the basis of its inherent natural features as well as the long-term management objectives determined by all stakeholders. It must also be remembered that the application of scientific information to management decisions will always be complicated by the natural variation inherent in benthic ecosystems and therefore there is clearly a need for a precautionary approach to the management of fisheries, other human activities that impact the seabed, and benthic ecosystems.

In formulating management advice, it is important to assess the significance of the impacts of mobile fishing gear on benthic habitat and communities observed in scientific studies. This can be somewhat subjective. While most impacts would be judged as negative by most stakeholders, some might be judged as positive. Considering the substantial natural variation that occurs, do the observed impacts really have significant long-term effects on fisheries and ecosystem structure that we wish to preserve?

While the impacts of existing benthic fisheries need to be assessed, it is suggested that priority be given to assessing the impacts of new or expanded fisheries before they are given approval, especially those that are proposed for areas not yet disturbed by fishing gear.

It is widely agreed that there are four general steps that can be taken to reduce the negative effects of mobile fishing gear on the seabed.

<u>Control of Fishing Effort</u>

The single most effective measure to protect fish populations and the benthic ecosystem is to reduce the overall fishing effort, both significantly and permanently. This has taken place in recent years in Atlantic Canada due to the collapse of groundfish stocks and subsequent fishing moratoria. Steps could also be introduced to control the distribution of effort within fishing grounds, both spatially and temporally. With today’s technology, it is relatively easy and inexpensive to control and monitor effort down to very small spatial scales. For example, patches of productive bottom could be left undisturbed and serve as a source of recruitment for nearby fished areas. Controls could also be set on the frequency of effort. For example, as a general principle, a given area of the seabed should not be refished until the habitat and communities have been able to recover from previous disturbances. An acceptable return period would be quite variable depending on ecosystem conditions and range anywhere from a few months to tens of years.

Gear Usage and Modification

Altering the way that gear is used also has the potential to reduce environmental impacts. For example, shorter tows could increase the survival of bycatch. Re-engineering the different gear components and how they are rigged to reduce contact with the bottom would also lessen environmental impacts.

Gear Substitution

Where effort controls will not work, benthic ecosystems can be protected to some degree by selecting the least-damaging gear type for a given habitat. This would be most effective in areas that have the most sensitive habitat, such as hard bottoms with abundant emergent, sessile, structure-forming epifauna. Replacing otter trawls with fixed gear (gillnets, longlines, traps, etc.) could reduce the degradation of sensitive habitats and, in some cases, mortality of non-target species. However, fixed gears have their own set of environmental concerns (e.g. bycatch of seabirds and cetaceans, entanglement in deep water corals, etc.) which must be considered.

Area Closures

Where effort and gear controls will not work, area closures can be an effective measure in protecting benthic ecosystems from fishing disturbance. They should be selected and designed with a clear purpose in mind, taking into account all available knowledge of the characteristics of benthic habitat and communities, including both traditional ecological knowledge possessed by the fishing community and the results of scientific investigations. While different spatial scales are possible, the most suitable will depend upon local environmental conditions. Such closed areas can protect sensitive and valuable areas of the seabed not yet affected by fishing disturbance, and also allow disturbed areas an opportunity to recover (or reach a new state of equilibrium). To be most effective, closed areas should be established concurrently with effort reductions so that the displaced effort is not transferred to other areas creating new problems. In some cases, closure for just a few months a year may provide sufficient protection while in others year-round closure over a large area may be necessary.

Closed areas offer many advantages. They can serve as a source of new recruits to re-populate disturbed areas immediately outside. They can also serve as natural control areas valuable for scientific research on undisturbed benthic ecosystems, including long-term studies of natural variability. Where closed areas are established, it is important to conduct long-term scientific studies of their effectiveness. Such studies should be based on testable scientific hypotheses and the results used in adaptive management. For example, if the anticipated benefits are not being achieved, the design of the closed areas should be reconsidered and modified as necessary to meet the management objectives.

An example of a large-scale area closure in Canada is the haddock nursery box on Emerald/Western Bank which has been closed to mobile groundfish gear (but not scalloping) since 1987 to protect juvenile haddock. The effectiveness of this management action has been evaluated by Frank et al. (2000). Other recent closures in Atlantic Canada are the coral conservation area (424 km^2) in the Northeast Channel established by DFO in June 2002 (and slightly modified in 2003) and the coral conservation area (15 km^2) centered over the *Lophelia* reef complex at the mouth of the Laurentian Channel established by DFO in June 2004. The latter are the first closures established in Atlantic Canada with the purpose of protecting sensitive benthic communities. Yet another closure is the establishment of the Gully Marine Protected Area (2364 km^2) by DFO in May 2004.

Some specific operational objectives for bottom-contacting fishing gear have been proposed by Gordon et al. (2005) as part of the ESSIM exercise.

RESEARCH RECOMMENDATIONS

The knowledge base needed to fully understand and properly manage this issue remains incomplete and further research is needed. We offer the following recommendations.

Mapping of fishing effort

The mapping of past fishing effort provides a picture of the spatial and temporal distribution of potential seabed disturbance. An excellent start on this has been made by Kulka and Pitcher (2001). The distribution of effort is very patchy. However, this work is restricted to data on offshore trawlers obtained by the observer program. It needs to be expanded to include inshore trawlers as well as scallop and clam dredging gear. It is particularly important to identify those areas of the Canadian seabed not yet disturbed by fishing gear (i.e. Frontier areas).

Mapping of benthic habitat

The mapping of benthic habitat and communities continues to be a high priority. Effective management requires accurate and detailed maps of the resources being managed. The basic tool is multibeam bathymetry supplemented with imaging and sampling equipment. A major national initiative called SeaMap was proposed several years ago but never funded. However, benthic mapping is proceeding on a piecemeal basis by government (DFO and NRCan) and industry.

Field research

We need to continue to study the recovery of habitat and organisms at the hydraulic clam dredging experimental site on Banquereau (which was incomplete at the last full sampling in 2000). Prior to the Banquereau experiment, this mobile gear type was the least understood in Canadian waters in terms of environmental impacts. It is proposed that a full survey be carried out in 2008, ten years after the dredging disturbance.

Conduct a full manipulative otter trawling experiment on a muddy seabed habitat, similar in design and duration to those we have conducted on sand and gravel seabeds.

Investigate long-term natural changes in benthic habitat and communities at sites undisturbed by fishing. The reference sites at our experimental sites on the Grand Banks, Western Bank and Banquereau provide ideal locations. Habitats and communities are already described in detail. Ideally they should be sampled on the order of every five years. They also should continue to remain closed to all fishing activity.

Investigate long-term natural changes in benthic habitat and communities at sites that are disturbed by fishing. This could include temporal observations at sites subjected to chronic disturbance, as has been done in the scallop fishing grounds in the Bay of Fundy. It could also include long-term temporal observations at sites which were subjected to heavy fishing disturbance but then closed. Examples include the coral conservation areas and any new closed areas that might be established.

Investigate the potential indirect effects of fishing gear such as biogeochemical exchanges between the seabed and water column, spawning and survival of juvenile fish, and benthic productivity.

Identification of preferred habitat for demersal fish

The use of benthic habitat by juvenile demersal fish is also very patchy over a broad range of spatial scales. It is important to understand what are the preferred habitats, where are they located, what makes them attractive, and how vulnerable are they to disturbance by fishing gear.

These questions are currently being investigated by a five year program being conducted by the Maritimes and Newfoundland & Labrador Regions on the Scotian Shelf (Anderson et al. 2005).

REFERENCES

Anderson, J.T., J.E. Simon, D.C. Gordon Jr. and P.C. Hurley. 2005. Linking fisheries to benthic habitats at multiple scales: eastern Scotian Shelf haddock. American Fisheries Society Symposium 41: 251-264.

Brylinsky, M., J. Gibson and D.C. Gordon Jr. 1994. Impacts of flounder trawls on the intertidal habitat and community of the Minas Basin, Bay of Fundy. Can. J. Fish. Aquat. Sci. 51: 650-661.

Caddy, J.F. 1970. Records of associated fauna in scallop dredge hauls from the Bay of Fundy. Fish. Res. Board Can. Tech Rept. 225, 11 p.

Caddy, J.F. 1973. Underwater observations on tracks of dredges and trawls and some effects of dredging on a scallop ground. J. Fish. Res. Board Can. 30: 173-180.

Frank, K.T., N.L. Shackell and J.E. Simon. 2000. An evaluation of the Emerald/Western Bank juvenile haddock closed area. ICES J. Mar. Sci. 57: 1023-1034.

Fuller, S., E. Kenchington, D. Davis and M. Butler. 1998. Associated fauna of commercial scallop grounds in the lower Bay of Fundy. Ecology Action Centre, Marine Issues Committee Special Publication Number 2.

Gilkinson, K.D. 1999. Impact of otter trawling on infaunal bivalves living in sandy bottom habitats on the Grand Banks. PhD Thesis, Memorial University.

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. J Exp. Mar. Biol. Ecol. 244: 291-312.

Gilkinson, K.D., D.C. Gordon Jr., G.B. Fader, D.L. McKeown, E.L.R. Kenchington, D. Roddick, C. Bourbonnais, K.D. MacIsaac, R. Charron, M. Lamplugh and W.P. Vass. 2002. Banquereau hydraulic clam dredging experiment 1998-2000, Interim summary report, March 2002. Internal DFO/NRCan Project Report for Joint Project Agreement F5244-7-0868.

Gilkinson, K.D., G.B.J. Fader, D.C. Gordon Jr., R. Charron, D.L. McKeown, D. Roddick, E.L.R. Kenchington, K. MacIsaac, C. Bourbonnais. W.P. Vass and Q. Liu. 2003. Immediate and longer-term impacts of hydraulic clam dredging on an offshore sandy seabed: effects on physical habitat and processes of recovery. Continental Shelf Research 23: 1315-1336.

Gilkinson, K.D., D.C. Gordon Jr., D.L. McKeown, D. Roddick, E.L.R. Kenchington, K. MacIsaac, C. Bourbonnais and W.P. Vass. 2005a. Susceptibility of soft corals (Anthozoa: *Gersemia rubiformis*, Ehrenberg, 1834) to capture by hydraulic clam dredges off eastern Canada: the significance of soft coral-shell associations. American Fisheries Society Symposium 41: 383-390.

Gilkinson, K.D., D.C. Gordon Jr., K.G. MacIsaac, D.L. McKeown, E.L.R. Kenchington, C. Bourbonnais and W.P. Vass. 2005b. Immediate impacts and recovery trajectories of macrofaunal communities following hydraulic clam dredging on Banquereau, eastern Canada. ICES Journal of Marine Science 62: 925-947.

Gordon, D.C. Jr., D.L. McKeown, G. Steeves, W.P. Vass, K. Bentham, and M. Chin-Yee. 2006. Canadian imaging and sampling technology for studying benthic habitat and biological communities. In: Todd, B.J. and H.G. Greene (eds) Mapping the sea floor for habitat characterization. Geological Association of Canada Special Publication, St. John's, NL.

Gordon, D.C. Jr. and K.D. Gilkinson. 2002. Habitat assessment: proposed ocean quahog fishery. Internal DFO expert opinion.

Gordon, D.C. Jr, K.D. Gilkinson, E.L.R. Kenchington, J. Prena, C. Bourbonnais, K.G. MacIsaac, D.L. McKeown and W.P. Vass. 2002. Summary of the Grand Banks otter trawling experiment (1993-1995): effects on benthic habitat and communities. Can. Tech. Rept. Fish. Aquat. Sci. 2416: 72 p.

Gordon, D.C. Jr, K.D. Gilkinson, E.L.R. Kenchington, C. Bourbonnais, K.G. MacIsaac, D.L. McKeown and W.P. Vass. 2005. Summary of the Grand Banks otter trawling experiment (1993-1995): effects on benthic habitat and macrobenthic communities. American Fisheries Society Symposium 41: 411-424.

Gordon, D.C. Jr., E.L.R. Kenchington and K.D. Gilkinson. 2005. ESSIM operational objectives worksheet. Draft submitted in January 2005

Gordon et al. 2006. Summary of Western Bank otter trawling experiment. DFO Tech. Report. In preparation.

Guigné, J.Y. P. Schwinghamer, Q. Liu and V.H. Chin. 1993. High resolution and broadband processing of acoustic images of the marine benthos. Proceeding of the Institute of Acoustics 15: 237-252.

Harrison, P.H., K.W. Strong and K.A. Jenner. 1991. A review of fishery related seabed disturbance on the Grand Banks of Newfoundland. Final contractors report to DFO from Maritime Testing (1985) Ltd, 32 p. plus figures and appendices.

Henry, L.-A., E.L.R. .Kenchington and A. Silvaggio. 2003. Effects of mechanical experimental disturbance on aspects of colony responses, reproduction and regeneration in the cold-water octocoral *Gersemia rubiformis*. Can. J. Zool. 81: 1691-1701.

Henry, L.-A. and E. Kenchington. 2004a. Differences between epilithic and epizoic hydroid assemblages from commercial scallop grounds in the Bay of Fundy, northwest Atlantic. Mar. Ecol. Prog. Ser. -266: 123-134.

Henry, L.-A. and E. Kenchington. 2004b. Ecological and genetic evidence for impaired sexual reproduction and induced clonality in the hydroid *Sertularia cupressina* (Cnidaria: Hydrozoa) on commercial scallop grounds in Atlantic Canada. Mar. Biol. 145: 1107-1118.

Henry, L.-A., E.L.R. Kenchington, T.J. Kenchington, K.G. MacIsaac, C. Bourbonnais and D.C. Gordon Jr. 2005. Impacts of trawling on colonial epifaunal assemblages on a cobble bottom ecosystem on Western Bank (northeast Atlantic). Mar. Ecol. Prog. Ser. 306: 63-78.

Hurley, S.J., K.D. Gilkinson and M.J. Paulin. 1997. Shell strength index tests on selected Grand Banks bivalves. Contract report for DFO, C-Core Publication 96-C35.

Jamieson, G.S. and A. Campbell. 1985. Sea scallop fishing impact on American lobsters in the Gulf of St. Lawrence. U.S. NMFS Fish. Bull. 83: 575-586.

Jenner, K., K.W. Strong and P. Pocklington. 1991. A review of fishery related seabed disturbance in the Scotia-Fundy Region. Industry Services and Native Fisheries Branch, Project Report No. 166.

Kenchington, E.L.R., J. Prena, K.D. Gilkinson, D.C.Gordon Jr., K.MacIsaac, C. Bourbonnais, P.J. Schwinghamer, T.W. Rowell, D.L. McKeown and W.P. Vass. 2001. The effects of experimental otter trawling on the macrofauna of a sandy bottom ecosystem on the Grand Banks of Newfoundland. Can. J. Fish. Aquat. Sci.: 58: 1043-1057.

Kenchington, E.L.R., D.C. Gordon Jr., C. Bourbonnais, K.G. MacIsaac, K.D. Gilkinson, D.L. McKeown and W.P. Vass. 2005. Effects of experimental otter trawling on the feeding of demersal fish on Western Bank, Nova Scotia. American Fisheries Society Symposium 41: 391-409.

Kenchington, E.L.R., K.D. Gilkinson, K.G. MacIsaac, C. Bourbonnais, T.J. Kenchington, S.J. Smith and D.C. Gordon Jr. 2006. Effects of experimental otter trawling on benthic assemblages on Western Bank, northwest Atlantic Ocean. Journal of Sea Research. In press.

Kenchington, E.L.R. and others. 2006. Changes in the bycatch of scallop dredges over 30 years attributed to chronic fishing. In preparation.

Ketchen, K.S. 1947. An investigation into the destruction of grounds by otter trawling gear. Prog. Rept. Fish. Res. Bd. Can. 73: 54-56.

Løkkeborg, S. 2005. Impacts of trawling and scallop dredging on benthic habitats and communities. FAO Technical Paper 472. 59 p.

Kulka, D.W. and D.A. Pitcher. 2001. Spatial and temporal patterns in trawling activity in the Canadian Atlantic and Pacific. ICES CM 2001/R:02.

McKeown, D.L. and D.C. Gordon Jr. 1997. Grand Banks otter trawling impact experiment: II. Navigation procedures and results. Can. Tech. Rep. Fish. Aquat. Sci. 2159: xi + 79 p.

Messieh, S.N., T.W. Rowell, D.L. Peer and P.J. Cranford. 1991. The effects of trawling, dredging and ocean dumping on the eastern Canadian continental shelf seabed. Cont. Shelf Res. 11: 1237-1263.

Mortensen, P.B., and L. Buhl-Mortensen. 2005. Deep-water corals and their habitats in The Gully, a submarine canyon off Atlantic Canada. In: Freiwald, A. and M. Roberts (eds), Cold-water corals and ecosystems, Springer-Verlag, pp. 247-277.

Mortensen, P.B., L. Buhl-Mortensen, D.C. Gordon Jr., G.B.J. Fader, D.L. McKeown and D.G. Fenton. 2005. Effects of fisheries on deepwater gorgonian corals in the Northeast Channel, Nova Scotia. American Fisheries Society Symposium 41: 369-382.

Mortensen, P.B., L. Buhl-Mortensen, S. E. Gass, D. C. Gordon Jr., E.L.R. Kenchington, C. Bourbonnais and K. G. MacIsaac. 2006a. Deep-water corals in Atlantic Canada: A summary of ESRF-funded research (2001-2003). ESRF Report 143..

Mortensen, P.B., D.C. Gordon Jr., L. Buhl-Mortensen and D.W. Kulka. 2006b. The first direct observation of a *Lophelia pertusa* reef complex in Atlantic Canada. Under revision.

Paulin, M.J., K.D. Gilkinson, and S.J. Hurley. 1995. Physical model of trawl door/seabed interaction. Contract report for DFO, C-Core Publication 95-C15.

Prena, J., T.W. Rowell, P Schwinghamer, K.Gilkinson and D.C. Gordon , Jr. 1996. Grand Banks otter trawling experiment: I. Site selection process, with a description of macrofaunal communities. Can. Tech. Rep. Fish. Aquat. Sci. 2094: viii + 38 p.

Prena J., P. Schwinghamer, T.W. Rowell, D.C. Gordon Jr., K.D. Gilkinson, W.P.Vass and D.L. McKeown. 1999. Experimental otter trawling on a sandy bottom ecosystem of the Grand Banks of Newfoundland: analysis of trawl bycatch and effects on epifauna. Mar. Ecol. Prog. Ser.181: 107-124.

Pringle, J.D. and D.J. Jones. 1980. The interactions of lobster, scallop and Irish moss fisheries off Borden, Prince Edward Island. Can. Tech. Rept. Fish. Aquat. Sci. 973, 17 p.

Pringle, J.D. and R.E. Semple. 1987. Drag raking impact on Irish moss (*Chrondus crispus*) frond size structure. CAFSAC Research Document No. 87/91, 16 p.

Robichaud, D.A., A.M. Williamson, and D.E. Graham. 1987. Characteristics of the St. Mary's Bay lobster stock in relation to scallop gear impact. Can. Manuscr. Rep. Fish. Aquat. Sci. 1955: 17 p.

Robinson, S.M.C., S. Bernier and A. MacIntyre. 2001. The impact of scallop drags on sea urchin populations and benthos in the Bay of Fundy, Canada. Hydrobiologia 465:103-114.

Roddick, D.L. and R.J. Miller. 1992. Spatial and temporal overlap of the American lobster (*Homarus americanus*) and sea scallop (*Placopecten magellanicus*) as related to the impact of inshore scallop dragging. Can. J. Fish. Aquat. Sci. 49: 1486-1492.

Rowell, T.W., P. Schwinghamer, K.D. Gilkinson, D.C. Gordon Jr., E. Hartgers, M. Hawryluk, D.L. McKeown, J. Prena, W.P. Vass, and P. Woo. 1997. Grand Banks otter trawling impact experiment: III. Experimental design and sampling equipment. Can. Tech. Rep. Fish. Aquat. Sci. 2190: viii + 36 p.

Scarratt, D.J. 1973. The effects of raking Irish moss (*Chondrus crispus*) on lobsters in Prince Edward Island. Helgol. wiss. Meer. 24:415-424.

Schwinghamer, P., Guigné, J.Y. and W.C. Siu. 1996. Quantifying the impact of trawling on benthic habitat structure using high resolution acoustics and chaos theory. Can. J. Fish. Aquat. Sci. 53: 288-296.

Schwinghamer, P., D.C. Gordon Jr, T.W. Rowell, J. Prena, D.L. McKeown, G. Sonnichsen, and J.Y. Guigné. 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.

Table 1. Summary of DFO projects. 1 Bay of Fundy (1990-1991), 2 Grand Banks (1993-1995), 3 Western Bank (1997-1999), 4 Banquereau (1998-2000), 5 Bay of Fundy (1993), 6 Bay of Fundy (1966/67 to 1997), 7 Bay of Fundy (2000), 8 lab studies with soft corals (2002), and 9 deep-water coral habitat (2000-2003).

		1	2	3	4	5	6	7	8	9
Gear	Otter Trawl	X	X	X						X
	Scallop Dredge					X	X	X		
	Hydraulic Clam Dredge				X					
Bottom	Sand	X	X		X					
	Gravel			X		X	X	X		X
Design	Manipulative Field Experiment	X	X	X	X	X				
	Observational						X	X		X
	Lab Experiment		X						X	
Impacts	Habitat	X	X	X	X	X				
	Benthic communities	X	X	X	X	X	X	X	X	X
	Immediate	X	X	X	X	X			X	
	Long term (> 1 year)		X	X	X		X	X		X

Table 2. Summary of benthic organisms most sensitive to mobile fishing gear as observed in DFO projects. 1 Bay of Fundy (1990-1991), 2 Grand Banks (1993-1995), 3 Western Bank (1997-1999), 4 Banquereau (1998-2000), 5 Bay of Fundy (1993), 6 Bay of Fundy (1966/67 to 1997), 7 Bay of Fundy (2000), 8 lab studies with soft corals (2002), and 9 deep-water coral habitat (2000-2003).

Organism	1	2	3	4	5	6	7	8	9
Sponges						X			
Hydroids							X		
Soft corals		X						X	
Gorgonian and stony corals									X
Amphipods				X					
Polychaetes		X	X	X		X			
Sand dollars		X							
Brittle stars		X							
Sea urchins		X			X				
Sea cucumbers				X					
Snow crabs		X							
Horse mussels			X			X			
Propellerclams				X					
Arctic surf clams				X					
Greenland cockles				X					
Ocean quohaugs				X					
Brachiopods			X						
Tunicates						X			
Kelp					X				

Table 3. Properties of different fishing gears used in Atlantic Canada.

Gear Type	Properties
Otter Trawl	Used on all bottom types
	Relatively limited penetration of the seabed
	Large area affected annually
	Can be short return period for trawling disturbance
	Major impacts on non-target species
	Little if any use of seabed acoustics by industry
Scallop Dredge	Used primarily on gravel
	Slight penetration of seabed
	Smaller area affected annually
	Longer return period for dredging disturbance
	Major impacts on non-target species
	Industry using seabed acoustics to locate fishing areas
Hydraulic Clam Dredge	Used only on sand
	Deep penetration of seabed (20 cm)
	Small area affected annually
	Return period ten years or more
	Major impacts on target species
	Industry using seabed acoustics to locate fishing areas