SUMMARY OF THE WESTERN BANK OTTER TRAWLING EXPERIMENT (1997-1999): EFFECTS ON BENTHIC HABITAT AND COMMUNITIES

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ABSTRACT

During 1997-1999 we conducted a three-year manipulative experiment on the effects of repetitive otter trawling on a gravel bottom ecosystem on Western Bank, an offshore fishing bank on the Scotian Shelf. This was a parallel experiment to the one we conducted on a sandy seabed on the Grand Banks of Newfoundland in 1993-1995. It is one of very few multi-year otter trawling impact experiments that have been conducted on gravel seabeds, a habitat type that is generally regarded to be particularly vulnerable to bottom fishing gear. The study site was located within the 4TVW Haddock Nursery Area that has been closed to trawling since its creation in 1987. At least 12 replicate trawl sets were made each year, one after the other, along the same line (2 km long) using an Engel 145 otter trawl. Fish catch was processed to determine species, abundance, weight and stomach contents. Surveys of habitat characteristics and benthic communities were carried out using various acoustic, imaging and sampling tools along both experimental and reference lines before and after trawling each year.

There was considerable spatial variability in the seabed disturbance. After 10 replicate sets most if not all the area within a 100 m wide corridor had been swept at least once by the entire trawl (60 m between the doors) while on the order of 65-80% of the area had been swept at least once by the footgear and net (20 m). It is estimated that locations of Videograb samples had been crossed over by the footgear and net between zero to eight times while the range of crossings by the entire trawl was two to 12 times. Habitat disturbance was evident in the sidescan sonograms and imagery and the level of disturbance was well predicted by the number of crossings by the footgear and net. After two passes, the probability of not observing disturbance was effectively zero.

Haddock dominated the trawl catch (about 75% by weight) while other common species included Atlantic cod, herring, pollock, mackerel, silver hake and redfish. Fish catch increased significantly after the first two sets each year suggesting scavenging behaviour. No structure-forming epibenthic organisms were captured in the trawl. The majority of the 341 benthic taxa observed in the Videograb samples were epifaunal. Biomass was heavily dominated by the horse mussel (76%) while the most abundant taxa were tube-dwelling amphipods and sabellid worms. Natural changes in the benthic communities were detected along the reference lines during the experiment.

The experimental trawling had very limited immediate impacts on the benthic community (i.e. within a few days). Over three years of trawling, some polychaetes and amphipods showed decreases in abundance and biomass but no significant differences in community composition were evident. Abundance/biomass comparisons showed a marked decrease in the relative biomass of the highest ranking species which was not seen along the reference lines. Of the various interactions tested, only epifaunal biomass as a proportion of total biomass showed a significant interaction. Epifaunal biomass was approximately

90% of the total biomass in the reference lines throughout but declined to 77% on the trawled line by the end of the experiment. The frequency of visible damage was greatest for the tube-dwelling polychaete *Thelepus cincinnatus*, the horse mussel *Modiolus modiolus* and the brachiopod *Terebratulina septentrionalis*. The probability of observing biological damage was significantly related to the number of passes by the trawl.

A total of 177 prey taxa were identified in the stomachs of fish and there were significant differences in diet between the five taxa examined. Haddock had the most diverse diet while American plaice had the least. Only three prey items were shared by all five taxa. All five fish taxa demonstrated proportional changes in their diets as trawling progressed. Atlantic cod, American plaice and yellowtail flounder also exploited new prey. The dominant organisms in the dietary changes were the tube-dwelling polychaete *Thelepus cincinnatus* and the horse mussel *Modiolus modiolus.* These two prey taxa also had the highest incidence of visible damage after trawling.

Assessing all results, the species most sensitive to trawling disturbance were the horse mussel *Modiolus modiolus*, the tube-dwelling sabellid worm *Thelepus cincinnatus*, the brachiopod *Terebratulina septentrionalis* and burrowing anemone *Cerianthus* sp. All these species are epibenthic, sessile and relatively large.

Both our Western Bank experiment and our parallel Grand Banks experiment indicate that the impacts of otter trawling are greatest on epibenthic organisms that are exposed to direct contact with the gear. Collectively, the results clearly indicate that the immediate impacts of otter trawling were greater on the sandy seabed studied on the Grand Banks than on the gravel lag seabed studied on Western Bank. However, both the habitat and communities at the Grand Banks site recovered in approximately one year while recovery at the Western Bank site was considerably longer. These differences between the sites are due to differences in habitat and benthic community composition. Collectively, the impacts we observed were generally less than those reported for other experiments on gravel seabeds. We feel that the major reason for this was that the epibenthic organisms present at the study site on Western Bank were relatively small and there was an absence of large, structure-forming taxa such as corals or sponges.

RÉSUMÉ

Pendant trois ans, soit de 1997 à 1999, nous avons procédé à une expérience de manipulations d’un chalut à panneaux afin d’étudier les effets de l’utilisation répétée de cet engin sur l’écosystème d’un fond de gravier du banc Western, un banc de pêche hauturière situé sur le plateau néo-écossais. L’expérience faisait pendant à celle qui avait été effectuée sur des fonds sablonneux des Grands Bancs de Terre-Neuve de 1993 à 1995. Elle constitue une des très rares études pluriannuelles sur les incidences des chaluts à

panneaux réalisées sur des fonds marins de gravier, un type d'habitat considéré comme étant particulièrement vulnérable à l'action des engins servant à la pêche de fond. L'expérience s'est déroulée au sein de l'alevinière d'aiglefin de 4TVW, délimitée en 1987 et fermée depuis aux chalutiers. Au moins 12 traits de chalut ont été effectués l'un après l'autre et répétés chaque année sur le même transect (de 2 km de long) au moyen d'un chalut à panneaux Engel 145. Un examen des prises a permis de déterminer les espèces, l'abondance, le poids et le contenu stomacal des poissons qui les composaient. Des études des caractéristiques de l'habitat et des communautés benthiques ont été effectuées à l'aide de divers outils de relevé acoustique, d'imagerie et d'échantillonnage le long du transect de chalutage et de transects de référence, cela avant et après l'opération de chalutage chaque année.

Nous avons observé une variabilité spatiale considérable dans les perturbations du fond marin. Après 10 traits répétés, la plupart, sinon la totalité, de la zone située au sein d'un corridor de 100 m de large avait été balayée au moins une fois par toute la largeur du chalut (60 m entre les panneaux) alors qu'une proportion de l'ordre de 65 à 80 % de la superficie avait été parcourue au moins une fois par la ralingue inférieure et le filet (20 m). Nous estimons que les endroits où des échantillons ont été prélevés au Videograb ont été traversés par la ralingue inférieure et le filet entre zéro et huit fois, tandis que les passages par l'ensemble du chalut étaient de l'ordre de deux à douze fois. L'imagerie et les sonogrammes obtenus par balayage latéral reflétaient une perturbation manifeste de l'habitat, selon une intensité étroitement corrélée au nombre de passages de la ralingue inférieure et du filet. Après deux passages, la probabilité d'une absence de perturbation était pratiquement nulle.

L'aiglefin dominait les prises au chalut (dont il représentait environ 75 % du poids); les autres espèces courantes parmi les prises étaient la morue, le hareng, la goberge, le maquereau, le merlu argenté et le sébaste. Chaque année, les captures de poisson augmentaient notablement après les deux premiers traits, ce qui semble refléter des comportements de charognard. Il n'y avait pas d'organismes épibenthiques qui forment des structures parmi les prises du chalut. La majorité des 341 taxons de la faune benthique observés dans les échantillons prélevés au Videograb étaient épifauniques. La biomasse était largement dominée par les modioles (76 %) et les taxons les plus abondants étaient les amphipodes tubicoles et les sabelles. Des changements naturels dans les communautés benthiques ont été détectés au cours de l'expérience le long des transects de référence.

Le chalutage expérimental a eu des effets immédiats (c.-à-d. dans les quelques jours qui suivaient) très limités sur la communauté benthique. En trois ans de chalutage, certains polychètes et amphipodes ont présenté des baisses de l'abondance et de la biomasse, mais aucune différence importante n'apparaissait dans la composition de la communauté. Des comparaisons de l'abondance et de la biomasse dénotaient une nette diminution de la biomasse relative des espèces du haut de la gamme, diminution qu'on n'a pas constatée sur les transects de référence. Il ressort des différentes interactions étudiées que sur la biomasse totale, seule la biomasse épifaunique reflétait une interaction importante. La biomasse épifaunique correspondait à environ 90 % de la biomasse totale sur les transects de référence, mais elle était tombée à 77 % à la fin de l'expérience sur le transect assujetti au chalutage. La fréquence des dommages visibles était la plus élevée dans le cas du polychète tubicole *Thelepus cincinnatus*, du modiole *Modiolus modiolus* et du brachiopode *Terebratulina septentrionalis*. La probabilité d'observer des dommages biologiques était largement corrélée au nombre de passages du chalut.

En tout, 177 taxons de proies ont été identifiés parmi les contenus stomacaux des poissons et il y avait des différences importantes dans l'alimentation des cinq taxons de poisson examinés. L'aiglefin était le poisson dont l'alimentation était la plus variée, tandis que la plie canadienne était celui dont l'alimentation était la moins variée. Les cinq taxons n'avaient en commun que trois proies. La morue, la plie canadienne et la limande à queue jaune avaient consommé aussi de nouvelles proies. Les principaux organismes visés par les changements dans l'alimentation étaient le polychète tubicole *Thelepus cincinnatus* et le modiole *Modiolus modiolus.* Ces deux espèces proies étaient aussi celles chez qui il y avait le plus de dommages visibles après le chalutage.

Il ressort de l'évaluation de tous les résultats que les espèces les plus sensibles aux perturbations par le chalutage étaient le modiole *Modiolus modiolus*, la sabelle tubicole *Thelepus cincinnatus*, le brachiopode *Terebratulina septentrionalis* et l'anémone de mer *Cerianthus* sp. Toutes ces espèces sont épibenthiques, sessiles et relativement grandes.

Il ressort à la fois de notre expérience sur le banc Western et de l'expérience parallèle sur les Grands Bancs que les chaluts à panneaux ont de plus grands effets sur les organismes épibenthiques qui sont exposés à un contact direct avec l'engin. Dans l'ensemble, les résultats montrent clairement que les incidences immédiates des chaluts à panneaux étaient plus grandes dans le banc sablonneux ayant fait l'objet de l'expérience réalisée sur les Grands Bancs que sur le fond de gravier visé par l'expérience sur le banc Western. Toutefois, l'habitat et les communautés touchés sur les Grands Bancs se sont rétablis en environ un an, alors que sur le banc Western, le rétablissement a été considérablement plus long. Cela s'explique par des différences dans la composition de l'habitat et de la communauté benthique aux deux endroits. Globalement, les incidences que nous avons observées étaient en général de moindre importance que celles qui ont été signalées dans les autres expériences réalisées sur des fonds de gravier. Nous pensons que cela est dû surtout au fait que les organismes épibenthiques présents sur les parties du banc Western où a eu lieu l'expérience étaient relativement petits et que les grands taxons qui forment des structures, comme les coraux et les éponges, étaient absents de cette zone.

INTRODUCTION

Mobile fishing gear such as beam trawls, otter trawls, scallop rakes and clam dredges are widely used around the world to harvest benthic fishery resources and concerns have been raised about their environmental effects. A large number of scientific studies of their impacts on benthic habitat and communities have been conducted and numerous reviews have been published, the most recent including Collie et al. 2000, Dayton et al. 2002, Johnson 2002, National Research Council 2002, Chuenpagdee et al. 2003, Barnes and Thomas 2005, Løkkeborg 2005 and Kaiser et al. 2006.

Understanding the impacts of mobile gear on benthic habitat and communities is a difficult and expensive undertaking, especially in offshore marine environments. Benthic habitats and communities display considerable natural variability, both spatially and temporally, which must be factored into the design of research programs. Sources of natural variation include storm waves, tidal currents, ice, bioturbation, recruitment variability and foraging by predators. While some useful information can be obtained from laboratory experiments, well-designed field programs are essential. Manipulative experiments can provide direct evidence on impacts of a known disturbance event on a particular habitat but, to date, most of these have been conducted in relatively shallow water and have been of limited spatial extent and short-term in nature. Alternatively, observational studies comparing areas with different fishing histories, or observations over time in the same area, can provide indirect evidence of longer-term impacts at the spatial scale of entire fishing grounds, though the conclusions may be equivocal as natural fluctuations may be mistakenly attributed to human impacts and it is difficult to accurately determine the magnitude of the fishing disturbance. With observational studies, it can be difficult to study the impacts of specific gear types since fished areas often have histories of multiple gear usage. Regardless of the experimental approach taken, it is necessary to include observations in reference areas not influenced by previous fishing disturbance but, because of the widespread use of mobile fishing gear, these can be difficult to find. Much can still be learned from conducting larger scale and longer-term manipulative experiments of gear impacts in deeper water habitats targeted by commercial fisheries.

The potential environmental impacts of fishing gear on benthic habitat and communities 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 Prince Edward Island. 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 Canadian studies was resolving conflicts between different fisheries in shallow coastal waters. More recently, the impact of shrimp trawling on mortality and damage to crab populations was investigated in Newfoundland and Labrador waters (Dawe et al. 2007).

In 1990, a collaborative research program between the Maritimes and Newfoundland & Labrador Regions of the Department of Fisheries and Oceans (DFO) 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. The geographic focus was fishing banks on the continental shelf off Atlantic Canada. 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 (ESSRF) 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 disturbance from all types of mobile gear (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 disturbance from fishing gear.

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. 2007) and used extensively in field programs. The DRUMS^{TM} acoustic imaging system was developed under contract by Guigné International Ltd. and integrated into the Videograb to provide information on 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 (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).

From the very beginning of our program, it was our intention to conduct a series of carefully designed multi-year field experiments to investigate and compare the direct impacts of different fishing gears on benthic habitat and communities in different environments. We also wanted to investigate the rates of recovery. We began our research with some relatively simple experiments with otter trawling in the intertidal region of the Bay of Fundy (Brylinsky et al. 1994). This work was done while we were developing sampling gear and seeking suitable sites for offshore studies.

Our first major experiment was a three-year manipulative experiment (1993-1995) on the effects of repetitive otter trawling conducted on a sandy bottom ecosystem on the Grand Banks of Newfoundland. The site had not been trawled commercially for at least 13 years. Experimental lines (13 km long) were trawled 10 times once each year at the same time. Parallel reference lines provided information on natural variation. Overall, the results indicated that the effects of annual otter trawling were detectable on habitat and epifauna but that recovery appeared to occur within a year and there was no evidence that the benthic community was altered by three years of repetitive trawling (Prena et al. 1996, Schwinghamer et al. 1996, McKeown and Gordon 1997, Rowell et al. 1997, Gilkinson et al. 1998, Schwinghamer et al. 1998, Gilkinson 1999, Prena et al. 1999, Kenchington et al. 2001, Gordon et al. 2002, 2005).

It was recognized that these conclusions were specific to the sandy bottom habitat and community present at the study site and that the results could be quite different on a hard bottom habitat with a greater abundance and diversity of sessile epifauna. Gravel habitats are widespread on the continental shelf off Atlantic Canada and are important fishing areas. Therefore, during 1997-1999, we conducted a similar three-year manipulative experiment on a gravel bottom on Western Bank using the same otter trawl as our Grand Banks experiment.

This report summarizes all the results of this major field experiment on Western Bank. Results of the effects of the experimental trawling on the feeding of demersal fish (Kenchington et al. 2005), colonial epifauna assemblages (Henry et al. 2006) and benthic assemblages (both macrofauna and megafauna) (Kenchington et al. 2006) have already been published. Data on the spatial distribution of the trawling disturbance and the observed impacts on seabed habitat are presented here for the first time. The combined results are then compared to those from the Grand Banks otter trawling experiment and with other experiments conducted on gravel bottoms elsewhere in the world.

We also have conducted a three-year experiment on the effects of hydraulic clam dredging on a sandy bottom ecosystem on Banquereau (Gilkinson et al. 2003, 2005a,b).

OTTER TRAWLS AND THEIR POTENTIAL EFFECTS ON BENTHIC HABITAT AND ORGANISMS

Otter trawls consist of a funnel-shaped net towed at a speed of 2-4 knots across the seabed by a single vessel. They have four major components: doors (also called otter boards), sweeps, footgear and net (Fig. 1). All components create turbulence that can affect both habitat and organisms. This turbulence is intended and is part of the working principle of the gear. The two doors keep the gear on the seabed and provide horizontal spread to the net. They can be quite large and heavy, and are usually in continuous contact with the seabed, often leaving well-defined tracks that, depending upon sediment composition, can be as deep as 30 cm. The cloud of sediment stirred up by the doors tends to herd fish toward the mouth of the net. The sweeps, leading from the doors to the net, can periodically come into contact with the seabed but the disturbance they create is much less than the doors. The footgear is found at the leading edge of the lower part of the trawl net. It is usually fitted with different kinds of bobbins or rollers that maintain constant contact with the seabed, except when they skip over features on rough bottom. Rockhopper footgear does not rotate but drags over the seabed. Therefore, this type of footgear can cause substantial disturbance. The bottom of the trawl net can also come into contact with the seabed, especially the codend when full, disturbing the area already passed over by the footgear. In some applications, such as towing for shrimp on a smooth bottom, tickler chains are installed in front of the footgear to stir up sediment and improve the capture rate of target organisms. When first developed, otter trawling was limited mainly to smooth bottoms. However, technology has evolved to the point where otter trawling can now be carried out on almost any kind of bottom, no matter how rough.

Otter trawls can potentially affect benthic habitat and organisms in a wide variety of ways. Immediate impacts can include:

- Resuspension and displacement of sediment, organic matter, shells and small organisms.
- Burial of habitat structures and organisms by redeposited sediment.
- Digging of furrows, creation of berms, realignment of rocks and shells, and smoothing of surficial sediment features.
- Destruction of habitat structures (mounds, tubes, burrows, etc.).
- Capture and removal of organisms including target species and bycatch (both fish and invertebrates).
- Damaging or killing organisms that are left on the seabed exposed to predation, including juvenile fish and structure-forming organisms such as sponges and corals.
- Temporary exposure of sediment-dwelling organisms, making them more available to predators.
- Attraction of scavengers because of the increased availability of prey.

Longer-term impacts, especially if otter trawling is repeated frequently over the same bottom, can include:

- Altering the sediment habitat structure that could affect its suitability for particular species and the rates of biogeochemical fluxes between the sediment and water column.
- Changing the composition of benthic communities (e.g. presence/absence, relative abundance, biomass and size of individual species).
- Changing ecosystem processes such as the rates of primary and secondary production and organic matter dynamics.
- Affecting fisheries recruitment through changes in physical habitat and food supply that affect the survival of juvenile fish.

STUDY SITE

The study site was located on Western Bank on the continental shelf off Nova Scotia, Canada (approximately 43^{o} 45' N, 61^{o} 41 W) (Fig. 2). This site, selected on the basis of sidescan sonograms and biological sampling, was considered to be the most suitable of several that were surveyed on Western and Emerald Banks during a cruise on the C.C.G.S. *Parizeau* in 1996. Surficial sediments are the gravel facies of the Sable Island Sand and Gravel Formation that covers a large area of the Scotian Shelf (King and Fader 1986). An abundant and diverse benthic community, dominated by epifauna, was present. Sidescan sonar and video surveys indicated that the seabed had a relatively high degree of spatial homogeneity over a large area. Depth was relatively uniform, averaging about 70 m. Historically, the site has been a productive fishing ground using both mobile and fixed gear. Spatial analysis of observer data indicated that it had been trawled in the early 1980's (Kulka and Pitcher 2001). The site is now within the large 4TVW Haddock Nursery Area, created in 1987, which is closed to all groundfishing activity to protect juveniles (Frank et al. 2000). This closed area has remained open to the scallop fishery but analysis of effort data indicated that the study site had not been dredged since at least 1987. Sidescan sonar surveys showed no evidence of any seabed disturbance by fishing gear. Therefore, we are confident that the seabed at the chosen site had not been disturbed by mobile gear for at least 10 years when we started the experiment in 1997.

EXPERIMENTAL DESIGN

A 2 km by 2 km box was laid out as the experimental frame over an area of relatively uniform gravel seabed (Fig. 3). Eleven north-south lines, 200 m apart, were plotted and labeled A to K. One line was randomly selected to be the experimental (i.e. trawled) line (Line E). Three additional lines were randomly selected as reference lines (i.e. untrawled). These four lines were the experimental units. Ten sampling stations were randomly selected along Line E and another 10 were randomly selected along Lines B, G and I (Fig. 3). The intent was to conduct a full sampling program on both experimental and reference lines before and after experimental trawling for three successive years to provide an asymmetric Before-After Control-Impact (BACI) experimental design. Unfortunately, due to logistic problems, we were unable to fully sample the reference (i.e. control) stations before trawling in 1997 and 1998. All other stations were repeatedly sampled all three years.

METHODS

Experimental Trawling

The experimental trawling was carried out by the C.C.G.S. *Needler* (1997 and 1999) and C.C.G.S. *Teleost* (1998) using an Engel 145 otter trawl with 1250 kg polyvalent otter boards fitted with a Scanmar net mensuration system (McCallum and Walsh 1997). This was the same trawl used in the Grand Banks otter trawling experiment (Kenchington et al. 2001). The trawl had a door spread of 60 ± 5 m while the spread of the footgear and net wings was 20 ± 2 m (Fig. 1). The trawl was rigged with 46 cm diameter rockhopper footgear and had mesh sizes of 180 mm in the wings and belly with 130 mm in the codend. A 30 mm square mesh liner was installed in the final 9 m of the 18.5 m long codend in order to capture organisms that may be damaged but not retained by commercial nets.

The experimental trawling was conducted in September/October 1997, May 1998 and June 1999 (Table 1). Each year, the trawled line (Line E) was trawled at least 12 consecutive times in alternating directions (14 trawl sets in 1997). The intent was to concentrate the trawling disturbance within a 100 m wide corridor and therefore the research trawlers were requested to steam back and forth between the same two waypoints to keep the sets as close together as possible. Each trawl set began at least 500 m beyond one end of Line E and continued until the trawl was at least 500 m beyond the other end of the line. The average distance on bottom of trawl sets was 3.2 km (SD = 0.26). Trawling speed was approximately 1.8 m sec^{-1} (3.5 knots) and the average time for each set was 31 min (range 25-36 min). Trawling took about 17 h each year.

This design represents high intensity trawling, at the upper end of the range of effort applied by the commercial fleet on the Scotian Shelf during the period of 1980-2000 as estimated from observer data by Kulka and Pitcher (2001). They estimate that the maximum trawling intensity ranged from 141 to 644% (i.e. the seabed was swept by a trawl 1 to 6 times a year) while only about 1.5 % of the total shelf area is swept by otter trawls at an intensity greater than 100% (i.e. once a year).

Trawl Catch

In 1997 and 1998, fish were collected from the first seven trawl sets while in 1999 fish were collected from 11 of the 12 trawl sets (Kenchington et al. 2005). At the completion of each trawl set, the catch was separated by species and the wet weight of each species recorded.

Stomach samples were collected from five species: Atlantic cod (*Gadus morhua*), haddock (*Melanogrammus aeglefinus*), American plaice (*Hippoglossoides platessoides*), yellowtail flounder (*Limanda ferruginea*) and winter flounder (*Pseudopleuronectes americanus*). The total length of each dissected fish was recorded. Following dissection, stomachs were individually placed in a hypersaline solution and frozen to stop digestive processes. Only stomachs containing a noticeable amount of ingested material were removed. In the laboratory, entire stomachs with contents were removed from the freezer, thawed, blotted with a paper towel, and weighed. Stomachs were then opened and all contents removed and weighed together. For the length stratified samples (N 1432), stomach contents were identified coarsely to phylum or class. For the fish selected for detailed analysis (N 444), prey items were identified to the lowest possible taxon, usually species, genus or family. Where possible, identifications were made on incomplete parts or segments of animals.

For analysis, the stomach content samples were broken down into two time categories. Time 1 included Sets 1 and 2 that were assumed to represent conditions before any trawling disturbance. Time 2 included all the remaining sets that were assumed to represent conditions at least one hour after the initial trawling disturbance.

Acoustic Seabed Surveys

Seabed surveys and sampling were done using the C.C.G.S. *Parizeau* in 1997 and the C.C.G.S. *Hudson* in 1998 and 1999. Sidescan sonar surveys were conducted along the experimental lines with a Simrad Model 992 towfish, equipped with 120 and 300 kHz transducers and operated at 100 m range. The theoretical resolution of the system is estimated to be 0.25 m at the tow speed of about 2 m sec^{-1} used during surveys. In 1999, a depressor weight and flotation package were added to the end of the cable to decouple the towfish from the motion of the ship. This improved the quality of the sonar imagery and the ability to characterize seabed features. Bathymetric data along survey lines were collected with a 30 KHz echo sounder and processed with the Questar Tangent QTCView sediment classification system (Collins et al. 1996). In July 1998, soon after the second trawling episode, a multibeam survey of the entire experimental site (Fig. 3) was conducted by the Canadian Hydrographic Service using the C.C.G.S. *Creed* equipped with a Konsberg-Simrad EM 1000 multibeam sonar system.

Seabed Imagery

Continuous video surveys of the seabed were run along the experimental lines using either BRUTIV (Rowell et al. 1997) or Towcam (Gordon et al. 2007), in most cases before and after trawling. Both platforms were fitted with a forward-looking, low-resolution colour video camera and quartz halogen lights. They were towed at an altitude of about 2 m off the seabed at a speed of about 1 m sec^{-1}. The field of view on the seabed was a few meters wide and it was possible to discern substrate, large epibenthic organisms and fish.

Higher resolution video and photographic imagery of habitat and epibenthic organisms was collected using Campod at the 20 randomly selected stations (Fig. 3) before and after trawling (Table 1). In 1997 and 1998, it was possible to collect Campod imagery on two occasions after trawling (After1 and After2). Campod is a light-weight instrumented tripod equipped with two colour video cameras (oblique and downward-looking), quartz halogen lights, a 35-mm still camera and high speed flashes (Gordon et al. 2007). Video transects were on the order of 20-30 m long, and Campod was landed at least five times along each transect to take a still photo (image size was approximately 37 by 52 cm or 0.2 m^2). Campod photos can resolve features down to several millimeters (i.e. can discern tubes and burrows). Except for the small footprint when it lands, Campod does not disturb the seabed. In 1998, an optical backscatter sensor was mounted on Campod for several deployments before and after trawling in the trawled corridor.

All video imagery was recorded on either VHS or DVCAM digital tape and reviewed later ashore. For Campod, the video from the high-resolution downward-looking camera was processed and occurrences of disturbance were recorded. After development, the 35 mm slides taken with Campod were digitized and burned to CD. Images were analyzed on PC using Adobe Photoshop in a random blind fashion so that their identity (i.e. year, period, treatment) was unknown. Observations of disturbance were categorized and recorded. In addition, the abundance of whole and damaged shells was tabulated, and the relative abundance of tubes and burrows plus white coralline algae was recorded. The coralline algae are usually pink in colour and it is assumed that white patches represent dead or damaged algae.

Seabed Sampling

Benthic organisms were collected with Videograb at the 20 randomly selected stations before and after trawling (Fig. 3). Videograb is a hydraulically actuated bucket grab equipped with two colour video cameras (Gordon et al. 2007). It was designed to minimize disturbance to the sampling area and to provide the scientific operator the ability to view the seabed being sampled and verify that the bucket closed properly prior to recovery. Area sampled is 0.5 m^2, sampling depth is 10-25 cm and at full penetration the sediment volume collected is about 100 L. Because of the hydraulic closing mechanism, Videograb worked well on the gravel sediment, although several attempts were often needed to get a satisfactory sample because of cobbles jamming the jaws. On a few occasions, we were not able to collect a suitable sample due to time limitations. Videograb leaves a relatively small footprint of just a few square meters on the seabed. In 1998, Videograb was equipped with a dynamically responding underwater matrix system (DRUMS^{TM}) to provide acoustic information on small-scale structural properties of surficial sediments (Schwinghamer et al. 1996, 1998).

The contents of Videograb were dropped into a dump tray, transferred to a sorting table and washed with seawater through a 1 mm screen (Kenchington et al. 2006). All material retained on the screen was transferred to a plastic bucket and preserved in buffered 10% formalin. Back ashore, samples were brought into suspension, screened over a 1 mm mesh screen, sorted under a dissecting microscope and preserved in 70% ethanol. Organisms were identified to the lowest taxonomic level possible and retained for subsequent referral for consistency of identification. Poor condition of specimens, lack of information about juvenile forms, gaps in taxonomic knowledge of some groups and lack of expertise necessary for accurate identifications of some types prevented species-level identification for some organisms. Ostracods and barnacles, although collected, were not analyzed. Abundance and, for most species, biomass (formalin wet weight, including both mantle cavity liquid and shells for molluscs) were determined for each taxon

(Kenchington et al. 2006).

Colonial epifauna (i.e. sponges, hydroids, soft corals, bryozoans, tunicates) were separated from other organisms under a dissecting microscope and preserved in 70% ethanol (Henry et al. 2006). The wet weights of each colonial taxon (after fixation and preservation) were measured to the nearest 0.1 mg. Abundance was not estimated because it was not known whether colony fragments were derived from one or more colonies. Subsequent analyses therefore used either biomass or presence/absence data.

In 1999, sediment samples for geological assessment (grain size, stratification, etc.) were collected at four stations with a large volume IKU bucket sediment grab (0.9 m^3).

Navigation

In order to meet the operational requirements of this experiment, it was necessary to determine the path of the otter trawl on the seabed with a high degree of accuracy so that the resultant zones of disturbance could be mapped. It was also essential to determine the precise location of towed survey (i.e. sidescan, BRUTIV and Towcam) and sampling (i.e. Campod and Videograb) gear in order to understand the spatial relationship of observational data to trawling disturbance.

All four vessels used in the experiment were equipped with dGPS. In 1997 and 1998, navigation data on the research trawler were logged and, in addition, the path of the trawl was recorded on as many sets as possible using an ORE Trackpoint II ultra-short baseline acoustic tracking system. A transponder was placed on the headrope at the centre of the trawl (Fig. 1) and tracked by a second vessel located approximately 300 m abeam of the trawl. This system determined the position of the trawl on the seabed with an accuracy of about 6-7 m (McKeown and Gordon 1997). Trackpoint was also used to determine the position of the sidescan towfish, towed video platforms and Campod on all deployments at a similar level of accuracy. The locations of Videograb samples were estimated using the position of the end of the boom when the Videograb hit bottom, which has been shown to be a reasonable proxy (McKeown and Gordon 1997). The AGCNav computer-based navigation display and logging program, specifically developed for marine scientific surveying and sampling, was used to display ship, towed body and sampling gear positions in real-time on the bridge and in the laboratories, and to log all the navigation data.

In order to reduce variability due to spatial patchiness of benthic organisms, the same positions (Fig. 3) were used for Campod and Videograb stations on all sampling dates. Because of sea state or problems collecting a good sample with Videograb, there was considerable variation in the distance of sampling locations from the targeted positions but most were within 50 m (Fig. 4). Over all three years, the average distance of samples from the intended positions was 23 m and 37 m for Videograb and Campod, respectively. In 1997 and 1998, it was not possible to collect all the intended samples before the research trawler arrived on site (Table 1).

In order to estimate the level of trawling disturbance to which individual Campod and Videograb samples had been exposed, the distance between the position of individual samples taken after trawling along Line E and the closest point of the centre line of the nearest trawl set was calculated for the 1997 and 1998 data sets using ArcView GIS software. If the distance was less than 10 m, it was assumed that the seabed sampled had been crossed by the footgear and net. If the distance was 10-30 m, it was assumed that the seabed sampled had been crossed by the sweeps (and perhaps at the outer edge by a door). If the difference was greater than 30 m, it was assumed that the seabed sampled was not crossed by any part of the trawl.

Statistics

A variety of uni- and multivariate statistical methods were used to process the data. Full details are given in Kenchington et al. (2005), Henry et al. (2006) and Kenchington et al. (2006).

RESULTS

Description of Physical Habitat

Gravel lag of the Sable Island Sand and Gravel Formation dominates the study site and consists of well-rounded to sub-rounded clasts, mostly in the pebble and cobble range. Their rounded nature attests to passage through the beach zone of the transgressing Holocene sea during the past 10,000 years after glaciation. Numerous boulders are present, and a large one (approximately 1 m in diameter) in the trawled corridor caused damage to the trawl net when encountered. Some boulders appeared clustered together and are likely the remains of transgressed glacial moraines or relict beach ridges.

The multibeam bathymetric data provided a detailed morphologic image of seabed relief for the entire experimental site (Fig. 3). The presence of different substrates was suggested by the occurrence of ridges and isolated and linear depressions. The backscatter processed from the multibeam data characterized the seabed as being very hard, which is consistent with the backscatter intensity from the sidescan imagery. The multibeam bathymetric survey, conducted after the study site was chosen, confirmed that a relatively uniform area of seabed had been selected for the experiment.

The towed video imagery revealed considerable variability in the abundance and distribution of shell hash and boulders along survey lines. The large volume IKU grab samples indicated that the gravel lag is just a thin veneer overlying medium to gravelly sand. Three of the samples contained over 90% sand in the subsurface. The fourth sample indicated that the sediment below the gravel lag was sand with gravel. Shell fragments and anoxic black zones were common. About half of the photographs showed clasts that were partially covered with pink coralline algae.

Distribution of Trawling Disturbance

Although the research trawlers were requested to steer back and forth between the same two waypoints on all sets, due to variable winds, currents, and the skill of the quartermaster on watch, there was considerable lateral spread in the path of the vessel. For example, in 1997 only 10 of the 14 sets conducted by *Needler* appeared to be wholly within the intended 100 m wide trawled corridor (Fig. 4). One set was completely outside the corridor, two sets were partly outside and one set was terminated prematurely when the trawler missed the trawled corridor by a wide margin.

Of more importance than ship track is the actual path of the otter trawl over the seabed (at an average depth of 70 m) which may not follow directly behind the vessel, especially when the wind or current are abeam. In 1997, useable Trackpoint data of the trawl path were available for seven of the 14 sets. When plotted, these tracks closely followed the ship tracks indicating that dGPS ship position, which is available for all sets (Fig 4), serves as a reasonable proxy for trawl position (corrected for layback) for those wind and current conditions under which trawling was done in 1997.

In 1998, the trawl was positioned successfully with Trackpoint on 10 of the 12 sets conducted by *Teleost* (Fig. 4). The position of the other two sets was estimated from ship position. Seven sets were entirely within the intended 100 m width trawled corridor, three were partly in and two were entirely outside. In general, the trawling disturbance was more spread out in 1998 than in 1997 (Fig. 4). Due to the lack of Trackpoint and ship navigation data, it was not possible to plot the trawl paths for the sets conducted by *Needler* in 1999.

The cumulative area passed over by the footgear and net (20 m wide) and the entire trawl (60 m between the doors) during those sets that were wholly within the 100 m wide trawled corridor was estimated for both 1997 and 1998 (Fig. 5). As expected, the cumulative area of disturbance increased with each set, but because of overlap in the sets the area disturbed for the first time decreased with set. In 1997, after 10 sets, about 93% of the 100 m wide corridor had been swept by the entire trawl while about 65% had been swept by the footgear and net. Including all 14 sets, the areas swept were 99% and 71% of the corridor, respectively. In 1998, after just five sets, about 98% of the 100 m wide corridor had been swept by the entire trawl while about 70% had been swept by the footgear and net (Fig. 5). Extrapolating these results to all 12 sets, the areas swept were 100% and 83% of the corridor, respectively.

These results indicate that after 10 sets most if not all of the area in the 100 m wide trawled corridor had been swept at least once by the entire trawl (60 m between the doors) while on the order of 65-80% percent of the area had been swept at least once by the footgear and net (20 m wide). The difference in the results between 1997 and 1998 reflects the variation in the lateral spread of the trawling (Fig. 4). The more lateral spread of individual sets away from the centre line of the trawled corridor, the greater the percentage of bottom swept.

Videograb and Campod samples along the trawled corridor were collected at locations exposed to variable levels of trawling disturbance, both in terms of frequency and the part of the trawl contacting the seabed (Fig. 4). With the navigation data available, it is possible to estimate the level of disturbance to which individual samples were exposed. Using the dGPS ship data as a proxy for trawl track from 1997, which is available for all 14 sets, it is estimated that the Videograb samples collected immediately after trawling had been crossed by the footgear and net an average of 3.9 times (ranging from zero to eight)(Table 2). The average number of crossings by the entire trawl was 8.4 times (ranging from one to 12 times). Using the Trackpoint data, available for 10 of 12 sets, and ship position for the remaining two sets (Fig. 4), it is estimated that the Videograb samples collected immediately after trawling in 1998 had been crossed by the footgear and net an average of one time (ranging from zero to three times), while the average number of crossings by the entire trawl was four times (ranging from two to six times) (Table 2). Each year, three of the 10 stations were not crossed at all by the footgear and net which is to be expected since the cumulative area calculations indicated that 17-29% of the area in the trawled corridor was not swept by this part of the gear (Fig. 5). All Videograb sample sites were swept at least once by the entire trawl, but none were swept by all sets. The level of disturbance was substantially greater in 1997 since sets were more concentrated near the centre line of the trawled corridor than they were in 1998 (Fig. 4).

Similar results were obtained for the Campod stations (Table 3). The average number of crossings by the footgear and net was 2.1-3.4 times in 1997 and 0.9-1.6 times in 1998, while the average number of crossings by the entire trawl was 7.4-7.9 in 1997 and 3.3-4.8 in 1998. As with Videograb samples, the level of disturbance in Campod samples was greater in 1997 than 1998 because of the more concentrated nature of the disturbance (Fig. 4).

Similar calculations cannot be done for 1999 since Trackpoint or ship navigation data were not available. However, since the research trawler was using the same waypoints, the level of disturbance should be in the same range as that observed in 1997 and 1998.

Effects on Habitat

Sidescan sonograms along the trawled corridor clearly showed seabed disturbance immediately after trawling each year (Fig. 6). This consisted of the formation of discontinuous to continuous lineations in the gravel lag formed by the trawl doors, rockhopper footgear, and perhaps the cod end of the net when weighted down with catch. This seabed linearity is interpreted to be due to changes in the orientation of the gravel clasts and the digging of shallow furrows. Clasts normally occur in random orientation but trawling appears to reorient some clasts into parallel patterns that are easily detected by sidescan sonar. Although slightly degraded, these lineations were still detectable before retrawling in 1998 and 1999, as well as in 2001 when the study site was resurveyed two years after the third trawling episode. Interpretation of the sonograms revealed a multi-ridged linear depression estimated to be up to 30 cm deep, presumably made by the otter trawl dragging the same large boulder back and forth at least three times along Line E in 1997 (which tore the net). The sidescan sonar surveys did not detect any seabed disturbance from commercial fishing at the study site during the three-year experiment.

The QTCView sediment classification system did not detect any alteration of the acoustic characteristics of the seabed by the repetitive trawling. The multibeam data did not reveal any seabed disturbance from trawling, in either the relief or backscatter. DRUMS was not able to detect any changes in sediment microstructure. The optical backscatter sensor showed no evidence of increased turbidity in the water column four hours after trawling.

In 1997 there was no sign of any visible seabed disturbance in the towed video along the trawled corridor after trawling. However, a few signs of physical disturbance after trawling were evident in 1998. These were suspected to be furrows made by the doors and what appeared to be scraped or displaced clasts. We also observed the large boulder that damaged the trawl in 1997, with part of the torn net still wrapped around it. In 1999, some tracks were visible but relatively infrequent.

A slightly greater degree of disturbance to the seabed from the trawling was observed in the high-resolution video obtained with Campod (Table 4). Categories of disturbance quantified were scraped clasts, displaced clasts and damaged organisms. Scraped clasts were more frequently seen than displaced clasts. Eight damaged organisms were also visible. While physical disturbance was seen at approximately half the stations after trawling, the frequency was relatively low, approximately one disturbance per 100 m^2. Door furrows were not evident at this scale of resolution. No disturbance was visible at any of the reference stations.

Physical disturbance from the trawling was much more evident in the Campod photos which provided a high-resolution image from a small area (0.2 m^2). Four different types of disturbance were seen and, in twelve instances, two types were found in the same photo. Most common (45%) were signs of scraping or scouring. Also relatively common (39%) were signs of recent sedimentation, presumably the result of some resuspension of finer sediment by the trawl. The sediment clasts in these images had a swept or “dirty” appearance. Displaced clasts, either rolled over or slid along the seabed, were also observed at times (15%). What seemed to be a door furrow was observed on just one occasion. Examples of the different kinds of physical disturbance observed are illustrated in Fig. 7. These are somewhat subjective and difficult to discern to the untrained eye.

The frequency of the physical disturbance observed in Campod photos (all categories combined) by year, period and treatment is given in Table 5. These data are summarized by photo and by station (stations were classified as disturbed if one or more photos showed signs of disturbance). There were some instances where disturbance was observed at the reference stations that must have been caused by natural processes. As expected, most disturbance was observed in the trawled corridor (86% by photo and 81% by station). No signs of disturbance were seen in the trawled corridor before trawling in 1997 and 1998. However, some disturbance before retrawling was observed in 1999, presumably the result of trawling in previous years. The percentage of photographs and stations from the trawled corridor showing damage was 22% and 58%, respectively. The differences in these two percentages are due to the large number of photos that did not display disturbance, even though collected in the trawled corridor after trawling. On average, approximately 0.8 disturbances were seen per square meter of the seabed in the trawled corridor after the initial trawling in 1997. This frequency of disturbance is several orders of magnitude greater than that observed in the lower resolution Campod video.

The mean volume of sediment collected by the Videograb in the trawled corridor was 52.4 L (SD 23.0) before trawling and 36.7 L (SD 17.4) after trawling. However, this difference was not statistically significant (T-test $p= 0.102$). These results suggest that trawling may have increased the packing of sediment clasts making it more difficult for the Videograb to penetrate the seabed after trawling. Trawling had no significant effect on the relative abundance of tubes, burrows or damaged coralline algae as enumerated in the Campod photos.

The logistic regression was significant (Chi-square 34.19, $P < 0.0001$) indicating that the habitat disturbance response within the trawled corridor is very well predicted by the number of encounters with the footgear and net. The logistic curve is close to the vertical (Fig. 8) and the R^2 was 0.60. As indicated in Fig. 8, the probability of not observing physical damage in at least one of the five photos at a station after two passes of the footgear and net is effectively zero.

Contingency table analysis showed a similarly strong association between encounter with the footgear and net of the trawl and physical damage to habitat (Chi-square = 40.83, $p < 0.0001$, $R^2 = 0.72$) (Fig. 9). The Kappa value was 0.90 (standard error = 0.07) indicating a strong agreement between the responses (i.e. most of the counts are on the diagonal). Repeating this analysis using individual photos showed similar results, with a significant association between predictor and response variables (Chi-square = 21.47, $p < 0.0001$). However the model had a poorer fit with a R^2 of only 0.11 due to the large number of photos that were recorded as encountering the footgear and net but not showing physical damage (Fig. 10).

Otter Trawl Catch

Over the three trawling events, the otter trawl captured 22 fish species and five invertebrate taxa (Kenchington et al. 2005). Most of the fish species were solitary groundfish, although seven were schooling taxa: haddock (*Melanogrammus aeglefinnus*), Atlantic cod (*Gadus morhua*), herring (*Clupea harengus*), pollock (*Pollachius virens*), mackerel (*Scomber scombrus*), silver hake (*Merluccius bilinearis*) and redfish (*Sebastes* sp.). Only 13 species were common to all three years. In total, 15,257 kg of fish were caught. Haddock dominated the catch (about 75% by weight) followed by Atlantic cod. Standardised fish catch weight increased significantly between the first two sets (Time 1) and the remaining sets (Time 2) each year. However, not all species contributed to this increase. Individually, only haddock, Atlantic cod, and winter flounder increased significantly between Time 1 and Time 2. These changes are indicative of scavenging behaviour with fish moving into the trawled area after trawling commenced. The trawl catch was consistent with expectations for the study area (Fisher and Frank 2002). The bycatch of invertebrates in the otter trawl was very small (28 kg over all sets), most of which was a single catch of squid in 1999. A few seastars, sea cucumbers, anenomes and toad crabs were also caught. No structure-forming epibenthic organisms were captured.

Description of the Benthic Community

A total of 341 taxa were identified in the 100 Videograb samples, with an average abundance and standard deviation of 104 ± 19 taxa per 0.5 m^2 sample (Kenchington et al. 2006). Abundance was recorded for 293 taxa, and biomass for 302, with 281 taxa common to both data sets. Twelve phyla were represented, with the Annelida being the most diverse with 115 species (all polychaetes except for one oligochaete). In addition, 91 Arthropoda, 54 Mollusca, 45 Cnidaria and 19 Echinodermata taxa were recorded, with the remaining phyla (Brachipoda, Bryozoa, Chordata, Nemertea, Platyhelmintha, Porifera, Sipuncula) represented by less than five taxa each. Average (with standard deviation) Shannon-Weiner diversity was 1.5 ± 0.18 while species richness was 14.6 ± 2. Taxa were evenly dispersed (J'= 0.77) but with a large variance. Mean biomass and abundance per grab were on the order of 293 g and 1210 individuals, respectively.

The majority of the observed species were epifaunal, and carnivory was the most common feeding mode (Kenchington et al. 2006). The species accumulation curve for the entire data set was not saturated but approached an asymptote indicating that the samples collectively provide a good representation of the benthic community present at the study site. Six taxa occurred in all of the Videograb samples; the polychaetes *Polycirrus* sp., *Nereis* sp., *Praxillella praetermissa* and *Thelepus cincinnatus*, the mollusc *Stenosemus albus* and the echinoderm *Strongylocentrotus pallidus.* Twenty seven taxa occurred in at least 95% of the samples and 95 taxa occurred in at least 50% of the samples.

Biomass was heavily dominated (76%) by the horse mussel, *Modiolus modiolus*, which was found attached to rocks or embedded in the substrate but did not form reefs (Kenchington et al. 2006). Seventeen taxa accounted for 95% of the biomass and included a variety of organisms, notably polychaetes, brachiopods, echinoderms and molluscs. In contrast, 87 taxa constituted 95% of the total abundance with 10 of them accounting for 50%. The most abundant species were the tube-dwelling amphipods *Ericthonius fasciatus* and *Unciola irrorata* and the sabellid worm *Chone duneri*.

The colonial epifaunal assemblage at the study site, also sampled by Videograb, was relatively rich and 53 taxa were identified (Henry et al. 2006). The majority of these were hydroids (42) but bryozoans (5), sponges (4), soft corals (1) and tunicates (1) were also present. The three most common colonial epifauna taxa were the leafy bryozoans *Dendrobeania* spp., the small vase sponge *Scypha ciliate* and the hydroids *Symplectoscyphus* spp. Overall, the colonial epifauna represented only 0.25% of the total benthic biomass.

The 792 Campod images captured information on 45 megafauna taxa, although only 18 could be identified to species (Kenchington et al. 2006). At least 10 phyla were represented: the Echinodermata were the most speciose with 11 taxa followed by the Mollusca with 7. The sponges, cnidarians and crustaceans were represented by six taxa each. The brachiopod *Terebratulina septentrionalis* was the most abundant species, followed by the tube-building polychaete *Thelepus cincinnatus*. Together, these accounted for almost 50% of the total number of organisms observed. Only three taxa were unique to the Campod dataset: *Corymorpha pendula*, an athecate hydrozoan which was too delicate to survive the screening procedures used with the Videograb samples, *Meganyctiphanes norvegica* (krill) and various fish species, the latter two being highly mobile and able to escape the Videograb.

Natural Changes in the Benthic Community

There were no significant differences over the study period in the total abundance, total biomass, individual biomass of the 17 taxa comprising 95% of the total biomass, number of species, species richness, Shannon-Weiner diversity, or evenness in samples collected along the reference lines (Kenchington et al. 2006). However, of the 87 taxa contributing to 95% of the total abundance, 24 showed significant changes in abundance over the three years. These taxa were a mixture of polychaetes, amphipods, echinoderms and molluscs. The majority showed increases over time and only one, the mollusc *Margarites* sp., decreased. Significant differences in the relative abundance of taxa were also detected over the study period. The species contributing to the dissimilarity between 1997 and 1999 were primarily a mixture of amphipods and polychaetes. Thirteen taxa accounted for 25% of the dissimilarity with a decrease in the amphipod *Ericthonius fasciatus* contributing the most by a single taxon. Except for *E. fasciatus*, 11 of the remaining 12 taxa showed increases in abundance. A significant change in relative biomass of taxa was also observed over the study period. As for abundance, many species contributed to the dissimilarity between years with no single species accounting for a large portion.

The mean number of taxa and the total biomass of colonial epifauna in the reference corridors increased significantly through the study period (Henry et al. 2006). The biomass of sponges, soft corals, bryozoans and tunicates did not change significantly but hydroid biomass increased by a factor of seven-fold. All taxa identified in 1997 were present in 1998 and 1999, while 10 new taxa appeared in 1998 and all but two of these were also observed 1999.

Immediate Effects of Trawling on Benthic Communities

Very few effects of trawling were observed when comparing the before- and after-trawling samples within years (Kenchington et al. 2006). In at least one of the three years, the median values of total abundance, total biomass, number of species, species richness and Shannon-Weiner diversity showed declines after trawling that were not observed in the reference samples but these were not statistically significant. No significant changes were found in the biomass of individual species.

Six of the 87 individual taxa did show significant changes in abundance in 1997, with all but one decreasing (Kenchington et al. 2006). In 1998 and 1999, the interaction between Period and Location was significant for the abundance of 14 taxa, a mixture of polychaetes and amphipods, with 13 of the significant results appearing in 1998 and only one in 1999. In all cases, there was a decrease in abundance after trawling while abundance increased on the reference lines, usually by more than it decreased on the trawled line. Two of the species affected in 1997, the amphipods *Tiron spiniferum* and *Paroediceros lynceus*, showed a similar significant decrease in 1998. Benthic community composition did not differ significantly before and after trawling in any of the three years, with respect to either abundance or biomass.

Trawling had no immediate effect on the number of colonial epifaunal taxa but there were non-significant decreases in the mean number of taxa per sample and their mean total biomass across each trawling event (Henry et al. 2006). Similarly, the biomass of colonial epifauna showed no significant immediate change with trawling. The biomass of sponges, soft corals, hydroids, tunicates and bryozoans were also not detectably affected by the trawling disturbance when analyzed separately.

Effects of Repeated Trawling on Benthic Communities

In analyses of Videograb data from the trawled line over the three years, 15 taxa, primarily a mixture of polychaetes and amphipods, and the abundance of individuals living at the sediment-water interface, showed significant declines in abundance or biomass (Kenchington et al. 2006) However, no significant differences in community composition were evident using either abundance or biomass data.

Abundance/biomass comparisons on the trawled line before trawling in 1997 and after trawling in 1999 showed a marked decrease in the relative biomass of the highest ranking taxa, particularly the horse mussel *Modiolus modiolus* (Kenchington et al. 2006), which was not seen along the reference lines. However, analysis of the rank order of the taxa dominating the biomass during these two time periods indicated no significant change. Of the various interactions tested between years and treatment, only the test of epifaunal biomass as a proportion of total biomass identified a significant interaction, with the trawled line showing a decrease in the proportion of epifauna at the conclusion of the experiment which was not seen on the reference lines. Epifaunal biomass was approximately 90% of total biomass in the reference lines throughout, but declined to 77% on the trawled line by the end of the experiment.

At the conclusion of the experiment in 1999, the relative abundances of taxa on the trawled line were significantly different from those on the reference lines (Kenchington et al. 2006). Thirteen taxa accounted for 25% of the dissimilarity with most showing somewhat lower abundance on the trawled line. These were a mixture of polychaetes, amphipods, two echinoderms and the sole brachiopod, and nine of them were among the taxa which showed changes in abundance over time on the reference lines. There were no corresponding significant differences in relative biomass.

Analysis of the colonial epifauna data collected over the three years indicated that there were immediate effects of trawling on the number of taxa and biomass that were not detectable in analyses of data from single years (Henry et al. 2006). However, there were no significant additional effects from the cumulative impact of repeated trawling over three years. Colonial epifaunal assemblage structure on the trawled line was not affected by repeated trawling. At the conclusion of the experiment, the total number of epifaunal taxa, the biomass of sponges, soft corals and tunicates, and the composition of colonial epifaunal assemblages on the impact line, after three years of repeated trawling, were not significantly different from those on the adjacent reference lines. However, the total biomass of colonial epifauna was significantly lower on the trawled line, as were the biomass of hydroids and bryozoans.

Assessment of Biological Damage

A total of 37 taxa and 3498 individual organisms were observed at the 41 Campod stations on the trawled line before and immediately after trawling in 1997 and 1998 (Kenchington et al. 2006). Of these, 14 taxa had damaged individuals, but only 3% of the total numbers of organisms were identified as damaged, most commonly in the form of crushed individuals, crushed or broken tubes, tube-living animals displaced from their tubes, chipped and cracked shells, or shells with broken hinges. The species most commonly damaged was the tube-building polychaete *Thelepus cincinnatus*. Of the 603 individuals of this species observed in Campod photos, 9% (55 individuals) were damaged. Eight percent of the observed horse mussels *Modiolus modiolus* (21 individuals) and 1% of the brachiopod *Terebratulina septentrionalis* (11 individuals) was visibly damaged. Less than four damaged individuals of each of the remaining taxa were observed. Contingency table analysis showed a significant association between encounters with the trawl and observed biological damage for *T. cincinnatus*, *T. septentrionalis* and *M. modiolus* (Kenchington et al. 2006). Of the 23 stations occupied immediately after trawling in 1997 and 1998, 19 showed evidence of damage to organisms. The probability of observing biological damage at a given location on the seabed was significantly related to the number of passes by the trawl, including passes by bridles, sweeps and otter boards as well as those by footgear and net. A logistic model estimated nearly a 50% probability of observing damage in the absence of trawling, rising to 60% after one pass of the gear and 90% after six passes.

Fish Stomach Contents

The studies of fish stomach contents focused on five taxa: Atlantic cod (*Gadus morhua*)(two size classes), haddock (*Melanogrammus aeglefinnus*), American plaice (*Hippoglossoides platessoides*), yellowtail flounder (*Limanda ferruginea*) and winter flounder (*Pseudopleuronectes americanus*) (Kenchington et al. 2005). In the coarse data set (low taxonomic resolution), 11 phyla were identified in the 1,432 stomachs processed. Numerically, arthropods were the dominant food source for Atlantic cod, haddock, American plaice and yellowtail flounder, while winter flounder stomachs were dominated by annelids. Haddock were the most generalized feeders with representatives from all 11 phyla in their stomachs. By weight, fish contributed the most to the stomach contents of large Atlantic cod and American plaice, whereas annelids did so in winter and yellowtail flounder, while haddock stomachs were primarily full of molluscs and echinoderms. Molluscs also predominated in the stomachs of small Atlantic cod.

In the more detailed data set (high taxonomic resolution), 177 prey taxa were identified from the 444 stomachs processed from the five species (Kenchington et al. 2005). These included six invertebrate taxa not identified in the Videograb data set (Kenchington et al. 06). Four of these six were pelagic species not expected to be collected by the Videograb. Only 10 of the phyla identified in the coarse data set were identified in the detailed data set (no Platyhelminthes were recorded). Of the 40 major prey taxa identified, 33 were arthropods or polychaetes. Echinoderms, molluscs and fish were also common.

The two size classes of Atlantic cod differed in their diets (Kenchington et al. 2005). The smaller fish had a greater overall diversity of diet, consuming 82 prey taxa with 15 major food items dominated by the shrimp *Eualus pusiolus.* A total of 50 prey taxa were consumed by the larger Atlantic cod of which 21 were major prey items. They too consumed *E. pusiolus* in large quantities but fish played a larger role in their diet compared to smaller Atlantic cod. Haddock consumed the greatest diversity of prey, with 141 prey taxa recorded. Nineteen constituted greater than 1% of the total abundance. As with cod, *E. pusiolus* was a numerically dominant item, although similar amounts of caprellids and ophiurids were also consumed. American plaice had the narrowest overall diet with only 42 species recorded. Ten of the 42 were taken in large quantities, with the tube-building amphipod *Ericthonius fasciatus* numerically dominant. American plaice consumed the highest proportion of fish by number. Although yellowtail flounder consumed 77 prey taxa overall, only four of these were consumed in large quantities with *E. fasciatus* dominating at 81% of the stomach prey abundance. Winter flounder consumed 91 prey taxa. Of these, 15 were major prey with the dominant prey taxon being the tube-building polychaete *Thelepus cincinnatus*. Only three prey taxa were shared by all five fish species: *T. cincinnatus*, *E. fasciatus* and a composite taxon of sabellid worms which could not be identified further.

Only 19 taxa contributed more than 1% of the total stomach weight for each fish species (Kenchington et al. 2005). As for abundance, the large and small size classes of cod showed different patterns for biomass. The horse mussel *Modiolus modiolus* comprised the greatest weight of the stomach contents of small cod, while fish contributed the most to the stomach weight of larger Atlantic cod. Haddock stomach weight was also dominated by *M. modiolus*, with the brittlestar *Ophiopholis aculeata* making a similar contribution. Fish were the dominant taxon by weight for American plaice, while sabellid worms accounted for half of the weight in yellowtail stomachs. Winter flounder stomach weight was divided between three taxa: *M. modiolus*, *T. cincinnatus* and sabellid worms. Fish prey items were common to all predators, including both large and smaller Atlantic cod, as was the horse mussel. Small whole mussels were found in the stomachs, as well as the crushed shells and tissue of larger individuals. The fish in the stomachs of most species could not be identified, though sand lance (*Ammodytes* sp.), haddock, and silver hake (*Merluccius bilinearis*) were identified in Atlantic cod.

Trawling Induced Changes in Fish Diet

Fish diets in Time 1 (Sets 1 and 2) and Time 2 (remaining sets) were compared in terms of both abundance and weight of each individual major prey taxon, prey taxa grouped into habitat classes and prey phyla (Kenchington et al. 2005). Of the numerous tests, 78 produced significant results which is more than what would be expected by chance alone.

For the smaller Atlantic cod, repetitive trawling resulted in an increased consumption of *Eualus pusiolus*, *Modiolus modiolus*, *Thelepus cincinnatus* and sabellid worms as well as annelids, arthropods and molluscs. The infauna was not exploited in Time 1 but formed a portion of the diet in Time 2 while consumption of pelagic species increased three-fold, suggesting that invertebrate scavengers and fish entered the area of trawl tracks. Increased consumption of *T. cincinnatus* and annelids was reflected in increased weight with the weight of *T. cincinnatus* 20 times greater in the stomachs in Time 2. Larger Atlantic cod also increased consumption of *T. cincinnatus* and *M. modiolus*, as well as of the hermit crab *Pagurus acadianus*. These were at the expense of fish taxa, which declined by 50%. At the phylum level, only the annelids showed a significant increase in consumption between the periods. Epifauna and tubiculous species were numerically more abundant in the stomachs in Time 2. The weight of *M. modiolus* in stomachs also increased in Time 2, as did the weight of annelids and molluscs.

In Time 2, haddock fed on fewer individuals of the brittlestar *Ophiopholis aculeata* and the amphipod *Paradalisca cuspidata* and this was reflected in a decline in consumption of epifaunal and shallow infaunal species. However, consumption of the polychaetes *Phyllodoce* spp. and *T. cincinnatus* increased. Stomach-contents weight showed an increased percentage of the horse mussel *M. modiolus*, the tube-building polychaete *T. cincinnatus* and fish species in Time 2, while the total weight of the stomach contents increased as well.

American plaice expanded their diets in Time 2 to include new species, feeding on *T. cincinnatus* and the brittlestar *O. aculeata*. For *T. cincinnatus*, this resulted in an increase in weight as well. The weight of fish in American plaice stomachs dropped sharply in Time 2, reflected in a negative change in the weight of Chordata.

Yellowtail flounder also fed on *T. cincinnatus* only during Time 2, resulting in significant increases in the abundance and weight of this species in their stomachs. Consumption of infauna increased six-fold in Time 2, while overall stomach contents were on average 4.5 times heavier.

Winter flounder increased consumption of three species, including the horse mussel *M. modiolus* which also increased by weight. Infaunal species were twice as abundant in the stomachs in Time 2. Winter flounder was the only fish species that did not increase consumption of *T. cincinnatus* in Time 2.

SYNTHESIS AND DISCUSSION

Experimental Design

This experiment is one of approximately 50 that have been conducted around the world to study the effects of otter trawling on benthic ecosystems. Most of the earlier experiments were done in relatively shallow water, were of limited spatial extent, and were short term in nature. Therefore, when we designed this experiment in 1997, we attempted to incorporate features that would extend the understanding of otter trawl impacts over broader scales of depth, time, habitat and other environmental variables measured. We also tried to maximize the chances of detecting any impacts that may have occurred.

The major features of our experimental design are summarized as follows:

- We targeted a gravel seabed which has been under-represented in the experiments conducted to date.
- Considerable effort went into the site selection process, in particular picking an area that had been protected from recent trawling activity and that had an abundant, diverse, representative and relatively uniform biological community representative of natural conditions.
- The gravel seabed habitat selected is widespread on the Canadian continental shelf and supports important commercial fisheries.
- The study site is located on an offshore fishing bank at an average depth of 70 m.
- A manipulative experimental approach was taken following an asymmetrical BACI design.
- An experimental corridor, two km long, was trawled at least 12 times a year for three years in a row. This was considered to be a relatively high level of trawling disturbance.
- Nearby parallel reference corridors were sampled both before and after trawling to provide information on the natural variability of the benthic ecosystem.
- A wide variety of acoustic, imaging and sampling methods was employed to investigate trawling impacts at different spatial scales and on different physical and biological characteristics of the benthic ecosystem.

This design allowed three separate assessments of immediate impacts and two assessments of recovery over one year. It also allowed assessment of possible cumulative effects of repetitive trawling on the same bottom over a three-year period, as well as a thorough assessment of natural variability in the benthic ecosystem in adjoining reference areas. Unfortunately, we were not able to fully sample the reference corridors before trawling each year which compromised to some degree our intended BACI design. None the less, the final experimental design provided a high probability of detecting any impacts of otter trawling on the benthic habitat and ecosystem at the study site. Like our previous Grand Banks experiment (i.e. Kenchington et al. 2001), this experiment remains unique in terms of its depth, repeat nature of trawling disturbance, duration, scope of data collected and assessment of natural variation.

The study site is located within the 4TVW Haddock Nursery which was created in 1987 and therefore the seabed had not been disturbed by fishing gear for at least 10 years before the experiment began. Analysis of effort data indicated it had been trawled in the early 1980s (Kulka and Pitcher 2001). It is possible that the benthic community at the study site may not have recovered completely from earlier damage at the time we conducted our experiment, especially long-lived epibenthic species such as the horse mussel.

General Description of Habitat and Biological Community

The habitat at the experimental site was relatively uniform and consisted of a thin gravel lag overlying gravelly sand. The average depth was 70 m. Most of the clasts were in the pebble and cobble range but numerous boulders were also present. Some structures were present that appeared to be relicts from glaciation and subsequent transgression as sea level rose. The site is a good example of what is commonly known as a "hard-bottom". It experiences moderate levels of natural physical disturbance with major perturbations induced by storms.

The benthic community had a rich and diverse assemblage of approximately 350 taxa representing 12 phyla (Henry et al. 2006, Kenchington et al. 2006). Molluscs, polychaetes, anemones, echinoderms and brachiopods dominated the biomass while amphipods, polychaetes and echinoderms were numerically dominant. Overall, the species present were typical of the assemblages on other hard-bottom areas of the Scotian Shelf (Kostylev et al., 2001, Hargrave et al., 2004) but rather different from those on nearby Georges Bank (Thouzeau et al. 1991, Collie et al. 2000) and in the Bay of Fundy (Fuller et al. 1998, Henry and Kenchington 2004a, Kenchington et al. 2007).

Biomass was dominated by a single species, the horse mussel *Modiolus modiolus*, which contributed three quarters of the total biomass (Kenchington et al. 2006). This species is long-lived, with individuals surviving in excess of 35 years. Three species of the bivalve *Astarte* were also major contributors to total biomass. *Astarte* also has a long lifespan with individuals attaining ages of up to 30 years or more. In contrast, the numerically dominant taxa, the tube-building polychaete *Thelepus cincinnatus*, the brachiopod *Terebratulina septentrionalis*, and the filter-feeding brittlestar *Ophiopholis aculeata*, are relatively short-lived. These three species together comprised 10% of the total biomass, immediately (though substantially) behind the horse mussel.

The benthic community at the study site can be classed as a surface-attached system. Eighty-nine percent of the biomass and 60% of the taxa were epifauna (Kenchington et al. 2006). However, most of the epifauna were relatively small (less than a few centimetres), even the colonial forms (Henry et al. 2006). There was no evidence of extensive biological turf as is observed on nearby Georges Bank (Collie et al. 2000). Video and photographic images indicated that much of the surface area was unoccupied by larger epifauna.

Natural Variability

The physical habitat at the study site appeared to be quite stable during the three-year experiment. While the depth (70 m) is well within the range influenced by major storms, the gravel lag seabed is difficult to resuspend and transport. No human disturbance occurred during the experiment except the experimental trawling.

The benthic community at the study site was generally stable showing no fundamental changes (e.g., replacement of functional groups) on the reference lines over the three-year experiment. However, there were considerable inter-annual variations in the abundance of some taxa which caused significant changes in community composition, with 1999 being particularly distinct from the earlier years. While at least one species declined, many increased in both abundance and biomass. This was especially true for colonial epifaunal species and the number of taxa per sample more than doubled over the course of the experiment (Kenchington et al. 2006). It appears that the period of the experiment provided favourable conditions for recruitment of a range of colonial epifaunal species at the study site, particularly hydroids (Henry et al. 2006).

The increase in biomass over time in reference samples suggests that the colonial epifauna were not space-limited in the late 1990s. Still photographs and video showing many unoccupied hard substrata also suggest that local habitats were not fully occupied, despite a period of at least 10 years without disturbance by mobile fishing gear. The gravel lag seabed of the study site had not been extensively overgrown by epibenthos. It is possible that recovery of the epifauna, following the cessation of trawling previous to 1987, was still ongoing. On similar gravel seabeds on Georges Bank, epifaunal recovery has continued for at least six years following closure to trawling (Hermsen et al. 2003). Alternatively, natural processes such as predation and periodic storm disturbance may repeatedly reset benthic assemblages to earlier successional stages, preventing colonial epifauna from saturating the available seabed space.

Trawling Disturbance

One of the advantages of manipulative experiments in studying fishing gear impacts is the opportunity to control the frequency and intensity of disturbance made by a specific gear type. It is important to document the details of the fishing disturbance so that the observed impacts can be related to a known level of effort, yet very few experiments have done this adequately. In order to create a heavy trawling disturbance, some experiments have repeatedly trawled back and forth along the same line (e.g. Prena et al. 1999, Palanques et al. 2001, Burridge et al. 2003). However, despite the availability of dGPS, it is impossible to keep the trawling vessel on the same line due to wind, current and sea state, no matter how skilled the quartermaster. In addition, the trawl does not necessarily follow the same path as the trawler, especially in deeper water and when the wind or current are abeam (McKeown and Gordon 1997, Engås et al. 2000). As a result, the lateral spread of the trawling disturbance on the seabed is substantially greater than intended, but this is usually not taken into consideration when interpreting results.

Palanques et al. (2001), using an otter trawl with a door spread of 30 m, reported a disturbance zone after 14 sets at a depth of 30-40 m on the order of 150 m wide. Burridge et al. (2003) recognized that the trawl does not sweep exactly the same path on each set and took this into consideration while calculating depletion rates for benthic fauna. They recommended that the trawl path be tracked acoustically so that the true impact on the seabed can be estimated. This had been done in our Grand Banks experiment and, using an otter trawl with a door spread of 60 m, we observed a disturbance zone after 12 sets at a depth of 120-146 m up to 264 m wide (Prena et al. 1999). We estimated that the seabed in the trawled corridors was swept on average by just three to six of the 12 sets and realized that the cumulative trawling disturbance was probably greatest nearer the centre line of the trawled corridors but that the local intensity of impact from the doors, sweeps, footgear and net was uneven (Kenchington et al. 2001).

It is well recognized that the different parts of the otter trawl have quite different impacts on seabed habitat and organisms. The most severe disturbance is caused by the heavy doors which are in constant contact with the seabed. In muddy and sandy sediments, they can form deep furrows (and associated berms). However, as shown in this experiment, furrows created on gravel lag appear to be quite shallow. The doors can also resuspend and displace sediment (Gilkinson et al. 1998), scrape and displace clasts, expose buried sediment, and damage organisms. However, since the door path is narrow (about 1 m each), only a small percentage of the total sweep of the trawl over the seabed is affected by the doors on any given pass. The next most damaging component of the otter trawl is the footgear which is dragged over the seabed and, like the doors, can resuspend sediment, scrape and displace clasts, and damage organisms. The rockhopper footgear on the Engel trawl we used disturbs a path about 20 m wide or about 33% of the area swept by the trawl. The net follows behind the footgear and therefore affects the same area, especially when weighted down with fish. More than 60% of the area swept by the trawl is affected only by the sweeps rigged between the doors and footgear and net. They have limited if any contact with the seabed and therefore the chance of causing disturbance is very low, especially on a gravel lag seabed where the potential for sediment resuspension is low. Therefore, we conclude that the disturbance we observed in our experiment was caused primarily by the passage of the rockhopper footgear and net but in some instances perhaps by the doors.

With the detailed navigation data collected for both the otter trawl and sampling stations, we are in the unique position of being able to estimate the number of times that each Videograb and Campod station was swept by either the entire trawl or just the footgear and net. In 1997, with a total of 14 trawl sets, the average number of encounters ranged between 7.4 and 8.4 for the entire trawl and between 2.1 and 3.9 for the footgear and net. In 1998, with a total of 12 trawl sets, the average number of encounters ranged between 3.3 and 4.8 for the entire trawl and between 0.9 and 1.6 for the footgear and net. The difference between the two years is caused by unplanned variations in the lateral spread of the sets. There was considerable variation in the number of encounters at individual stations. All stations were swept at least once by the entire trawl and the maximum number of encounters was 12. Several stations each year were not impacted by the rockhopper footgear and net while the maximum number of encounters was eight.

The intensity of disturbance measured in this experiment is lower than we expected. While most of the 100 m wide trawled corridor was swept at least once by the entire trawl in 1997 (14 sets) and 1998 (12 sets), it is clear that 20-35% of the area was not passed over by the footgear and net. Plots of cumulative disturbance indicate that an asymptote is reached at about 10 sets such that each additional set passes over a very small area of undisturbed seabed. Therefore, despite the intention to impose a heavy trawling disturbance of at least 12 sets along the same line, it appears that there are patches of seabed in the trawled corridor that were undisturbed, or lightly disturbed, and these may have been sampled with both Videograb and Campod.

Calculations of the frequency of encounter can not be done for 1999 due to the lack of detailed navigation data. However, since the research trawler was requested to steam between the same two waypoints as 1997 and 1998, we assume that the 1999 disturbance intensity was within the same range as that determined for the first two years. Therefore, by the end of the experiment, after 38 sets, the entire trawled corridor had probably been swept at least once by the entire trawl with an average number of cumulative encounters for each station being on the order of 16 or more. The average number of cumulative encounters with the footgear and net was probably on the order of five or more, and small patches of undisturbed seabed likely remained within the trawled corridor.

The intensity of trawling applied in this experiment was designed to be at the upper end of the range of effort applied by the commercial fleet in Atlantic Canada in recent years. Analysis of the DFO offshore trawler Observer Program database from Atlantic Canada, collected between 1980 and 1998 and scaled up to total effort, indicated that the detailed distribution of effort has been very patchy (Kulka and Pitcher 2001). Most trawling was concentrated in specific regions and large areas were 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. The maximum trawling intensity calculated ranged from 141% to 644 % per year (i.e. the seabed was swept by a trawl one to six times a year).

Comparison of Biological Sampling Gear

Four sampling devices were used to quantify the benthic community: Videograb, Campod, the otter trawl and the contents of fish stomachs. The 100 Videograb samples provided the most comprehensive species list (341 taxa), and species accumulation curves approached saturation (Henry et al. 2006, Kenchington et al. 2006). A total of 45 megafauna taxa were identified from the 792 Campod photographs. These included three taxa not observed in the Videograb samples: an athecate hydrozoan, krill and various species of fish (Kenchington et al. 2006). The total catch of invertebrates by the otter trawl was very small, just 9 kg over all sets, and only five taxa were collected: the northern shortfin squid, seastars, sea cucumbers, anemones and toad crabs (Kenchington et al. 2005). Squid and sea cucumbers were not collected by Videograb. The demersal fish collected in the trawl also proved to be useful biological samplers and Kenchington et al. (2005) identified 177 prey taxa from 444 stomachs of five species. These included six invertebrate taxa not collected by Videograb, four of which were pelagic mysids or euphausiids. While we did not record every species present at the study site, we are confident that, collectively, our data provide an accurate picture of the composition of the macro- and megabenthos at the study site since the various tools employed provided for effective sampling of everything from small, abundant infauna to large, widely-dispersed epifauna.

Immediate Impacts on Habitat

Overall, the impacts of the otter trawling on the gravel habitat at the study site were relatively minor. Those impacts that were detected were dependent upon the spatial scale of observation. Disturbance to the seabed was clearly visible in the sidescan sonograms collected immediately after trawling which covered the entire trawled corridor (e.g. tracks made by the doors, rockhopper footgear and net). However, very little disturbance could be detected at the scale of observation of our towed video systems (transects about 2 m wide) and consisted of possible door furrows and what looked like scraped clasts. The difference in these two sets of observations, which covered the entire length of the experimental corridor, is presumably due to the fact that sidescan sonar is very good at detecting subtle linear features over large seabed areas because of the low acoustic grazing angles of the system while the towed video cameras operate at high angle and cover only a small area of the seabed.

Slightly more disturbance was seen after trawling each year at the scale of the Campod video which covered an area on the order of 50 m^2 at each station. Disturbance was classified as scraped or displaced clasts. It is estimated that there was one sign of disturbance for every 100 m^2 of seabed examined so again the level of disturbance visible at this scale of observation was very low.

Physical disturbance from the trawling was most evident in the high resolution but small scale Campod photos (0.2 m^2). Disturbance was classified as scraping and scouring, resuspension and sedimentation, displacement of clasts, and creation of furrows. A total of 22% and 58% of the photos and stations, respectively, in the trawled corridor showed at least one sign of disturbance. This works out to about 0.8 disturbances m^{-2} of seabed, about two orders of magnitude more frequent than observed in the lower resolution Campod video. As expected, most of the visible signs of disturbance were seen in the trawled corridor immediately after trawling and there was a highly significant relationship between the number of encounters with the footgear and net and the level of disturbance. After two passes of the footgear and net, the probability of not observing physical damage in at least one of the five photos at a given station is effectively zero.

It appears that the armoured nature of the gravel lag seabed at our experimental site prevented the excavation of deep furrows by the doors. However, some shallow furrows were created. These were evident in the sidescan sonograms but only rarely seen in the video or photographs. The primary physical impact of the trawl appears to be the scouring, scraping and displacement of gravel clasts which was most evident at the small spatial scales of resolution offered by the Campod photos. Most of this disturbance is thought to be due to the rockhopper footgear and net which swept a path of 20 m. While potentially more damaging, the doors swept a path of only a few meters. While some signs of sediment resuspension were noted at small scales, this probably causes little overall impact on a gravel lag seabed. Our results also indicate that the otter trawl can drag large boulders, if present, along the seabed and create deep furrows which could expose underlying sand. It is expected that recovery of the gravel lag seabed from the trawling disturbance will take on the order of at least five years.

The apparent difference in the volume of sediment collected by the Videograb before and after trawling suggests that the trawling may have increased the packing of sediment clasts.

In summary, the otter trawl clearly caused some limited physical disturbance to the seabed that was most evident at the scale of the sidescan sonograms and Campod photos. However, with the exception of an apparent increase in the packing of sediment clasts, we did not observe any significant changes in the structure or complexity of the gravel lag seabed, even after three years of repetitive trawling.

Immediate Impacts on Benthic Organisms

Much to our surprise, our experiment detected only limited immediate impacts of trawling on benthic organisms (Kenchington et al. 2006). In the first year of trawling, when impacts were expected to be greatest, only five species showed a significant decrease in abundance and none in biomass. Greater immediate impacts were seen in the second year when the abundances of 13 taxa, primarily amphipods and polychaetes, declined. Only one species declined in the third year. The only large organism to show a significant decline was the burrowing anemone *Cerianthus* sp. but only in 1998.

Since most of the dominant organisms at the study site are relatively small and the trawl is very inefficient at capturing benthic organisms (Prena et al. 1999, Kenchington et al. 2005), it is highly unlikely that the observed decreases were due to removal by the trawl. However, there is evidence that disturbance associated with the trawling could have made them more vulnerable to predation by scavenging fish that moved into the trawled corridor during trawling. For example, three of five taxa that declined in 1997 were major constituents of the stomach contents of demersal fish caught during the experiment (Kenchington et al. 2005). The shrimp *Eualus pusiolus* was the most abundant prey item of Atlantic cod and haddock, while the amphipods *Tiron spiniferum* and *Paroediceros lynceus* were common in the stomachs of haddock. In larger cod, consumption of *E. pusiolus* increased significantly after trawling. Likewise, three of the 13 taxa which declined in 1998 were abundant dietary components (Kenchington et al. 2005). The amphipod *Leptocheirus pinguis*, the polychaete *Glycera capitata* and the chiton *Stenosemus albus* were major prey for winter flounder while the polychaete *Lumbrineris fragilis* was a major prey item for yellowtail flounder. The haddock prey *Tiron spiniferum* and *Paroediceros lynceus* declined again as they had in 1997. Only one species, the polychaete *Petaloproctus tenuis*, declined in 1999 but it was not a major dietary item of the fish sampled.

Damage to individuals which escape predation also represents a negative impact to the benthos since injuries require costly resources for regeneration, have the potential for impairing growth and sexual reproduction, and may ultimately limit population recruitment (Henry and Hart 2005). They may also lead to delayed mortality (Freese 2001).

Similarly-limited immediate impacts of mobile fishing gear have been previously reported for infaunal communities on soft bottoms (e.g. Eleftheriou and Robertson 1992, Kenchington et al. 2001) but were not expected for hard-bottoms dominated by sessile epifauna. The contrary results of our experiment may be due, in part, to the morphological configurations and life-histories of the resident taxa that render them less vulnerable to the gear. Unlike sessile epifaunal assemblages dominated by erect, rigid megabenthic sponges and corals, the colonial epifauna in the study area was dominated by flexible *Dendrobeania* spp. (Bryozoa), a small epizoic sponge *Scypha ciliata* and several hydroids which may generally be less vulnerable to immediate damage than more rigid species (Henry et al. 2006). Morphological rigidity has been suggested as an important factor in determining the fate of benthos exposed to bottom fishing (Bremner et al. 2003). The erect but small (most less than 5 cm) and flexible colonial taxa at our study site likely passed under the otter trawl and its rockhopper gear with only limited harm, this net being relatively inefficient at removing benthos (Prena et al. 1999, Kenchington et al. 2005). The cobbles themselves may also afford protection by providing an uneven surface with crevices untouched by the gear.

Longer-Term Impacts on Habitat

As reviewed above, immediate impacts on habitat were minor and we were unable to detect any significant changes to habitat structure or complexity, even after three years of trawling. However, recovery from the impacts observed appears to be quite slow. For example, door tracks persisted at least two years after the final trawl sets. The gravel clasts are much more difficult to rework by waves and current, and bioturbation does not appear to be an important factor at this site. The recovery time of habitat is probably on the order of five years, if not longer.

Longer-Term Impacts on Benthic Communities

There was little direct experimental evidence of accumulated impacts on the benthic communities over the three years of experimental trawling. Five taxa did show significant inter-annual trends in abundance in the trawled corridor but four of these increased (even though they decreased across the individual trawling events). Only the amphipod *Caprella linearis* declined substantially from 1997 to 1998.

While the hypothesis tests did not detect it, the comparison of Abundance-Biomass curves before trawling in 1997 and after trawling in 1999 showed that the taxa which dominated the benthic biomass, particularly the horse mussel *Modiolus modiolus*, was reduced from approximately 80% to 60% (Kenchington et al. 2006). This loss contributed to a decline in the proportion of epifauna in the total benthic biomass in the trawled corridor from 90% to 77% over the duration of the experiment. This is consistent with the information on damage from the Campod images which showed that the three top-ranking species for biomass, the horse mussel *M. modiolus*, the tube-building polychaete *Thelepus cincinnatus* and the brachiopod *Terebratulina septentrionalis*, were the most affected. Sub-lethal damage to 8% of the *M. modiolus* was observed in 1997 but the persistence of their damaged shells prevented the detection of additional damage in subsequent years.

The damage to and decline of the horse mussel suggests a potentially-serious effect of trawling across a much longer scale of time. While horse mussels dominated the benthic biomass at the study site in the late 1990s, they were present as solitary individuals or in small clumps averaging six individuals per 0.5 m^2 (ranging from zero to 18). However, this species is capable of forming persistent beds at depths to 200 m and known extensive mussel reefs or mounds are found in the nearby Bay of Fundy (Wildish et al. 1998). There is no direct evidence that Western Bank previously supported such growths. Collins and Rathbun (1887) noted only that the Bank "abounds" in mussels and other shellfish, which could describe their frequency in 1997, while Rich (1929) was even less specific. In contrast to the Bay of Fundy, lower productivity or weaker currents, which influence food supply, may prevent their formation. Nevertheless, if such reefs had existed in the pre-trawling era, they would have been severely impacted if the rate of decline in mussel biomass seen over our limited experiment was continued through several decades of commercial trawling. Given the life-history traits of *M. modiolus*, the decade of closure after 1987 would have been insufficient for their re-establishment. Thus, it remains possible that the predominant member of the natural benthic community on the area site has been so severely affected by trawling as to have substantially modified the community itself – a change that would have had wider ecosystem effects and from which the benthos has yet to fully recover. If so, the vulnerability of this particular benthic community is not to a single pass of a trawl but to chronic impacts of repeated trawling over the long life cycle of the horse mussel.

Apart from this decrease in horse mussel biomass, all of the impacts detected by our experiment were short-term, apparently persisting for less than a year, and minor, at least in comparison with the natural inter-annual variation seen on the reference lines (Kenchington et al. 2006). Such limited impacts of otter trawling might be expected for the infauna of a sandy seabed (e.g. Eleftheriou and Robertson 1992, Kenchington et al. 2001) but were contrary to expectations for the epifauna of a cobble bottom (Collie et al. 1997, 2000, 2005 and Hermsen et al. 2003).

The relatively narrow swath of experimental trawling, relative to broadly-disturbed commercial fishing effort, may have allowed rapid recovery through a degree of recolonization from the unfished areas on either side, which might not have occurred if the whole bank had been subject to the intensity of trawling used on the experimental line. Also, the effects of the annual, pulsed experimental disturbance may have differed from those which would have resulted if the disturbance had been spread throughout the year, as would be more typical of commercial fisheries.

Fish Feeding

Our study has shown that the fish collected during our experimental trawling were feeding on about half (~ 51%) of the invertebrate taxa comprising the benthic community, including deep infaunal species (Kenchington et al. 2005). This indicates strong coupling between benthic invertebrate and demersal fish communities. This breadth of diet and the associated estimates of feeding preference were only observed because of a combination of thorough taxonomic identification and the availability of comparative data sets from Videograb samples and fish stomachs, a combination of observations that we recommend for future studies.

Detailed dietary changes associated with fishing disturbance have rarely been examined through experimentation and this study adds significantly to existing knowledge of the effects of trawling on fish feeding. Two classes of effects have been documented (Kenchington et al. 2005), quantitative changes in the proportion of species consumed and qualitative changes through opportunistic feeding on newly available food items.

All five focus predator species demonstrated proportional changes in their diets associated with the trawling disturbance, while Atlantic cod, American plaice and yellowtail flounder also exploited new diet items (Kenchington et al. 2005). Atlantic cod consumed significantly more annelids after trawling and both size classes increased their consumption of horse mussels. Smaller Atlantic cod also exploited 14 infaunal species after trawling commenced that were not detected in their diet before trawling, while larger Atlantic cod increased consumption of epifauna and tubiculous species at the expense of fish. Haddock greatly increased the weight of fish and horse mussels in their stomachs after trawling while epifaunal and shallow subsurface prey items were significantly less frequent in the diets after trawling commenced. With American plaice, the tube-building polychaete *T. cincinnatus*, the brittlestar *O. aculeata*, and the horse mussel *M. modiolus* became new dietary items not found in the stomachs before trawling. *T. cincinnatus* also became a new dietary item in yellowtail and 18 other species were consumed in greater quantity once trawling commenced. In winter flounder, trawling increased consumption of 20 infaunal species including the amphipod *Unciola* and the horse mussel. Most of the invertebrate prey species that were consumed in greater amounts, or added to the diets of the fish, after trawling were abundant at the study site and were epifaunal or subsurface dwellers.

As described by Kenchington et al. (2006), the experimental trawling did have some effects on the benthic community at our study site. Eighty-two percent of the benthic sampling stations on the experimental line showed some degree of biological damage in the high-resolution photographs taken by Campod immediately after trawling. The species showing the greatest damage were the horse mussel *M. modiolus*, the tube-building polychaete *T. cincinnatus* and the brachiopod *Terebratulina septentrionalis*, all surface-dwelling organisms. *M. modiolus* and *T. cincinnatus* were also the dominant organisms in the dietary changes. Thus, for those two species, trawl-induced damage clearly increased their availability to predators.

Our data show evidence of fish moving into the study site to scavenge on newly available prey items, as indicated by increasing catches as trawling progressed (Kenchington et al. 2005). These increases were most significant for the visual predators Atlantic cod, haddock and winter flounder.

Sensitivity of Benthic Organisms to Trawling Disturbance

Assessing all results, the species most sensitive to trawling disturbance observed in our experiment were the horse mussel *Modiolus modiolus*, the tube-building polychaete *Thelepus cincinnatus*, the brachiopod *Terebratulina septentrionalis* and the burrowing anemone *Cerianthus* sp. (Kenchington et al. 2006). All these species are epibenthic, sessile and relatively large.

Lessons Learned about Experimental Design

In general we were pleased with our experimental design. The major problem encountered was that due to logistical constraints we were not always able to do all the sampling on the reference lines before the experimental trawling began and therefore we did not have a full BACI design as intended.

Extrapolation of Results to Other Conditions

The conclusions of this experiment are specific to the conditions of the disturbance regime employed (i.e. annual experimental trawling along a narrow corridor surrounded by undisturbed seabed) and the characteristics of the benthic habitat and community at the study site (i.e. gravel bottom dominated with sessile epifauna). It can not be assumed that the same conclusions would be reached for different disturbance regimes and different benthic ecosystems for numerous reasons. The disturbance regime employed in this experiment did not completely replicate that imposed by commercial fishing activity. While the annual intensity of trawling may have been realistic, at the upper end of the range estimated from past trawling activity off eastern Canada (Kulka and Pitcher 2001), the pattern, timing and duration of trawling do not replicate the scale of the disturbance regime that would be expected from commercial fishing. The disturbed zone was only 120-250 m wide and bordered on both sides by undisturbed habitat and communities. The zone of disturbance under commercial fishing pressure can be expected in most cases to be more widespread. Therefore, the rate of biological recovery observed in our experiment is probably higher than would take place under conditions of a wider disturbance zone where organisms would have to travel greater distances to re-colonize.

With regard to timing, all the experimental trawling was done within a day each year. In contrast, commercial trawling generally takes place throughout the year, subject to regulations. Impacts may have been different if this concentrated disturbance had been applied at other times of the year when organisms were possibly more vulnerable. In addition, impacts may have been different if the study site had been trawled once a month. Spreading the trawling intensity over the year would most likely slow down the rate of recovery since the seabed would be disturbed more frequently. Reproductive timing and therefore recruitment of many benthic species on Western Bank is highly seasonal so a monthly disturbance would be more likely to interfere with recruitment processes than a pulsed once-a-year trawling event. Finally, commercial trawl fisheries usually operate in a given area for more than three years, the time span of this experiment. We may have observed some long-term changes if we had extended the length of the experiment.

Otter trawls are designed to capture demersal species while being towed in limited contact with the seabed, but other gear types such as scallop rakes and clam dredges are designed to collect benthic species that live on or in the seabed. Therefore, the physical disturbance that these penetrating gear types create is much greater for each square meter of the seabed contacted. As the intensity of use increases, so does the potential for lasting effects, especially if the time interval between disturbance events is less than the recovery period of the benthic ecosystem.

COMPARISON WITH THE GRAND BANKS OTTER TRAWLING EXPERIMENT

The Western Bank experiment was conducted so that we could compare the results of otter trawling on a gravel habitat with those observed on a sandy habitat in our Grand Banks otter trawling experiment. We expected to find that the impacts would be greater on the gravel habitat because of the greater proportion of attached epibenthos. The following is a brief summary comparing the results of the two experiments.

Site

Both study sites were selected after conducting preliminary surveys at a number of candidate sites. They had not been disturbed by mobile fishing gear for at least 10 years before the experiments began and were closed to all fishing activity while the experiments were being conducted. Therefore, with the possible exception of vulnerable sessile organisms with slow growth rates such as horse mussels, the benthic communities at the start of the experiments should have been relatively natural and not influenced by human activities. The Western Bank site was situated inside a haddock nursery area which had been closed to trawling since 1987. The Western Bank site (mean depth 70 m) was substantially shallower than the Grand Banks site (mean depth 137 m) and therefore subjected to more wave activity. The most important difference between the sites, and the reasons they were selected, was the nature of the seabed; sand on the Grand Banks and gravel on Western Bank.

Design

The experimental designs were quite similar. Both experiments employed trawled and reference corridors that were sampled before and after trawling (BACI design). However, there was just one trawled corridor in the Western Bank experiment compared to three for the Grand Banks. There was also a major difference in spatial scale. The single trawled corridor on Western Bank had a length of 2 km while those on the Grand Banks were 13 km. The sampling tools were also very similar or identical for the two experiments with the exception of sampling epibenthic organisms. In the Grand Banks experiment, we used a quantitative epibenthic sled which worked well on a sandy seabed but would not sample quantitatively on a gravel seabed. Therefore, in the Western Bank experiment, we relied on video and photographic imagery collected using Campod to quantify epibenthic organisms. These optic techniques are much easier to deploy, are non-destructive and provide valuable information on habitat. Our experimental design allowed us to examine three immediate impacts, two one year recovery periods and the cumulative effects of three annual trawling disturbance in both experiments. The Grand Banks experiment was conducted in 1993-1995 while the Western Bank experiment was conducted in 1997-1999.

Benthic Communities

Both sites had rich and diverse biological communities. However, as expected, these were quite different in composition. A total of 341 taxa were identified at the Western Bank site. Polychaetes, crustaceans and molluscs dominated. The mean Shannon-Weiner diversity was 1.5 while species richness was 14.6 and evenness 0.77. Mean biomass and abundance were 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 and sessile. There was a rich colonial epifauna containing at least 53 taxa, the majority of which were hydroids.

A total of 246 taxa were identified at the Grand Banks site. The dominant taxonomic groups were echinoderms, polychaetes, molluscs and crustaceans. Mean biomass and abundance were on the order of 1000 g m^{-2} and 2100 individuals m^{-2}, respectively. The dominant epibenthic species were sand dollars (*Echinarachnius parma*), brittle stars (*Ophiura sarsi*), sea urchins (*Strongylocentrotus pallidus*) and snow crabs (*Chionoecetes opilio*). These are all large and mobile organisms. With the exception of the soft coral *Gersemia* sp., there were few large sessile species.

Gear Disturbance

Both experiments used the same Engel 145 otter trawl equipped with rockhopper gear and applied the same level of trawling disturbance for three successive years, 12 continuous sets back and forth between two waypoints. The only difference was that the experimental trawling took longer on the Grand Banks due to the greater number and length of trawled corridors. Also, due to improvements in navigation the tracking of the otter trawl along the trawled corridor and positioning of the sampling gear were more precise in the Western Bank.

Trawl Catch

The invertebrate bycatch was low at both sites, indicating the poor efficiency of the Engel 145 otter trawl in capturing benthic organisms. There was an extremely low fish catch in the Grand Banks experiment due to the very poor condition of groundfish stocks that had led to the groundfish moratorium established in 1992. Dominant species were American plaice (*Hippoglossoides platessoides*) and thorny skate (*Raja radiata*). In contrast, the fish catch at the Western Bank experiment was relatively high, possibly reflecting the effectiveness of the haddock nursery area established in 1987. Dominant species were haddock (*Melanogrammus aeglefinnus*) and Atlantic cod (*Gadus morhua*). These two species plus winter flounder (*Pseudopleuronectes americanus*) increased in the trawl catch with successive sets suggesting scavenging behaviour by demersal fish. Detailed analysis of stomach contents showed changes in diet attributed to trawling. Stomach contents were not examined in the Grand Banks experiment.

Natural Changes

Natural temporal changes in the benthic communities along the reference corridors were detected in both experiments. At the Grand Banks site, there was a general decrease in both total abundance and the number of species per sample over the three-year sampling period. At the Western Bank site, there was a general increase in the number of taxa, total abundance and biomass. Of particular note was a seven-fold increase in the biomass of hydroids.

Immediate Impacts on Habitat

The immediate impacts of otter trawling on seabed habitat were much more pronounced in our Grand Banks experiment. Tracks from the doors and footgear were readily visible on the sandy seabed. Video observations 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. Untrawled seabed had a hummocky, mottled appearance with abundant organic detritus, while trawled seabed was generally smoother and cleaner. While some new structural features were created by trawling (i.e. furrows and berms), the visual observations showed a generally smooth sediment surface with an overall decrease in habitat complexity. Acoustic data indicated that trawling increased sediment hardness and 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.

Physical disturbance to the seabed from trawling was less evident in the sidescan sonograms at the Western Bank site, presumably due to the armoured nature of lag gravel seabed making it more difficult to disturb. No changes in habitat were detected by the various acoustic tools. Little physical disturbance was evident in the video but small-scale disturbance was apparent in the high resolution photos taken with Campod stations.

The difference in the volume of Videograb samples before and after trawling suggests that trawling may have increased the packing of sediment clasts.

Immediate Impacts on Epifauna

An immediate impact on epifauna was evident in the Grand Banks experiment. On average, the total biomass of organisms was 24% lower in trawled corridors than reference corridors. At the species level, this biomass reduction was significant for snow crabs, sand dollars, brittle stars, sea urchins and soft corals. 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 is presumably due to several factors including direct removal by the trawl, displacement, predation and possibly migration of non-captured organisms.

In contrast, trawling had few detectable immediate effects on the epifauna taxa at the Western Bank site. 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.

Immediate Impacts on Macrofauna

Few significant immediate impacts on macrofauna were observed in the Grand Banks experiment. However, in one year (1994) there was a significant drop in total community abundance, with polychaetes being the most affected taxonomic group. In the same year, there also was a drop in the biomass of sand dollars and several species of polychaetes. 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. Multivariate analysis indicated changes in community structure only in 1994. No impacts could be detected on the abundance of adult or juvenile mollusk. Levels of bivalve damage and recruitment rates were similar in both reference and trawled corridors.

Trawling at the Western Bank site also had few detectable immediate effects on the abundance or biomass of macrofauna taxa and none on community composition. A few taxa, primarily a mixture of polychaetes and amphipods, decreased significantly after trawling, and fish stomach data showed that some of these were scavenged by demersal fish.

Longer-Term Impacts on Habitat

The sandy habitat at the Grand Banks site appeared to recover from the trawling disturbance in about one year while the recovery rate at the Western Bank site was definitely slower. Some lineations in sidescan sonograms were still evident in 2001, two years after the third trawling event. However, no significant changes in the structure or complexity of the gravel lag seabed were observed, even after three years of repetitive trawling. The faster recovery rate observed at the Grand Banks site presumably reflects the greater mobility of sand compared to gravel. Higher levels of bioturbation may also have been a factor.

Longer-Term Impacts on Epifauna

No longer-term impacts on epifauna were evident at the Grand Banks site. The epibenthic community appears to have recovered from the pronounced immediate impacts observed in approximately one year. Since most of the affected species are mobile, this rapid recovery is presumably due to migration. In contrast, longer-term impacts were clearly evident at the Western Bank site. There was a marked decrease in the biomass of the horse mussel *Modiolus modiolus* in the trawled corridor over the three year experiment. At the same time, the proportion of epifaunal biomass declined significantly from 90% to 77%. These changes are in part due to trawl-induced damage and subsequent predation by demersal fish. However, no cumulative effects were detected on the assemblages of colonial epifauna. It is not surprising that recovery at the Western Bank site takes longer because the impacted species are sessile and must be replaced by recruitment and growth.

Longer-Term on Macrofauna

Overall both experiments showed only minor longer-term impacts on macrofauna against a background of considerable natural variation. There was no evidence of any cumulative effects on community structure of the macrofauna in either experiment.

Most Impacted Benthic Species

In the Grand Banks experiment the most impacted benthic species were the snow crab *Chionoecetes opilio*, the sand dollar *Echinarachnius parma*, the brittle star *Ophiura sarsi*, the sea urchin *Strongylocentrotus pallidus*, the soft coral *Gersemia* sp. and several species of polychaetes. These are primarily large, free-living epibenthic organisms. In the Western Bank experiment, the most impacted species were the horse mussel *Modiolus modiolus*, the tube-building polychaete *Thelepus cincinnatus* and the brachiopod *Terebratulina septentrionalis*. These too are epibenthic organisms but they are sessile and grow attached to the substrate. The pronounced differences between the results of the two experiments reflect the differences in the resident biological communities.

Summary

Both experiments indicate the impacts of otter trawling are greatest on epibenthic organisms which are exposed to direct contact with the gear. Collectively, the results clearly indicate that the immediate impacts of otter trawling were greater in the Grand Banks study conducted on a sandy seabed than in the Western Bank experiment conducted on a gravel lag seabed. However, both the habitat and communities at the Grand Banks site recovered in approximately one year while recovery at the Western Bank site is considerably longer. These differences between the sites are due to differences in habitat and benthic community composition. Therefore, these comparable experiments provide no support for the hypothesis that gravel habitats and communities are more susceptible to the impacts of otter trawling than sandy habitats and communities. The reason for this surprising conclusion is probably due to the relative lack of large, structure-forming epibenthic organisms at the Western Bank site compared to other hard bottoms where experiments have been recently conducted.

COMPARISON WITH OTHER EXPERIMENTS ON GRAVEL SEABEDS

Bay of Fundy

Various gear impact studies have been conducted on hard bottoms in the nearby Bay of Fundy using both trawling and scallop gear. Kenchington et al. (2007) analyzed presence/absence records from two comparable megabenthic surveys conducted using scallop dredges in 1966-67 and 1997 on the scallop grounds off Digby, NS. This data set allows assessment of the potential effects of combined otter trawling and scallop dredging in a large area over a 30 year period. Profound changes were observed in large epibenthic organisms. No species were lost and the average number of taxa per station remained constant but the spatial heterogeneity of the community sampled decreased and species composition changed significantly. The whelks *Buccinum undatum* and *Colus* spp., the bivalves *Astarte* spp. and *Cyclocardia borealis* , the toad crab *Hyas* spp., the sea urchin *Strongylocentrotus droebachiensis* and the brittle stars (Ophiurida) increased while the boring sponges *Cliona* spp., the horse mussel *Modiolus modiolus*, the scallop *Chlamys islandica*, the fan worm *Pseudopotamilla reniformis* and the stalked tunicate *Boltenia ovifera* decreased. The replacement of attached, fragile, epifaunal, filter-feeding taxa by motile scavengers, motile filter-feeders and robust, burrowing filter-feeders strongly suggests that the primary cause of the observed changes over a 30 year period was the chronic physical disturbance of fishing gear (otter trawls and scallop dredges).

These impacts are much greater than those observed in our Western Bank study where the major significant impact was a decline in the proportion of epibenthic biomass (Kenchington et al. 2007). One possible explanation is the use of scallop dredges which in general have a greater impact than otter trawls (Kaiser et al. 2006). However, we believe that the major reason is the difference in time period between observations. Our Western Bank experiment was conducted over a three year period compared to 30 years for the Bay of Fundy observations. In both experiments, the long-lived horse mussel was a key impacted species. It appears that in some situations short term fishing has limited impacts and that chronic fishing over prolonged time is needed to produce major impacts. We probably would have seen more significant effects in the Western Bank experiment if it had extended longer.

In a related study, Henry and Kenchington (2004a) compared the hydroid assemblages on scallop shells and cobbles collected from the commercial scallop grounds in the Bay of Fundy. The scallop shells were considered to represent undisturbed habitats while cobbles were expected to represent disturbed habitat. The number of taxa was significantly lower on cobbles and the hydroid assemblage was different than that found on the scallop shells. Runner-like forms with small, unbranched colonies and medusa life stages were more frequent on cobbles. It was concluded that these differences could result from chronic disturbance of cobbles caused by fishing activity, in particular scalloping. Henry and Kenchington (2004b) also examined the evidence for impaired sexual reproduction and induced clonality in the hydroid *Sertularia cupressina* collected in the same area. They found that colonies on scallop valves were more abundant and sexually fertile than their counterparts on cobble and all were sexually derived. In contrast, colonies on cobbles had a greater frequency of injury, were less fertile and were frequently clonally-derived. The long term implications of these impacts are not understood but they could affect the adaptability, recruitment and recovery potential of these and related organisms.

Robinson et al. (2001) conducted an experiment on the impacts of scallop drags on large epibenthos in Passamaquoddy Bay and off Grand Manan Island, NB. Observations were made by divers. There was a significant decrease in the abundance of sea urchins and an increase in the number of broken sea urchin tests. The density of lobsters declined to zero while the abundance of whelks increased. The authors concluded that there were short-term impacts from dragging but the observable effects from a single disturbance disappeared in less than three months.

Georges Bank

The effects that we observed on Western Bank appear to be much less than those reported by Collie et al. (1997, 2000 and 2005) on the gravel pavement on Georges Bank (40-90 m deep) which has a long history of fishing using both otter trawls and scallop dredges. These two sites are 500 km apart, separated by the Northeast Channel. These authors followed the approach of comparing the benthic characteristics of relatively large areas subjected to different levels of inferred fishing disturbance. They reported that undisturbed (or lightly disturbed) sites had higher numbers of organisms, biomass, species richness and species diversity. These sites also had a greater abundance of bushy epifauna that provides complex habitat for other organisms. Disturbed sites on the other hand had higher evenness, were dominated by larger, hard-shelled molluscs, scavenging crabs and echinoderms and had fewer colonial epifauna. They concluded that bottom fishing reduces the complexity and species diversity of the epibenthic community.

There are several possible reasons for these pronounced differences in results. The disturbed sites studied on Georges Bank by Collie et al. (1997, 2000 and 2005) had been fished with scallop dredges as well as otter trawls, and it is well known that scallop dredges have a much greater impact (Collie et al. 2000, Kaiser et al. 2006). Therefore, the level of seabed disturbance could have been greater than created in our Western Bank manipulative experiment. There also are major differences of scale. The Georges Bank observations examined the cumulative impacts of the total commercial fishery over large areas for many years while our Western Bank experiment was restricted to a very small area and was just three years in duration. Another possible reason is that the fishing effort on Georges Bank was not experimentally controlled and some of the differences between sites could be due to natural factors. However, we feel that the major reason for the difference in results is the relative lack of a bushy, structure-providing epifauna on Western Bank despite the 10 year absence of fishing gear disturbance. Therefore, the benthic assemblage was most likely less vulnerable to fishing gear, including our experimental otter trawling, than some parts of Georges Bank.

Collie et al. (2005) also examined the recovery of benthic megafauna at a site on Georges Bank that was closed to bottom fishing in 1995. They observed significant shifts in species composition and significant increases in abundance, biomass, production and epifaunal cover. After five years, they were still seeing increases in biomass and abundance of certain taxa and predicted that the full recovery time of the gravel habitat would take on the order of 10 years.

In a companion study, Hermsen et al. (2003) observed that fishing disturbance also affects benthic megafaunal production in gravel habitats on Georges Bank. Production was significantly higher at undisturbed sites compared to disturbed sites and production increased markedly when fishing disturbance was terminated. However, much of the latter difference was due to an increase in the biomass of scallops which were no longer being harvested.

Stokesbury and Harris (2006) investigated the impacts of a limited short-term scallop fishery on the epibenthic community of Georges Bank using video surveys. Their study design included control areas so they were able to assess natural changes as well as gear impacts. They observed that the limited short-term scallop fishery appeared to have altered the epibenthic community less than was observed as natural change. These results are in contrast to those of Collie et al. (1997, 2000 and 2005). As mentioned above, one of the reasons for the difference could be that some of the differences between sites observed by Collie et al. (1997, 2000 and 2005) are natural and not due to gear impacts. Another reason could be that Stokesbury and Harris (2006) were looking at the effects of a limited short-term fishery, not a chronic fishery. Different spatial scales could also be factors.

Alaska

Freese et al. (1999) conducted a manipulative otter trawling experiment on a gravel bottom in the Eastern Gulf of Alaska at a depth range of 206-274 m. The site had been subjected to little or no trawling since the 1970s. They trawled eight sites with single sets using a Nor'eastern bottom trawl with rockhopper gear and observations were made before and after trawling using a submersible. Immediately after trawling, they observed that boulders were displaced and large epifaunal invertebrates were removed or damaged. A significant decrease in density and increase in damage to sponges and anthozoans was observed in the trawl path. However, no changes in density or damage to motile invertebrates were detected. One year later, there was no sign of recovery and indeed some indication of further loss as damaged sponges died (Freese 2001).

These results are similar to what we observed on Western Bank. However, the magnitude of impacts seems to be greater, despite just a single set, presumably because of the abundance of large sponges that provided structural habitat. In contrast, the sponges at our site were small and much less abundant (Henry et al. 2006).

Irish Sea

A series of studies have been conducted on the impacts of scallop dredging on gravelly seabed communities around the Isle of Man in the Irish Sea. Bradshaw et al. (2000 and 2001), who compared open and closed areas as well as conducted short-term dredging experiments, reported that scallop dredging had a significant effect on the structure of benthic communities. Their results also suggest that closure of areas to commercial dredging may allow the development of more heterogeneous communities and allow some species to increase. Bradshaw et al. (2002) compared data sets collected 60 years apart and observed an increase in mobile, robust and scavenging taxa while slow-moving or sessile, fragile taxa decreased. These differences could not be explained by natural variation and are judged to indicate real long-term impacts of scallop dredging. One of the species negatively affected in these studies was the horse mussel *Modiolus modiolus* which was the most impacted species in our Western Bank experiment. The much greater impacts observed in the Irish Sea studies can be explained by the higher level of disturbance inflicted by scallop dredges than otter trawls (Collie et al. 2000, Kaiser et al. 2006).

Australia

A manipulative otter trawling experiment was conducted on a hard bottom on the northwestern continental shelf (50 m) of Australia by Moran and Stevenson (2000). The site had not been previously trawled and had an abundance of large, sessile species, in particular sponges, soft corals and gorgonians. The trawling reduced the density of large benthic organisms by 15.5% on each pass, and four passes reduced density by approximately half. These impacts are much greater than we observed on Western Bank and the differences appear again to be due to differences in the epibenthic communities.

The Australian site had an abundance of large species easily removed or disturbed by the otter trawl while on Western Bank the sponges are relatively small and octocorals are rare.

Pitcher et al. (2000) investigated the effects of trawling on sessile megazoobenthos on Australia's Great Barrier Reef. The removal rates of most seabed fauna were between five and 20% per pass. Burridge et al. (2003) found similar rates of depletion of some taxa when a prawn otter trawl was towed through areas of sponges, gorgonians and hard corals in channels in the Great Barrier Reef. These high rates of removal caused changes in the composition of benthic communities with a shift to less vulnerable species. In contrast the removal rates of benthic organisms by the otter trawl used in our Western Bank experiment were extremely low because the sessile epibenthic forms were small (i.e. most less than 5 cm).

Georgia

Van Dolah et al. (1987) conducted a manipulative otter trawling experiment on a hard bottom with abundant sponges and corals. After a single set, some damage to individuals of all target species was observed but only the density of barrel sponges was significantly reduced. Damage to other sponges and corals varied depending on species but was not significant. Twelve months after trawling, organism abundances had recovered and damage to sponges and corals was no longer detected due to healing and growth.

SUMMARY

During 1993-1995 we conducted a three-year manipulative experiment on the effects of repetitive otter trawling on a sandy bottom ecosystem on the Grand Banks of Newfoundland. The published results indicated that the effects of annual otter trawling were detectable on both habitat and epifauna but that recovery appeared to occur within a year and there was no evidence that the benthic community was altered by three years of repetitive trawling.

It was recognized that these conclusions were specific to the sandy bottom habitat and community present at the study site and that the results could be quite different on a hard bottom habitat with a greater abundance and diversity of sessile epifauna. Therefore, during 1997-1999, we conducted a similar three-year manipulative experiment using the same Engel 145 otter trawl on a gravel bottom on Western Bank.

This experiment is very unique. It is one of very few multi-year otter trawling impact experiments that have been conducted on gravel seabeds, a habitat type that is generally regarded to be particularly vulnerable to bottom fishing gear. It is the first trawling impact experiment that has examined in detail the spatial pattern of the experimental trawling disturbance and calculated the disturbance level of individual samples. It is also the first trawling impact experiment that has incorporated an assessment of the effects on fish feeding.

The study site (average depth 70 m) was located within the 4TVW Haddock Nursery Area that has been closed to trawling since its creation in 1987. An abundant and diverse benthic community dominated by epifauna was present which had not been disturbed by fishing gear for at least 10 years before the experiment began. Observations were made along a single trawled line (2 km long) and three reference lines (also 2 km long) before and after experimental trawling each year. At least 12 consecutive trawl passes were made once each year in alternating directions along the trawled line. Fish catch was processed to determine species, abundance, weight and stomach contents. Benthic sampling included sidescan sonar, video and photographic imagery (using BRUTIV, Towcam and Campod) and grab sampling (using Videograb). The use of dGPS and an acoustic tracking system assured highly accurate positioning of vessels, the trawl path and sampling gear.

Despite steaming back and forth between the same two waypoints, there was considerable variability in the exact area of the seabed disturbed by trawl. The cumulative area of disturbance increased with each set. After 10 sets most if not all the area within a 100 m wide corridor had been swept at least once by the entire trawl (60 m between the doors) while on the order of 65-80% of the area had been swept at least once by the footgear and net (20 m). Individual samples were clearly exposed to different levels of disturbance. It is estimated that Videograb samples had been crossed over by the footgear and net over a range of zero to eight times while the range of crossings by the entire trawl was two to 12 times.

Habitat disturbance was evident in the sidescan sonograms and imagery but was mostly limited to the digging of shallow furrows and reorientation of clasts (a mixture of sand, pebble and cobbles with some boulders). There was no sign of disturbance at the scale of the towed video but some was observed at the scale of the Campod video (recorded while on station). Physical disturbance was most evident in the high resolution Campod photographs (0.2 m^2), the most common type being signs of scraping or scouring. The level of disturbance was well predicted by the number of crossings by the footgear and net. After two passes, the probability of not observing disturbance at a station was effectively zero.

Haddock dominated the trawl catch (about 75% by weight) while other common species caught included Atlantic cod, herring, pollock, mackerel, silver hake and redfish. In total, over 15 tonnes of fish were caught over the course of the three year experiment. Fish catch increased significantly between the first two sets and the remaining sets each year suggesting scavenging behaviour. The bycatch of invertebrates was miniscule (28 kg) and was dominated by a single catch of squid. No structure-forming epibenthic organisms were captured.

A total of 341 taxa representing 12 phyla were identified in the 100 Videograb samples. Mean biomass and abundance per grab (0.5 m^2) were on the order of 293 g and 1210 individuals, respectively. The majority of taxa were epifaunal. Biomass was heavily dominated by the horse mussel (76%). The most abundant taxa were tube-dwelling amphipods and sabellid worms. The colonial epifaunal assemblage, also sampled by the Videograb, was composed of 53 taxa of hydroids, bryozoans, sponges, soft corals and tunicates but only made up 0.25% of the total benthic biomass. A total of 45 megafauna taxa were observed in the Campod images. The most abundant were the brachiopod *Terebratulina septentrionalis* and the tube-building polychaete *Thelepus cincinnatus*.

Some natural changes in the benthic communities were detected along the reference lines during the experiment. A mixture of polychaetes, amphipods, echinoderms and molluscs showed significant changes in abundance with most increasing with time. Hydroid biomass increased by a factor of seven-fold.

The experimental trawling had very limited immediate impacts on the benthic community. Declines in some benthic indices were observed but most were not statistically significant. Benthic community composition did not differ significantly before and after trawling in any of the three years with respect to either abundance or biomass. No immediate effects were observed on the colonial epifauna.

Over three years of trawling, some polychaetes and amphipods showed decreases in abundance and biomass but no significant differences in community composition were evident. Abundance/biomass comparisons showed a marked decrease in the relative biomass of the highest ranking species, particularly the horse mussel, which was not seen along the reference lines. Of the various interactions tested between years and treatments, only the test of epifaunal biomass as a proportion of total biomass showed a significant interaction. Epifaunal biomass was approximately 90% of the total biomass in the reference lines throughout but declined to 77% on the trawled line by the end of the experiment. The structure of the colonial epifaunal assemblage was not affected by repeated trawling over three years. However, the total biomass of colonial epifauna was significantly reduced.

Analysis of Campod photos indicated that 3% of the megafauna were visibly damaged. The frequency of damage was greatest for the tube-dwelling polychaete *Thelepus cincinnatus*, the horse mussels *Modiolus modiolus* and the brachiopod *Terebratulina septentrionalis*. The probability of observing biological damage at a given location on the seabed was significantly related to the number of passes by the trawl.

The stomach contents of five fish taxa (Atlantic cod G*adus morhua*, haddock *Melanogrammus aeglefinnus*, American plaice *Hippoglossoides platessoides*, yellowtail flounder *Limanda ferruginea* and winter flounder *Pseudopleuronectes americanus*) collected during the experimental trawling were determined. A total of 177 prey taxa were identified and there were significant differences in diet between the five taxa. Haddock had the most diverse diet and American plaice the least diverse diet. Only three prey items were shared by all five taxa.

All five fish taxa demonstrated proportional changes in their diets as trawling progressed. Atlantic cod, American plaice and yellowtail also exploited new prey. Most of the benthic taxa consumed in greater amounts or added to diets after trawling commenced were abundant at the study site and were epifaunal or subsurface dwellers. The dominant organisms in the dietary changes were the tube-dwelling polychaete *Thelepus cincinnatus* and the horse mussel *Modiolus modiolus*. These two taxa also had the highest incidence of visible damage after trawling. It therefore appears that fish were moving into the disturbed area to feed on damaged organisms.

Assessing all results, the species most sensitive to trawling disturbance observed in our experiment were the horse mussel *Modiolus modiolus*, the tube-dwelling sabellid worm *Thelepus cincinnatus*, the brachiopod *Terebratulina septentrionalis* and the burrowing anemone *Cerianthus* sp. All these species are epibenthic, sessile and relatively large.

Both our Western Bank experiment and our parallel Grand Banks experiment indicate that the impacts of otter trawling are greatest on epibenthic organisms that are exposed to direct contact with the gear. Collectively, the results clearly indicate that the immediate impacts of otter trawling were greater on the sandy seabed studied on the Grand Banks than on the gravel lag seabed studied on Western Bank. However, both the habitat and communities at the Grand Banks site recovered in approximately one year while recovery at the Western Bank site is expected to take considerably longer. These differences between the sites are due to differences in habitat and benthic community assemblages.

The impacts that we observed on the gravel seabed were not as great as those observed in other gear impact experiments on other hard bottoms. This could be due to several reasons. Many of the other studies were done with scallop rakes that are much more damaging than otter trawls. Also, the epibenthic organisms at our study site were relatively small and there were no megabenthic, structure-forming taxa such as large corals or sponges. It is possible that horse mussels had not completely recovered from potential damage that occurred before the study site was closed to trawling in 1987.

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FIGURE LEGENDS

Figure 1. Diagram of the three different disturbance zones created by the Engel 145 otter trawl used in this experiment: door path, footgear and net path, and sweep path.

Figure 2. General location of the study site and the Haddock Closed Area on Western Bank on the Scotian Shelf off Nova Scotia, Canada.

Figure 3. Experimental layout superimposed on multibeam bathymetry. Experimental trawling was done along Line E (yellow). Lines B, G, and I (black) served as reference lines. Campod and Videograb samples were collected at the ten stations along Line E and the ten stations along Lines B, G, and I (red circles). Depth at the sampling stations ranged from 64 to 73 m. Areas of blue indicate slight depressions.

Figure 4. Location of targets and actual Videograb and Campod samples collected after trawling along the trawled corridor (Line E) in 1997, 1998 and 1999. Three extra Campod stations were occupied immediately after trawling (After 1) in 1998 (E02, E09, and E33). The path of the centre of the trawl, as estimated from ship position, is shown for 1997. The path of the centre of the trawl, as measured by Trackpoint, is shown for 1998. Navigation data are not available for 1999. The length of the trawled corridor was 2 km and width approximately 100 m.

Figure 5. Cumulative percent of area disturbed by those trawl sets entirely within the 100 m wide trawled corridor in 1997 and 1998. The upper curves represent the area passed over by the entire trawl (60 m between the doors) while the lower curves represent the area passed over by only the footgear and net (20 m wide).

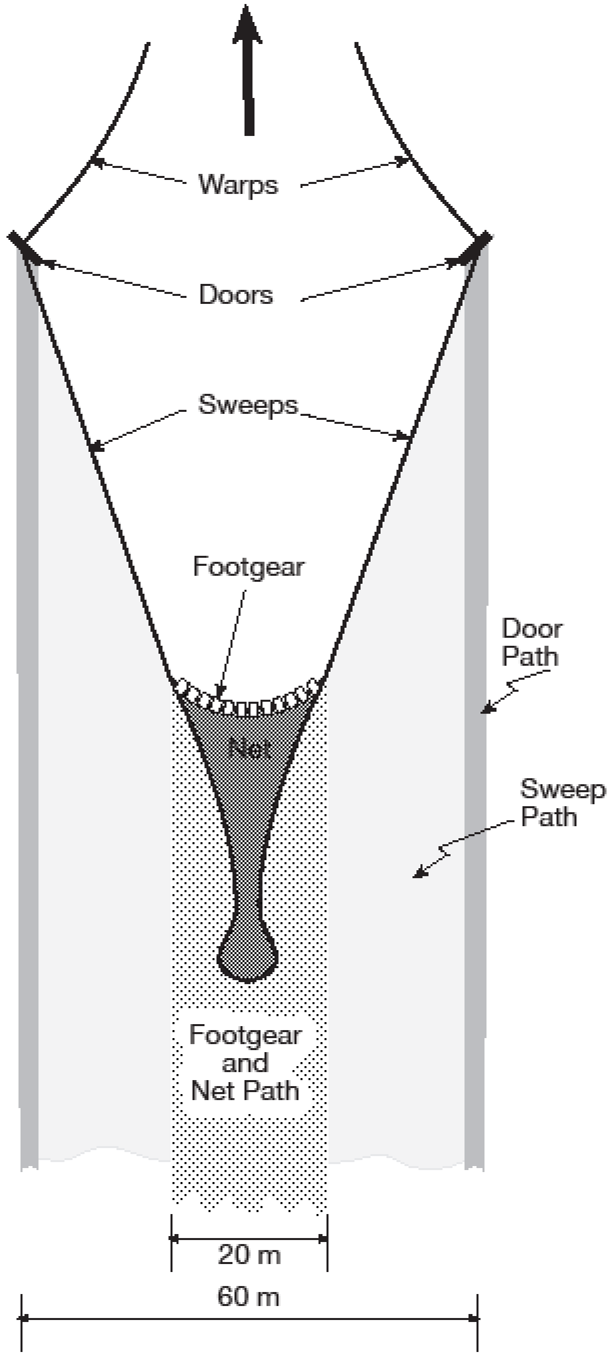
Figure 6. Sidescan sonogram showing trawl disturbance immediately after trawling in 1998.

Figure 7. Representative Campod photos taken in the trawled corridor. A. Before trawling (Station E01C, 1997, Photo 1423-021). B. Scraping/scouring of a large clast (Station E28C, 1997, Photo 1434-077). C. Sedimentation (Station E06C, 1999, Photo 0607-017). D. Displaced (rotated) clast (Station E28C, 1999, Photo 0607-056). E. Possible furrow (Station E01C, 1999, 0582-009).

Figure 8. Logistic fit of damage (0 = no damage, 1 = physical damage observed) with impact by trawl footgear and net. The logistic probability model of falling into one or other damage category according to the number of encounters with the footgear and net is indicated by the line. Data summarized by station.

Figure 9. A mosaic plot portraying the two-way contingency table of counts of damage (1 = yes, 0 = no) by trawl encounter (1 = yes, 0 = no) using data for each Campod station (N 41). The area of each rectangle is proportional to the frequency count of each cell.

Figure 10. A mosaic plot portraying the two-way contingency table of counts of damage (1 = yes, 0 = no) by trawl encounter (1 = yes, 0 = no) using individual Campod photos as data sources (N = 197). The area of each rectangle is proportional to the frequency count of each cell.



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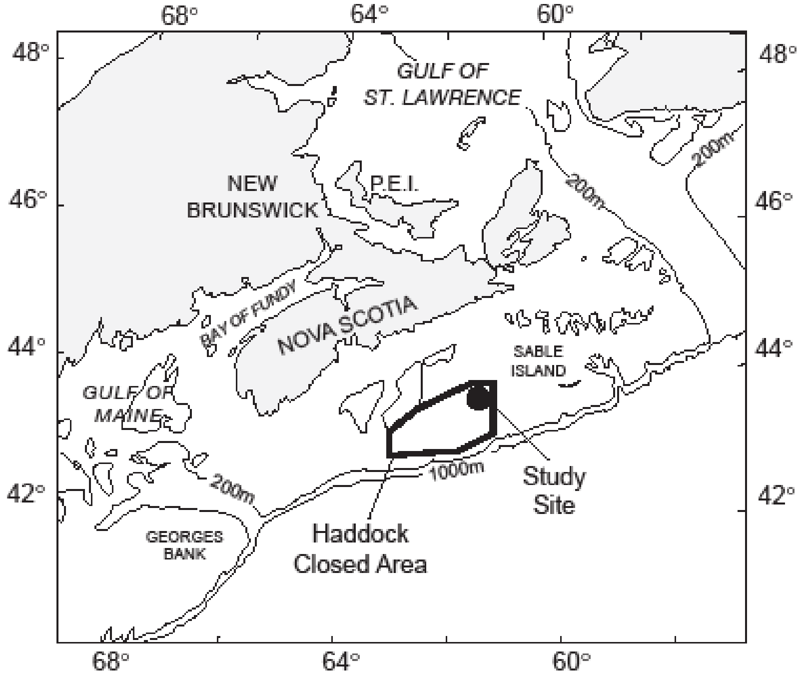

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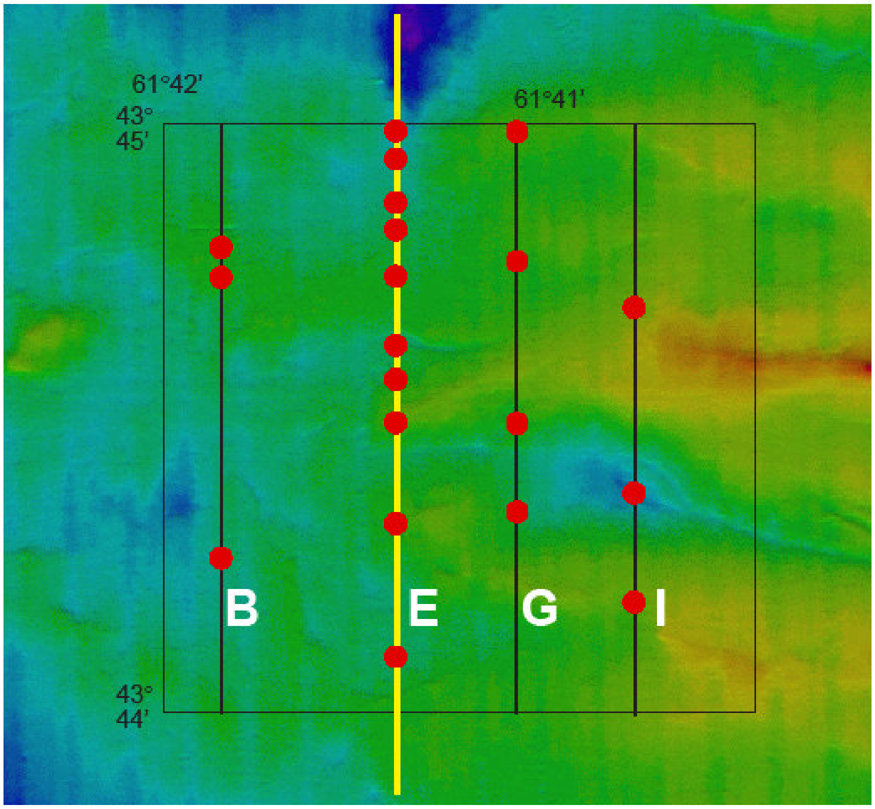

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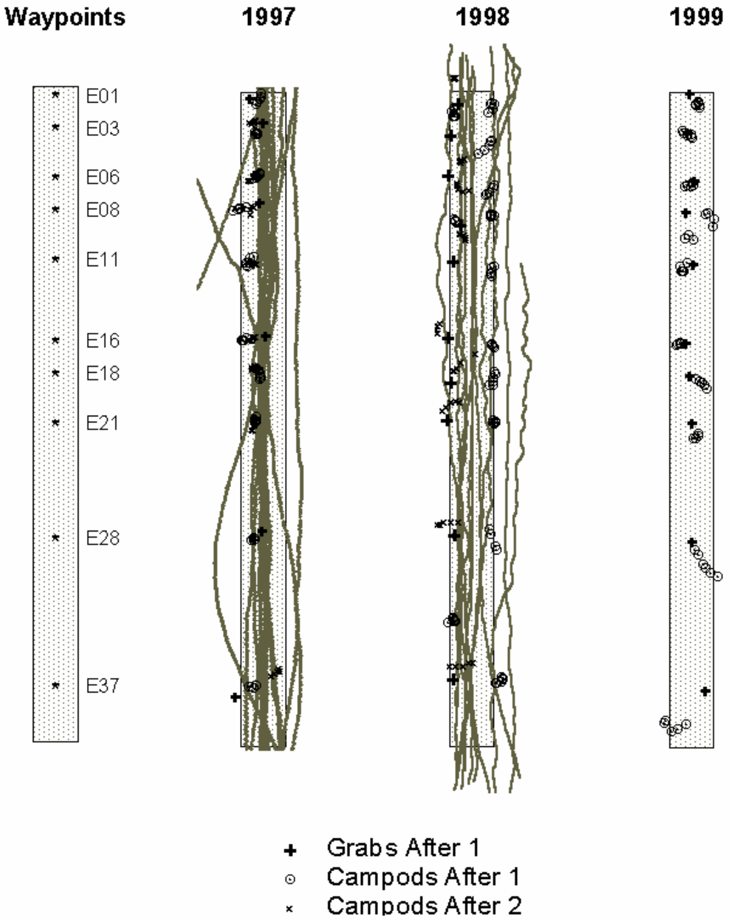

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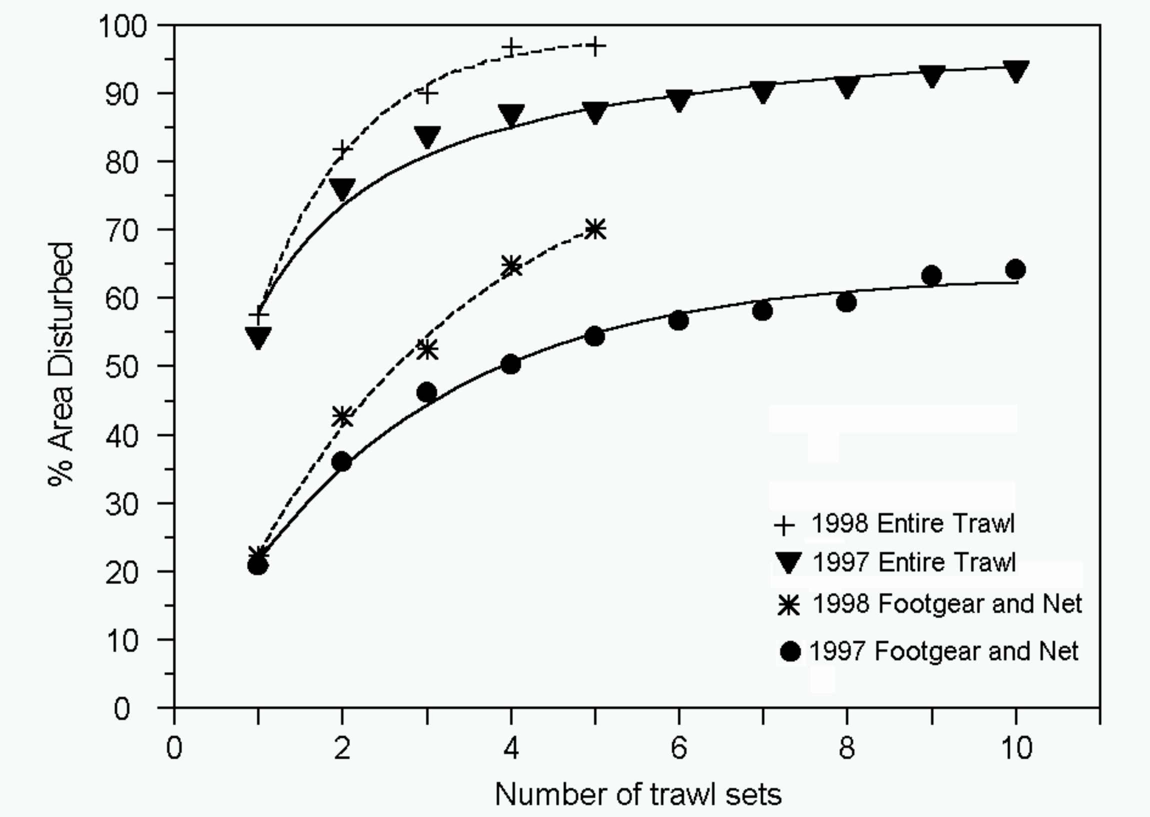

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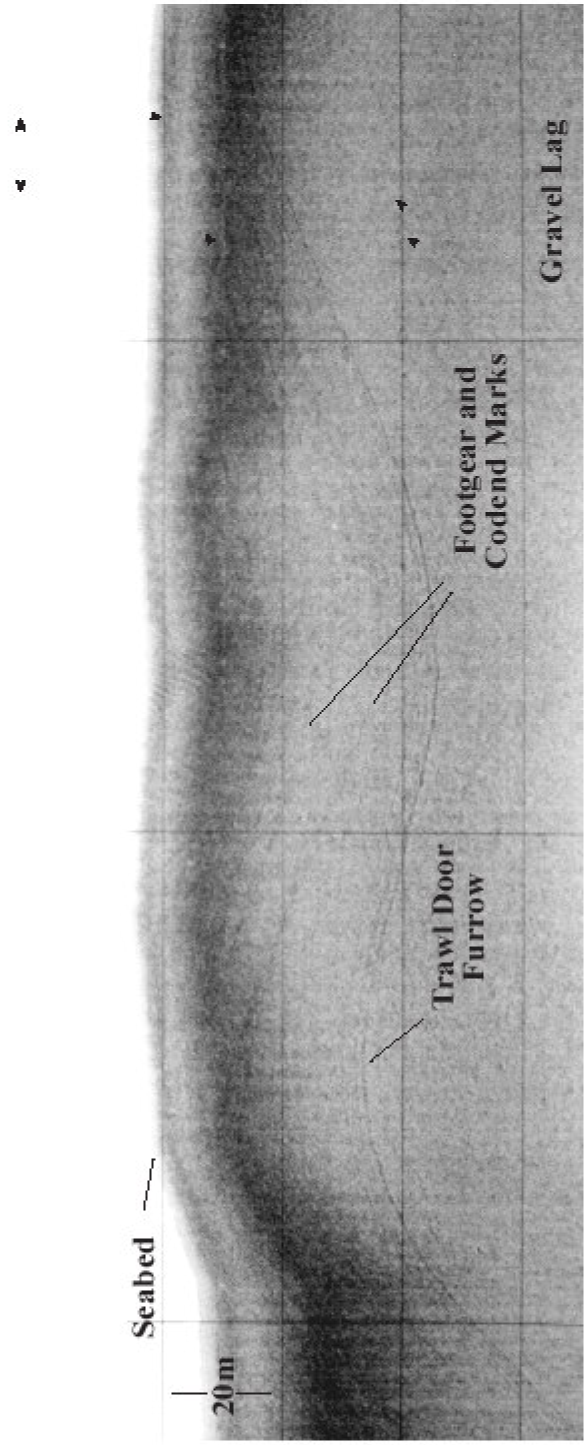

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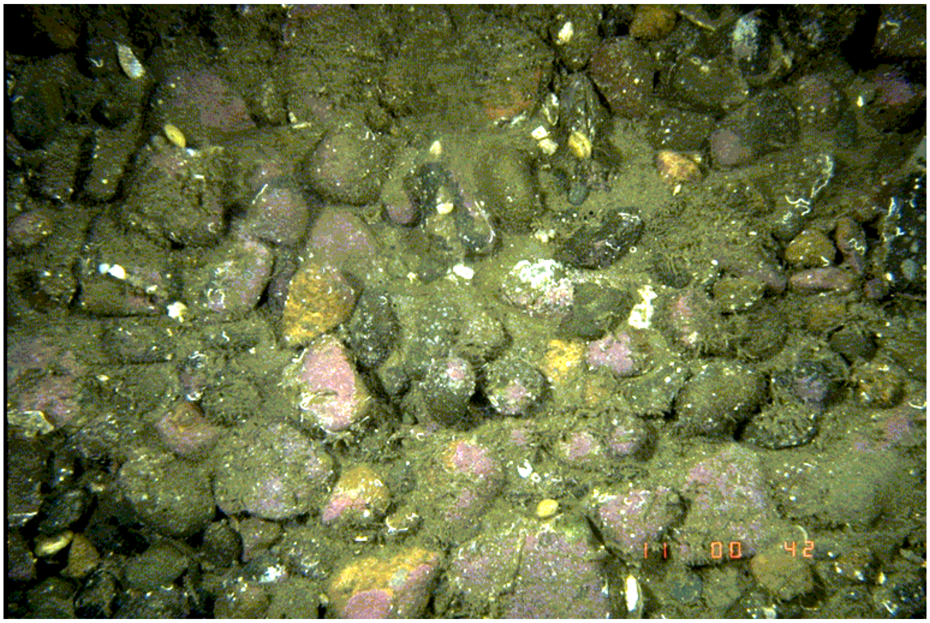


Figure 7A.

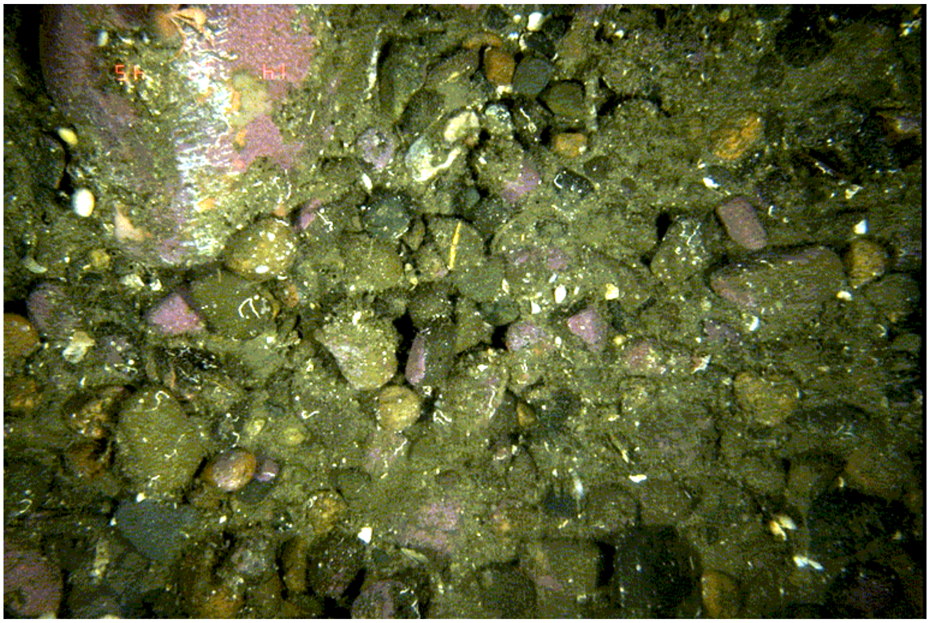
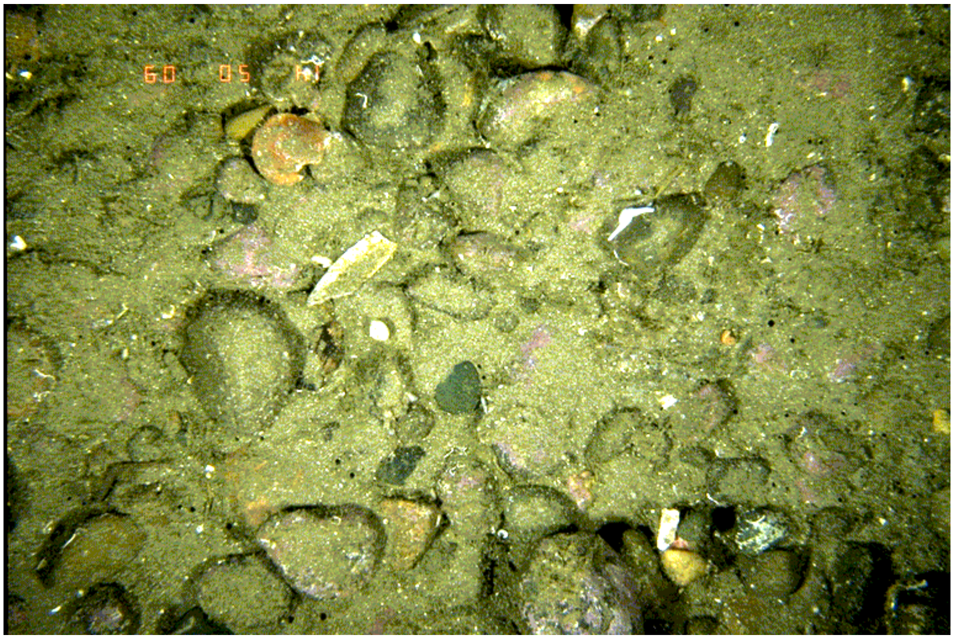


Figure 7B.



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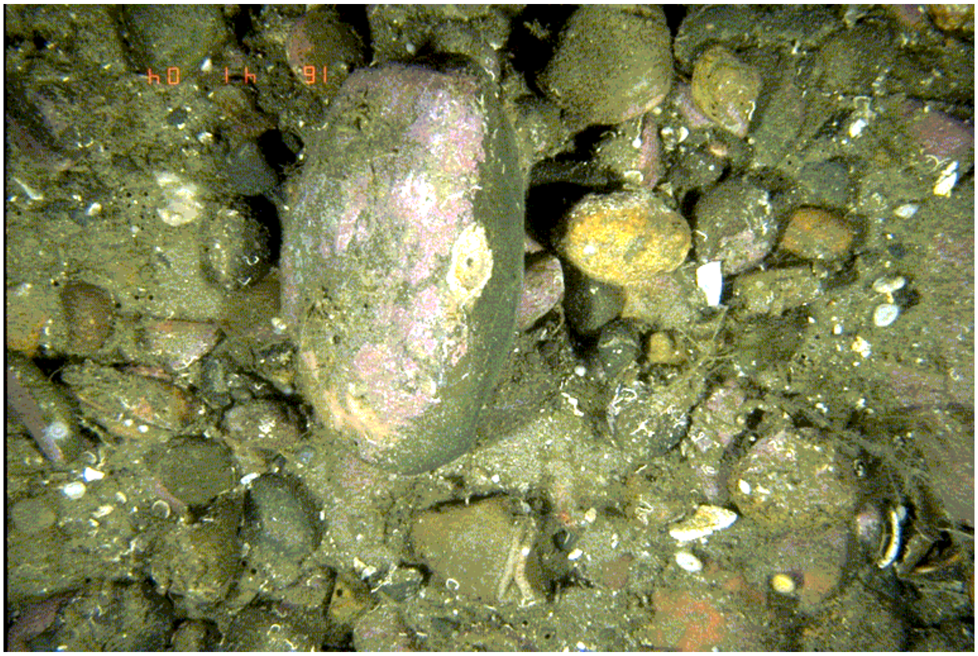
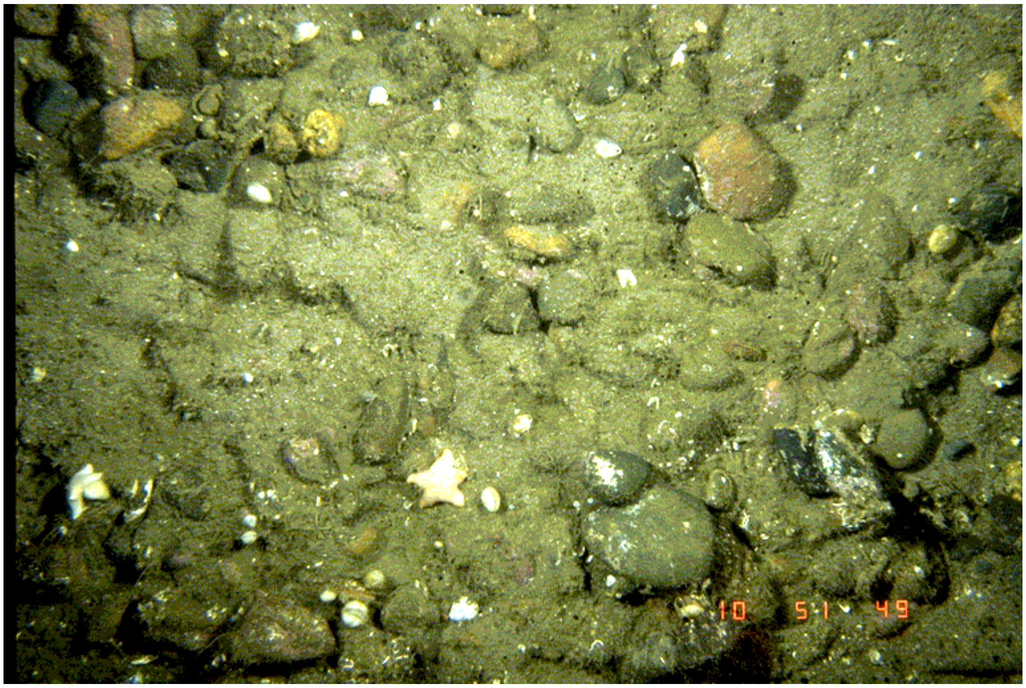


Figure 7D.



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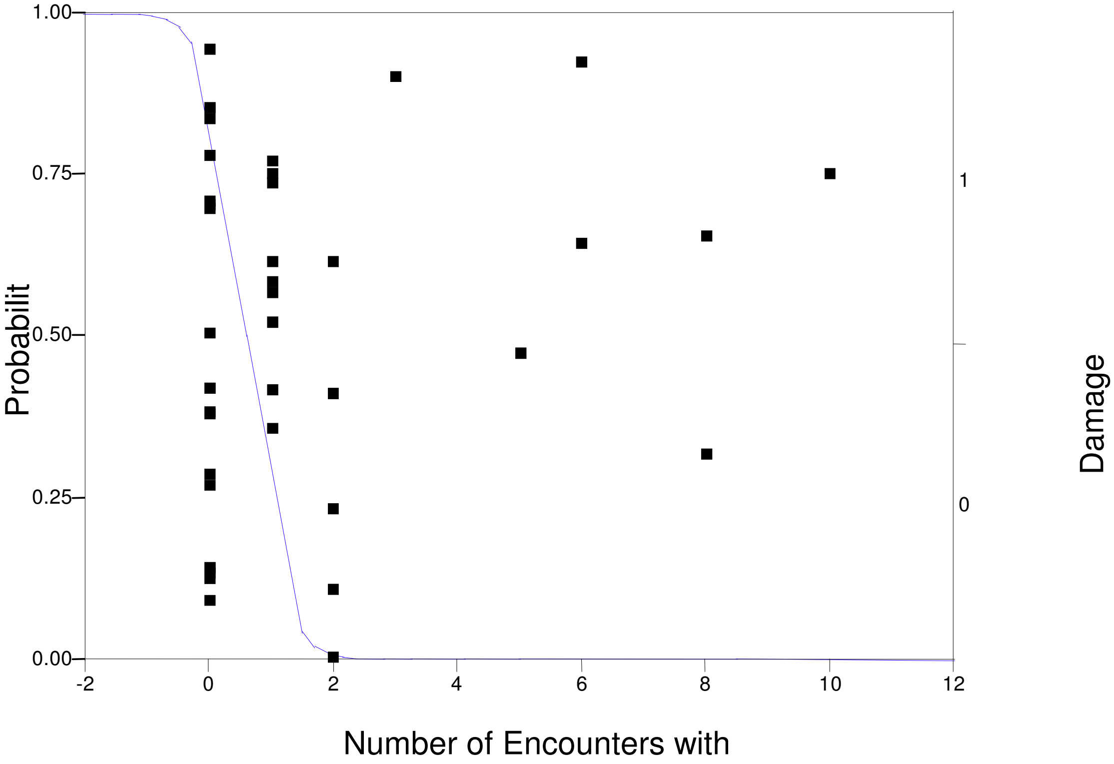

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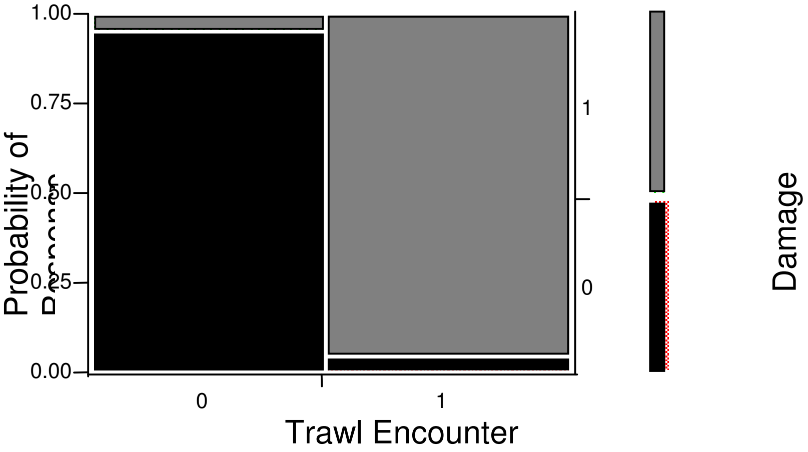

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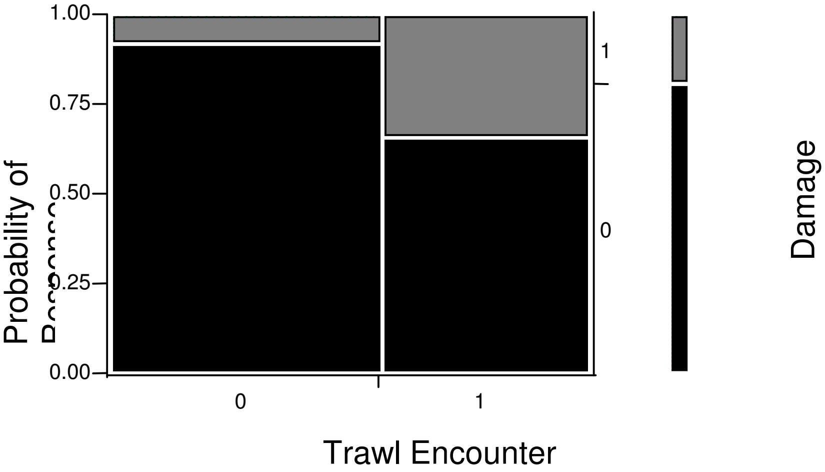

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Table 1. Date, treatment and number of stations sampled by Videograb and Campod during this three-year experiment. The same waypoints were targeted all sampling periods (Fig. 2). Some intended samples were not collected due to shortness of time before the research trawler arrived on site or closure problems with Videograb.

Date	Period	Line	Treatment	Videograb Stations	Campod Stations
28-29 September 1997	Before	B	Reference	0	3
		E	Trawled	10	10
		G	Reference	0	4
		I	Reference	0	3
30 September-1 October	Trawling				
1-2 October	After1	B	Reference	2	3
		E	Trawled	10	10
		G	Reference	3	4
		I	Reference	0	3
6 October	After2	B	Reference	0	3
		E	Trawled	0	10
		G	Reference	0	4
		I	Reference	2	3
23-24 May 1998	Before	B	Reference	0	0
		E	Trawled	9	8
		G	Reference	2	2
		I	Reference	2	1
24 May	Trawling				
24-25 May	After1	B	Reference	3	3
		E	Trawled	10	13
		G	Reference	4	4
		I	Reference	3	3
15 June	After2	B	Reference	0	3
		E	Trawled	0	10
		G	Reference	0	4
		I	Reference	0	3
13-14 May 1999	Before	B	Reference	3	3
		E	Trawled	10	10
		G	Reference	4	4
		I	Reference	3	3
2-3 June	Trawling				
4-5 June	After1	B	Reference	3	3
		E	Trawled	10	10
		G	Reference	4	4
		I	Reference	3	3

Table 2. The number of times that the seabed sampled by Videograb in the trawled corridor (Line E) after trawling had been swept by the footgear and net (20 m path) and the entire trawl (door to door including sweeps, footgear and net)(60 m path). Fourteen sets were made in 1997 and 12 sets in 1998. Calculations for 1997 were made using ship position as a proxy for trawl position while 1998 calculations used trawl position as determined by Trackpoint (except for two sets that used ship positions as a proxy). Navigation data are not available for 1999.

After1 Year	Station	Footgear and Net	Entire Trawl
1997	**E01G**	0	7
	E03G	6	10
	E06G	1	7
	E08G	4	9
	E11G	0	4
	E16G	7	12
	E18G	8	12
	E21G	6	12
	E28G	7	10
	E37G	0	1
	Mean for Line	3.9	8.4
1998	**E01G**	3	6
	E03G	1	4
	E06G	1	3
	E08G	2	5
	E11G	0	4
	E16G	1	3
	E18G	0	3
	E21G	1	2
	E28G	1	5
	E37G	0	5
	Mean for Line	1.0	4.0

Table 3. The number of times that the seabed photographed by Campod in the trawled corridor (Line E) after trawling had been swept by the footgear and net (20 m path) and the entire trawl (door to door including sweeps, footgear and net)(60 m path). An average of five photos was taken at each station. Fourteen sets made in 1997 and 12 sets in 1998. Calculations for 1997 were made using ship position as a proxy for trawl position while 1998 calculations used trawl position as determined by Trackpoint (except for two sets that used ship positions as a proxy). Navigation data are not available for 1999.

		After1		After2	
Year	Station	Footgear and Net	Entire Trawl	Footgear and Net	Entire Trawl
1997	**E01C**	6.4	9.6	0.4	7.8
	E03C	3.6	8.6	3.4	9.8
	E06C	3.6	8.0	0	4.0
	E08C	0.2	1.0	0.2	4.6
	E11C	0.2	2.8	0.8	6.0
	E16C	0	3.0	3.2	10.8
	E18C	9.6	12.0	4.4	11.6
	E21C	6.4	12.0	4.6	11.4
	E28C	2.0	8.8	2.6	9.0
	E37C	1.6	8.2	1.2	4.4
	Mean for Line	3.4	7.4	2.1	7.9
1998	**E01C**	0.8	1.8	0.8	4.8
	E02C	1.0	5.8	-	-
	E03C	0.6	3.6	1.0	5.0
	E06C	1.6	3.4	2.8	6.8
	E08C	1.4	3.0	2.4	5.6
	E09C	0	3.8	-	-
	E11C	1.0	2.2	2.0	6.4
	E16C	1.0	2.0	0.2	1.0
	E18C	1.2	2.2	1.8	5.6
	E21C	1.0	2.4	0.8	3.8
	E28C	0.4	2.4	1.0	2.6
	E33C	1.2	7.4	-	-
	E37C	0.8	3.4	3.2	6.8
	Mean for Line	0.9	3.3	1.6	4.8

Table 4. Type and frequency of disturbance at Campod stations seen in the video collected along the trawled corridor (Line E) before and after trawling each year. The number of stations in each period are given in Table 1. The area of seabed surveyed at each station was approximately 50 m^2.

Year	Period	Type of Disturbance	Frequency
1997	Before	None	0
	After1	Displaced clast	1
		Scraped clast	6
	After2	Displaced clast	2
		Scraped clast	4
		Damaged urchin	1
1998	Before	None	0
	After1	Scraped clast	4
		Damaged sponge	1
	After2	Scraped clast	1
		Damaged sponge	1
1999	Before	Dead crab	1
		Scraped clast	1
	After1	Displaced clast	3
		Scraped clast	4
		Damaged horse mussel	3
		Damaged starfish	1

Table 5. Frequency of physical disturbance (all types) to seabed habitat observed each year in the Campod photos (0.2 m^2) collected at Campod stations along both trawled and reference corridors. A total of 791 photos were taken at 154 stations (i.e. an average of 5 photos per station). Stations were classified as disturbed if one or more photos showed signs of disturbance.

		Frequency by Photo		Frequency by Station	
Year	**Period**	**Reference**	**Trawled**	**Reference**	**Trawled**
1997	Before	0	0	0	0
	After1	1	15	1	8
	After2	2	12	2	7
1998	Before	0	0	0	0
	After1	1	22	1	13
	After2	7	9	4	4
1999	Before	2	6	2	6
	After1	1	25	1	9
Sum (%)		14 (4%)	89 (22%)	11 (15%)	47 (58%)