

Photographic evaluation of the impacts of bottom fishing on benthic epifauna

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The gravel sediment habitat on the northern edge of Georges Bank (East coast of North America) is an important nursery area for juvenile fish, and the site of a productive scallop fishery. During two cruises to this area in 1994 we made photographic transects at sites of varying depths that experience varying degrees of disturbance from otter trawling and scallop dredging. Differences between sites were quantified by analyzing videos and still photographs of the sea bottom. Videos were analyzed for sediment types and organism abundance. In the still photos, the percentages of the bottom covered by bushy, plant-like organisms and colonial worm tubes (*Filograna implexa*) were determined, as was the presence/absence of encrusting bryozoa. Non-colonial organisms were also identified as specifically as possible and sediment type was quantified. Significant differences between disturbed and undisturbed areas were found for the variables measured in the still photos; colonial epifaunal species were conspicuously less abundant at disturbed sites. Results from the videos and still photos were generally consistent although less detail was visible in the videos. Emergent colonial epifauna provide a complex habitat for shrimp, polychaetes, brittle stars and small fish at undisturbed sites. Bottom fishing removes this epifauna, thereby reducing the complexity and species diversity of the benthic community.

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Key words: benthic communities, bottom fishing, Georges Bank, habitat disturbance, *in situ* photography.

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Introduction

The potential impact of bottom fishing gear on non-target species has long been recognized (e.g. Alexander *et al.*, 1914) and has become an issue of increasing concern in the 1990s (Jones, 1992; Dayton *et al.*, 1995). Large field programmes to evaluate the effects of bottom fishing have been conducted in the North Sea and Irish Sea (Lindeboom and de Groot, 1998) and off the East coast of Australia (Poiner *et al.*, 1998). Several recent review articles (Jennings and Kaiser, 1998; Watling and Norse, 1998; Auster and Langton, 1999) summarize the results of these and other gear-impact studies. Effects of bottom fishing include alterations to the physical structure of the sea floor and reduction in habitat complexity. In general, bottom fishing favours

scavenging species at the expense of large bodied and fragile taxa.

One reason for this increasing concern about gear impacts is that fishing effort has increased to the point at which it may be reducing the productivity and biodiversity of continental shelf communities (Boehlert, 1996). Bottom trawls and dredges are used pervasively on continental shelves around the world. The total area of a fishing ground disturbed by fishing gear can be estimated by multiplying the number of tows by the average width and length of each tow. Such calculations suggest that the total area trawled annually on Georges Bank between 1984 and 1990 was over three times the area of the bank itself (Auster *et al.*, 1996). Likewise, some areas of the North Sea were trawled, on average, three to five times per year (Welleman, 1989). These averages are

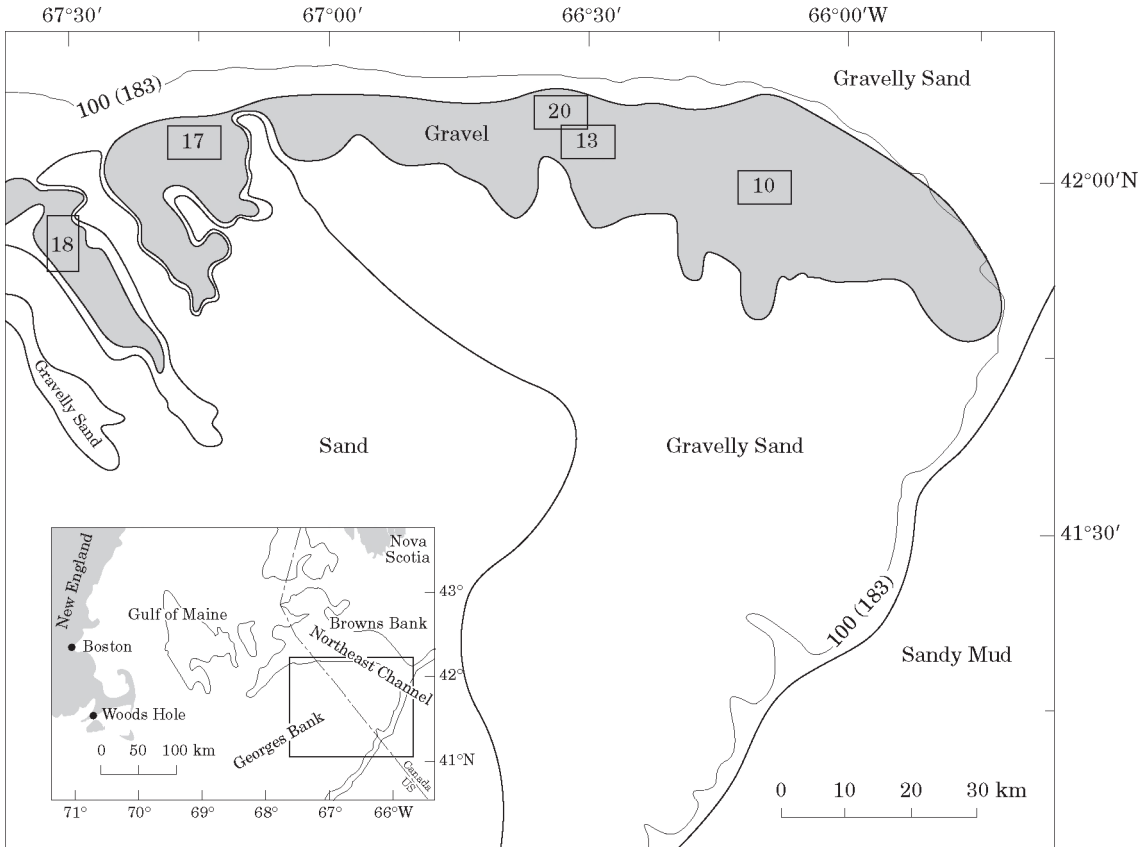


Figure 1. Map of northeastern Georges Bank showing the locations of areas surveyed and sampled. The approximate dimensions of each rectangle are 5 km \times 10 km. Depths in fathoms (m).

misleading because the distribution of fishing effort is far from uniform (Rijnsdorp *et al.*, 1998), but they are at least useful for expressing fishing effort statistics as areal equivalents.

A second reason for concern is that fishing effort has spread to deeper grounds and areas of rough sea bottom that were previously avoided by mobile gear fishermen (Watling and Norse, 1998). For example, a boulder habitat in the Gulf of Maine that supported dense colonies of sponges in 1987 was found to have been disturbed when a repeat submersible survey was made in 1993 (Auster *et al.*, 1996). “Rock-hopper” gear allows trawls to ride over rough bottom, often dragging and overturning boulders and cobbles, thereby crushing and removing attached epifauna (Freese *et al.*, 1999). As a result, refugia for species vulnerable to fishing disturbance may be disappearing.

Thirdly, there is increasing concern about the indirect effects of fishing disturbance on the ecosystem, beyond the direct removal of target organisms (Gislason, 1994). Fishing has been identified as the most pervasive threat to marine biological diversity (NRC, 1995; Boehlert, 1996). In addition to reducing fishing effort, the preser-

vation of fisheries habitat is increasingly considered important for sustaining fish production. In the USA, the Magnuson-Stevens Fishery Conservation and Management Act requires fishery management plans to “describe and identify essential fish habitat . . . and to minimize, to the extent practicable, adverse effects on such habitat caused by fishing” (USDC, 1996). This act requires an inventory of fish habitat and is motivating basic research on what aspects of habitat limit fish production. Given that most areas of the continental shelf are already fished with some sort of mobile gear, it is also important to determine which sorts of habitats are most sensitive to fishing disturbance.

Finally, the advent of underwater photography has revealed the complexity of underwater habitats to a concerned public. By necessity, early studies (Alexander *et al.*, 1914; Graham, 1955) evaluated the impacts of bottom trawling by examining damage to organisms caught by the trawl itself. Given their methodological constraints, it is not surprising that these studies minimized the impacts, or that the ocean bottom was considered to be a featureless plain. Fishery-independent sampling devices and underwater photography make

Table 1. Summary of video transects and still photographs analyzed from two cruises to northern Georges Bank. The site locations are indicated in Figure 1.

Site	Depth (m)	April 1994 No. of video transects	November 1994 No. of still photos	Disturbance level
10	Deep (85–90)	6	12	Undisturbed ¹
13	Deep (80–85)	7	12	Disturbed
17	Shallow (47–49)	4	12	Disturbed
18	Shallow (42–47)	4	12	Undisturbed ²
20	Deep (83–86)	0	18	Undisturbed

¹Light dredging disturbance was observed in November 1994.

²This site may have been previously disturbed.

possible the direct detection of impacts to benthic communities (Auster *et al.*, 1989). Photographs of the sea floor, including some of those analyzed in this study, have been widely published in newspapers and magazines.

In general, benthic habitats with three-dimensional structure (mud and gravel bottoms) tend to be more sensitive to fishing disturbance than communities with mobile sandy sediments and little emergent structure (Anon., 1996; Jennings and Kaiser, 1998). In mud habitats, animal burrows create three-dimensional habitat complexity that can be destroyed by bottom fishing (Watling and Norse, 1998). Stable sand environments often support emergent colonial epifauna such as sponges and bryozoans. When this epifauna is removed by repeated bottom fishing, the habitat may become less suitable for commercially valuable fish and shellfish species (Bradstock and Gordon, 1983; Poiner and Kennedy, 1984; Sainsbury, 1988). Gravel habitats with a high diversity of encrusting species are particularly sensitive to scallop dredging, which removes the attached epifauna, thereby reducing habitat complexity and species diversity (Dayton *et al.*, 1995). Numerous trawl-impact studies have been completed on continental shelves around the world (reviewed by Watling and Norse, 1998; Auster and Langton, 1999). However most of these studies measured the short-term impacts of an experimental fishing disturbance and most occurred in shallow depths on unconsolidated sediments (Collie *et al.*, 2000). Our study differs in that we measured the longer-term impacts of disturbance on a gravel pavement habitat ranging in depth between 45 and 90 m.

Georges Bank is a shallow, elongate extension of the North American continental shelf east of New England (Fig. 1). It has historically been a highly productive fishing ground for haddock, cod, flounder, and scallops (Fogarty and Murawski, 1998). Both otter trawls and scallop dredges are used on Georges Bank; we refer to them collectively as bottom fishing or dredging. The main factors regulating the distribution of megabenthic (>10 mm) organisms on Georges Bank were found by

Thouzeau *et al.* (1991) to be sediment type, tidal current speed, turbulent mixing and food availability. They found the richest benthic communities on gravel substrates with a biogenic cover of attached epifauna. The gravel pavement habitat that covers approximately 3000 km² of northern Georges Bank is an important habitat for scallops, it is a herring spawning ground, and it is a nursery area for juvenile cod and haddock (Lough *et al.*, 1989). Submersible studies of the gravel habitat documented the presence of colonial worm tubes, bushy hydroids and bryozoans encrusting the gravel particles (Valentine and Lough, 1991). These attached epifauna provide food and shelter for many animals, including the prey of demersal fish. Upright, attached organisms are quite fragile and are often destroyed by bottom fishing gear, leaving a uniformly smooth gravel surface. Survival of juvenile Atlantic cod in St Margaret's Bay, Nova Scotia, was found to be higher in structurally complex habitats, apparently because of increased shelter availability and decreased predator efficiency (Tupper and Boutilier, 1995). Disturbance of the benthic epifauna may therefore increase the predation risk for juvenile fish.

In 1994 we conducted two cruises to northern Georges Bank to sample disturbed and undisturbed sites on the gravel habitat. The degree of bottom disturbance was determined with side-scan sonar. Samples of the benthic megafauna were collected with a 1 m wide Naturalists' dredge. Analyses of the megabenthic animals collected with the Naturalists' dredge indicated that the disturbed sites had lower density of organisms, biomass and species diversity than the undisturbed sites (Collie *et al.*, 1997). Many of the species that were absent or less common at the dredged sites are small, fragile polychaetes, shrimps and brittle stars.

The most apparent difference between the sites was the lack of colonial, epifaunal taxa at the disturbed sites. These taxa are not quantitatively sampled by the Naturalists' dredge but they can be enumerated with *in situ* photography. In April 1994 photographic surveys were made with a video-equipped grab sampler. On the

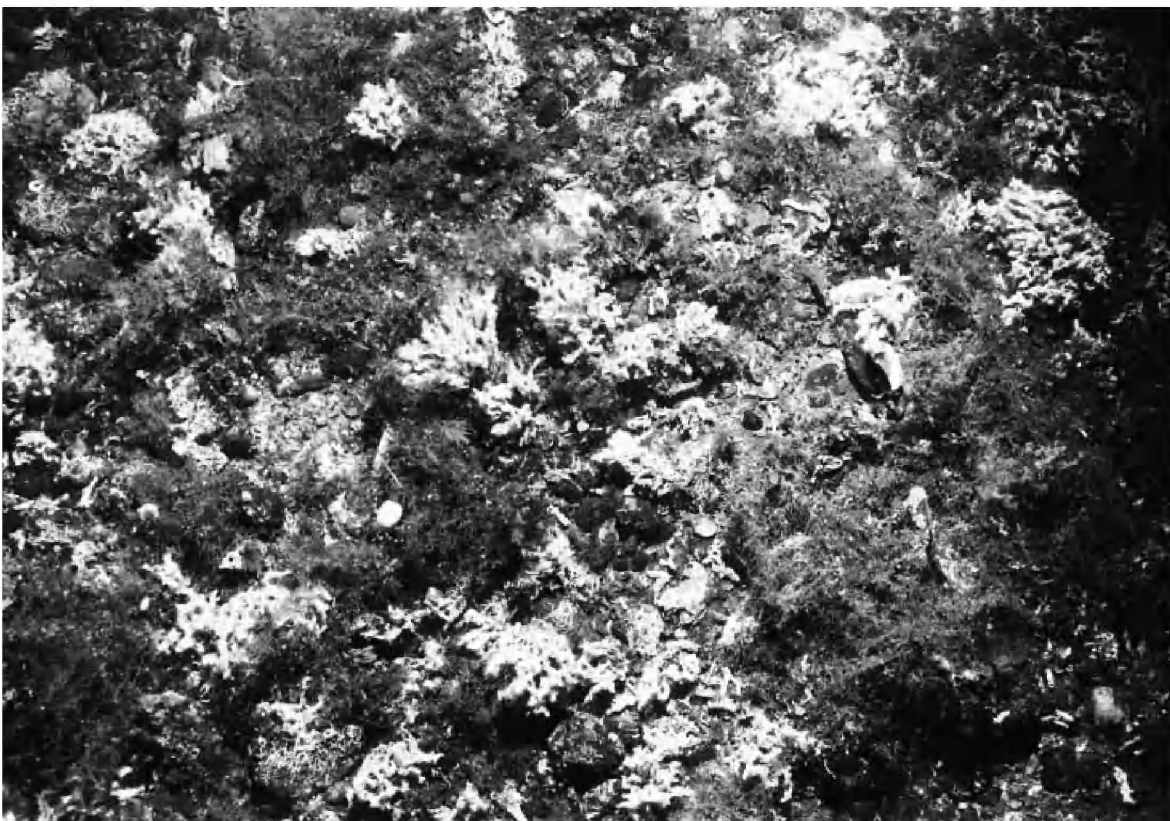
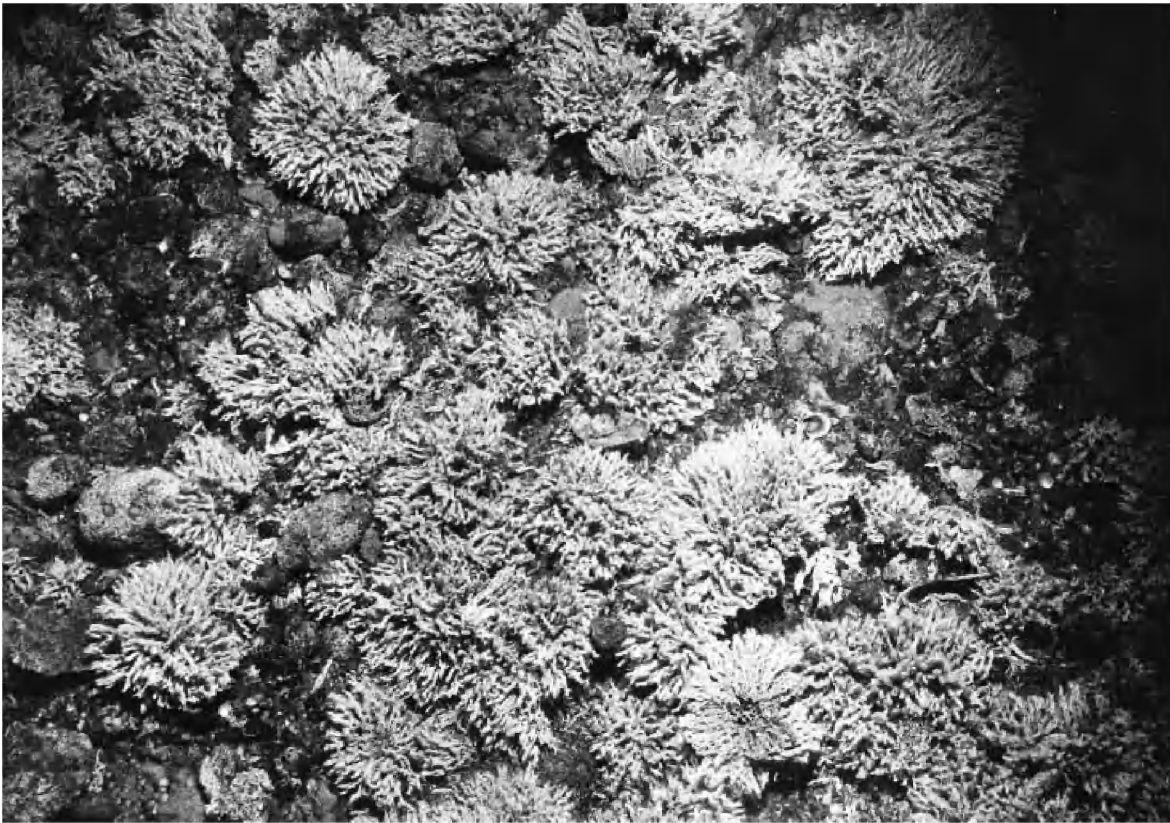




Figure 2. Photographs of the gravel habitat on northern Georges Bank taken in November 1994. The approximate dimensions of each photograph are 75 cm \times 50 cm and the gravel particles range up to 5 cm. (a) Site 10 (undisturbed) was characterized by a high percent cover of *Filograna implexa*. (b) In addition to *F. implexa*, site 20 (undisturbed) had a high percentage cover of hydrooids. (c) Site 13 (disturbed) is next to site 20 but had very little attached epifauna. Some bivalves (*Astarte* spp.) are visible. (d) The shallow, disturbed site 17 was dominated by burrowing anemones. Photographs by Dann Blackwood, USGS.

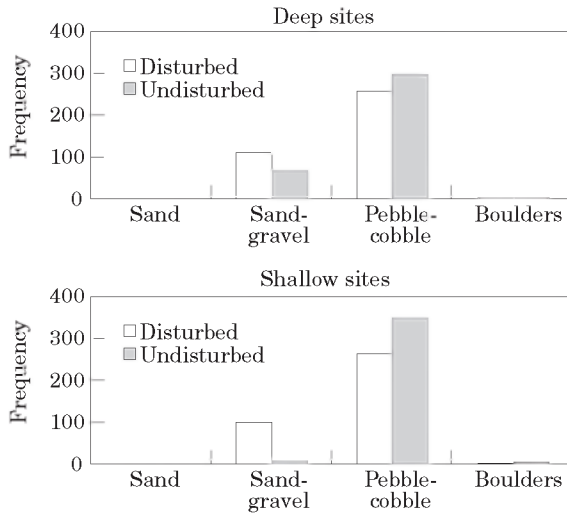


Figure 3. Frequency distributions of sediment categories observed in underwater videos taken on northern Georges Bank in April 1994. The sediment categories are defined in the Materials and Methods.

second cruise, in November 1994, a still camera was also mounted on the grab sampler. Selected photographs from our study sites have been published widely in newspapers and magazines to illustrate the impacts of bottom fishing. This paper represents the first quantitative analysis of the benthic epifauna seen in these photo transects. The results complement the analyses of the dredge samples collected on the same cruises (Collie *et al.*, 1997). A secondary objective was to compare the usefulness of videos and still photographs in detecting impacts due to bottom fishing.

Materials and methods

This study is based on two research cruises to northern Georges Bank, the first aboard the R/V "Albatross IV" in April 1994 and the second on R/V "Delaware II" in November 1994. Five study sites with approximate dimensions of 5 km \times 10 km were surveyed with side-scan sonar (Fig. 1). Scallop dredging leaves tracks that are visible in the sonagrams. The degree of disturbance was assessed from the presence or absence of dredge tracks at each site (see Collie *et al.*, 1997 for more details). The sites varied in depth, clustering around 40 m and 80 m. At each depth level we chose sites with contrasting levels of disturbance. To make the data amenable to statistical testing, the sites were categorized as deep or shallow, disturbed or undisturbed (Table 1).

Within each site, stations were chosen for 15 min video transects of the sea floor. A video camera and lights were attached to a grab sampler frame which was suspended approximately 65 cm above the sea floor. The

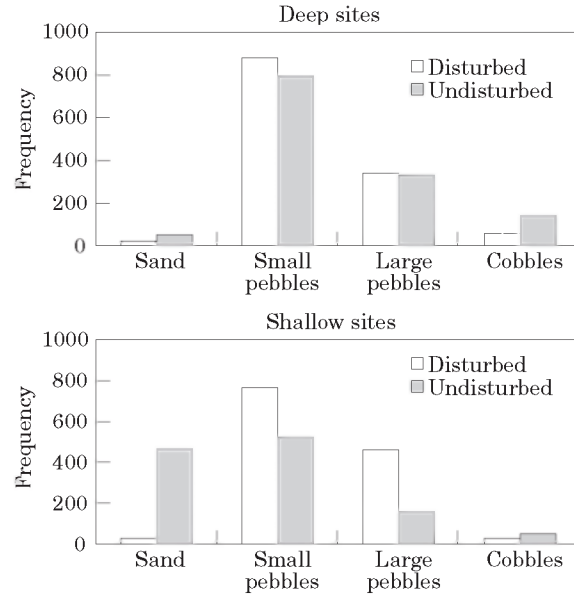


Figure 4. Frequency distributions of sediment categories observed in still photographs taken on northern Georges Bank in November 1994. The sediment categories are defined in the Materials and Methods.

direction of the transect depended on tidal drift and the average distance covered was 620 m. The video images were recorded on Hi-8 video tapes. In November 1994, a 35-mm still camera was also mounted on the grab frame, so that a still photograph could be taken along the video transects approximately every minute. A scale bar, visible in the video, was suspended from the camera frame to ensure that still photographs were taken at a uniform height off the bottom. For the purposes of analyzing the photographs, a grid with 5-cm squares was photographed at the same working distance as the bottom photographs.

Videos were analyzed for sediment types and organism abundance on a Hi-8 video cassette player. At 10 s intervals, the video was frozen and each frame was analyzed for sediment type and cover. With a mean tidal drift of 50 cm s^{-1} , there was no overlap of the selected video frames. Sediment type was divided into four categories based on the percentage of the video frame covered by each type of sediment: 1, sand (60–100% coarse sand and 0–40% gravel); 2, sand-gravel (40–60% coarse sand and 40–60% gravel); 3, pebble-cobble (60–100% gravel and 0–40% coarse sand); 4, presence of boulders. Frequency distributions of sediment type per treatment were plotted to compare habitat types. The dependence of sediment type on depth and disturbance level was tested with the likelihood ratio test of fitted log-linear models (Sokal and Rohlf, 1981).

The presence or absence of attached epifauna (sessile, colonial animals) was also recorded for each frame. The

Table 2. Maximum likelihood analysis of variance tables for frequencies of sediment types at study sites on Georges Bank.

Source	DF	χ^2	Probability
A. Saturated log-linear model of sediment type frequencies from underwater videos.			
Depth	1	3.94	0.047
Disturbance	1	13.06	0.000
Depth \times disturbance	1	1.02	0.313
Sediment	3	517.83	0.000
Depth \times sediment	2*	36.69	0.000
Disturbance \times sediment	2*	66.65	0.000
Depth \times disturbance \times sediment	2*	27.63	0.000
B. Saturated log-linear model of sediment type frequencies from still photographs, standardized to 12 photos.			
Depth	1	1.97	0.160
Disturbance	1	64.04	0.000
Depth \times disturbance	1	1.66	0.198
Sediment	3	2361.81	0.000
Depth \times sediment	3	123.37	0.000
Disturbance \times sediment	3	227.88	0.000
Depth \times disturbance \times sediment	3	85.08	0.000

*Contained one or more singularities (i.e., redundant parameters).

percentage of frames with presence of epifauna was calculated and, after arcsine of square root transformation, tested by two-way ANOVA with depth and disturbance level as factors. Megafaunal animals were identified to the lowest taxonomic level possible and counted whenever they were observed. Frequencies of megafaunal animals were standardized to a common transect distance of 3.7 km to facilitate comparisons between sites. Shannon–Wiener diversity (H') was calculated from the \log_2 abundance of taxa. The evenness diversity index was computed as $2^{H'}/S$, where S is the number of different taxa in the sample (Buzas and Gibson, 1969). Numerical abundance, species diversity, and evenness were tested with two-way ANOVA for significant differences associated with depth and disturbance level. The frequency distributions of megafaunal taxa were tested for independence between sites with log-linear models.

Approximately 700 still photographs of the sea bed were taken in November 1994. Because analyzing all 700 photos was impractical, 16 stations of greatest interest were chosen that had predominantly gravel sediments and corresponded with dredge samples taken on the same cruises. Some three to six photographs were chosen at random from each station to give roughly the same total number of photos from each site. The photo of the grid was transferred to a transparency, which was used to divide the photos into 108 cells. The total area analyzed in each photograph was therefore approximately 0.27 m². In each cell, the percentages covered by bushy, plant-like organisms and worm tubes (*Filograna implexa*) were determined, as was presence/absence of low-encrusting bryozoans. Free-living and other non-

colonial organisms were identified to the lowest taxonomic level possible. The dominant type of sediment in each cell was classified into five categories: (1) sand; (2) small pebbles (<2.5 cm); (3) large pebbles (2.5–5 cm); (4) cobbles (>5 cm); and (O) obscured by bushy organisms, shadow, etc. The abundant bivalve, *Anomia* spp., and the worms *Protula tubularia* and *Spirorbis* sp. were counted separately.

Voucher specimens of attached epifauna were examined and identified as specifically as possible, but analysis beyond the family or genus level was seldom possible. Analyzing the voucher specimens aided somewhat in identifying organisms in the photographs. However, as hydroids and bryozoan species often cannot be distinguished without a microscope, exact identification in the photos was impossible. Hereafter, we refer to bushy hydroids and bryozoans collectively as plant-like animals.

Preliminary analysis suggested that the sampling unit should be one photo rather than one cell because of the wide variability and lack of independence between cells. Therefore, the proportion of cells per photo containing bryozoans was calculated as were the means of percent cover of *F. implexa* and plant-like animals. These proportions were arcsine of square root transformed prior to analysis of variance. The numbers of *Anomia* spp., *Protula tubularia*, and *Spirorbis* sp. per photo were square-root transformed for ANOVA. One-way ANOVA was used between stations and between sites, while two-way ANOVA was used between groups with depth and disturbance as causal factors.

Sediment types and non-colonial taxa were classified as frequency distributions and arranged as three-way

contingency tables. The log-linear model of a three-way contingency table is:

$$\ln f_{ijk} = \mu + \alpha_i + \beta_j + \gamma_k + \alpha\beta_{ij} + \alpha\gamma_{ik} + \beta\gamma_{jk} + \alpha\beta\gamma_{ijk}, \quad (1)$$

where μ is the mean of the logarithms of the expected frequencies α_i , β_j , and γ_k are the effects of categories i , j , and k of factors A, B, and C, respectively, and the interaction terms express the dependence of factors A, B, and C on each other (Sokal & Rohlf, 1981). In our case, factors A, B, and C are depth, disturbance level, and the variable being tested. We were primarily interested in the $\beta\gamma_{jk}$ term which is the interaction between dredging and the response variables (sediment type or species). TWINSPLAN (Hill, 1979) was used to order the taxa seen in videos and photographs according to their occurrence by depth and disturbance level.

Results

Differences between the sites were readily apparent in the bottom photographs (Fig. 2). Deep undisturbed site 10 was characterized by a high percent cover of the colonial worm *Filograna implexa*. In addition to *F. implexa*, deep undisturbed Site 20 also had a dense cover of colonial hydroids and bryozoans. In contrast, at the disturbed sites the gravel was free of epifaunal cover and few animals were visible. Animals visible at deep, disturbed Site 13 include hard-shelled mollusks (*Astarte* spp.) and the sunstar, *Crossaster papposus*. Shallow disturbed Site 17 was dominated by burrowing anemones. The following statistical analyses are aimed at quantifying these visual differences.

Sediment types

Our study sites are located on a lag gravel deposit which is partly bounded by mobile sand. In the videotapes, this was indicated by the predominance of the pebble-cobble category (Fig. 3). The second most frequent category, sand-gravel, may reflect the occurrence of sand patches on the gravel pavement. Patches of pure sand or boulders were rarely seen in the video tapes. The distribution of sediment types was similar at deep and shallow sites. The undisturbed sites had slightly coarser sediments, with higher frequencies of pebble-cobble and correspondingly less sand-gravel.

A different sediment classification scheme was used for the still photographs, but the results were generally consistent with the videos. A total of 12 still photos were analyzed for each combination of depth and disturbance level (treatment) except at the deep undredged sites (sites 10 and 20), from which a total of 30 photos was analyzed. To simplify interpretation of histograms and to balance the log-linear models, the frequencies from

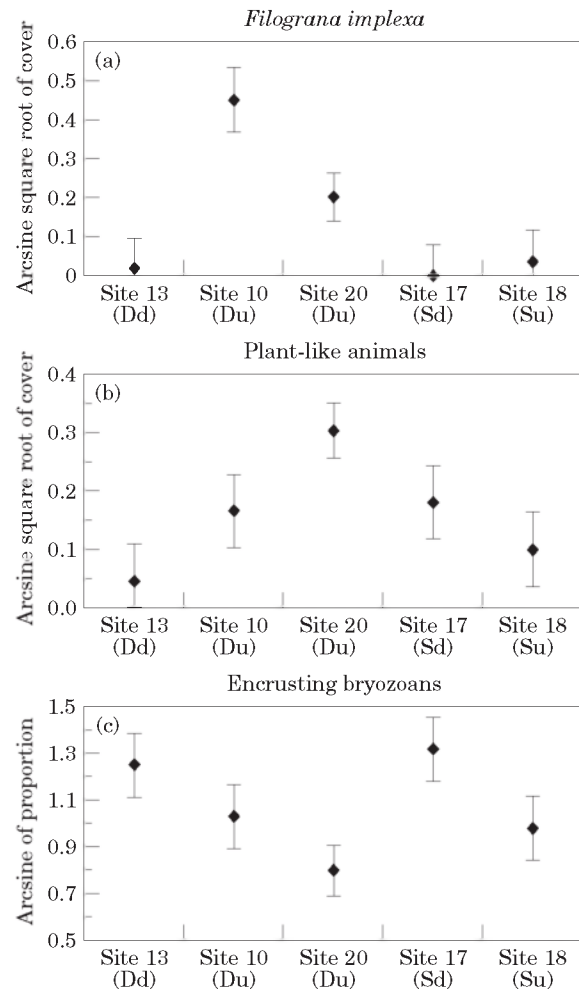


Figure 5. Percentage cover of colonial epifauna measured from still photographs taken at five sites on northern Georges Bank in November 1994. The symbols indicate the means and 95% confidence intervals at each site. The site identifiers are: D, deep; S, shallow; d, disturbed; u, undisturbed.

the deep undisturbed sites were multiplied by (12/30) to standardize them to the 12 photos. The dominant sediment type was small pebbles, followed by large pebbles (Fig. 4). Higher frequencies of sand were seen in the still photographs because it was more common to see pure sand in a 5 cm \times 5 cm still photo grid than in an entire video frame. The undisturbed sites had higher frequencies of sand and cobbles than the disturbed sites, which had more uniform gravel bottoms. Shallow undisturbed site 18 had an anomalously high frequency of sand because it is located on a patch of gravel pavement between two sand ridges.

In the log-linear models all the terms that include sediment-type frequencies were significant for both the video and still photo data (Table 2). In contrast to

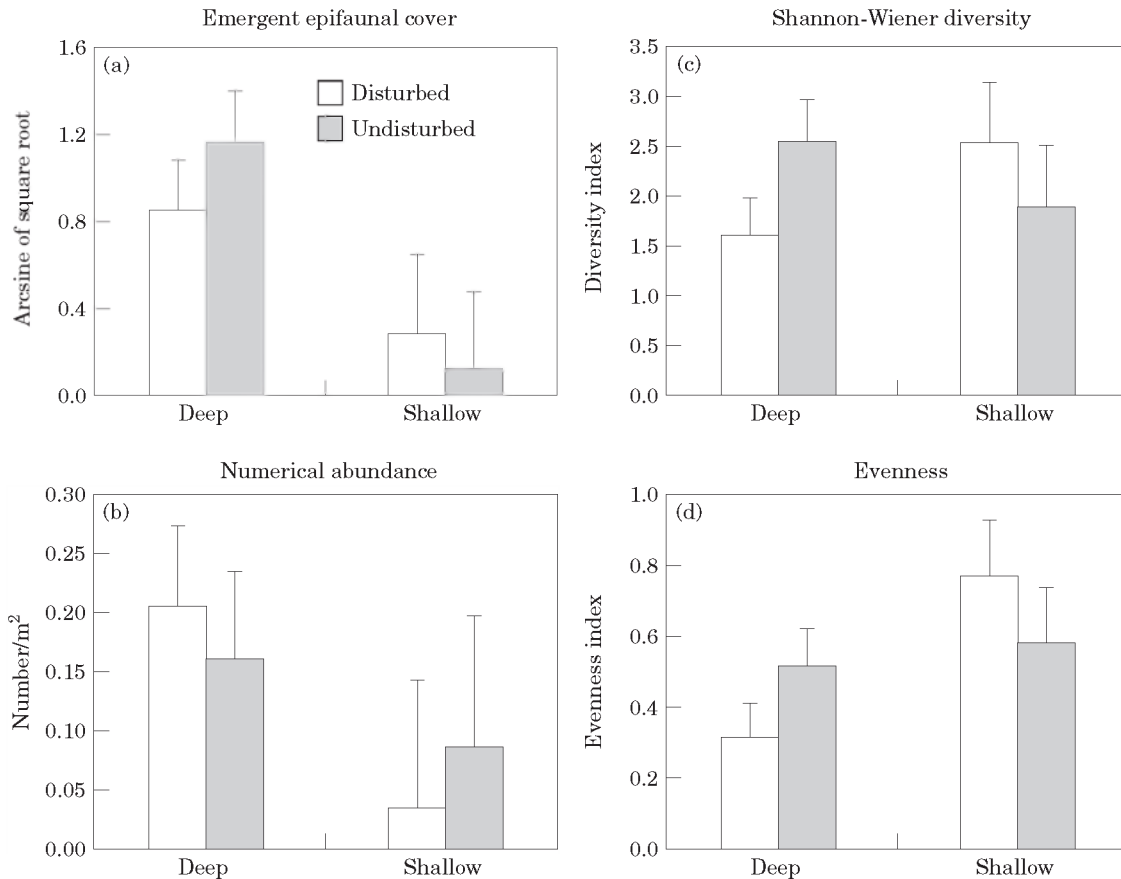


Figure 6. Epifaunal cover and ecological indices measured from underwater videos taken on northern Georges Bank in April 1994. The bars indicate means and the vertical lines are 95% confidence intervals.

ANOVA, with log-linear models we are primarily interested in testing for interaction effects (Sokal and Rohlf, 1981). The disturbance \times sediment interactions had higher chi-squared values than the depth \times sediment interactions, indicating that disturbance level was the more important factor. The statistical significance of the log-linear models should not be over-interpreted due to the high frequencies involved (total of 1464 for the videos and 5183 observations for the still photos). All the study sites had predominantly pebble-gravel bottoms.

Epifaunal cover and ecological indices

In the still photographs, the percent cover of the colonial polychaete, *Filograna implexa*, was statistically greater at depth ($p=0.0015$) and also at the undisturbed sites ($p=0.0002$). However, there was a significant depth \times disturbance interaction because the difference due to dredging was greater at the deep sites than at the shallow sites (Fig. 5a). The percentage cover of plant-like animals was also statistically greater at the deep

undisturbed sites (Fig. 5b). However, in this case, the effect of dredging was actually reversed at the shallow sites, with disturbed site 17 having a higher percent cover than undisturbed site 18. The proportion of photo grid cells with low, encrusting bryozoans was statistically higher in the disturbed sites ($p=0.0001$) and there was no significant difference with depth ($p=0.15$, Fig. 5c). This result for low encrusting bryozoans is in contrast to the emergent epifauna which generally had higher percent cover at the undisturbed sites.

The percent cover of emergent epifauna estimated from the videos was statistically higher at the deep sites (Fig. 6a). At the deep sites, the percent cover was higher at the undisturbed sites, but the reverse was true at the shallow sites, which resulted in a significant depth \times disturbance interaction and an insignificant disturbance effect in the ANOVA (not shown). These data are generally consistent with the still photos, in that both indicate a significantly greater epifaunal cover at the deep sites (Figs 5 and 6). Disturbance reduced epifaunal cover at the deep sites but results at the shallow sites were mixed. There was greater cover of

Table 3. A. Frequencies of taxa seen in underwater videos taken on northern Georges Bank in April 1994.

Taxon	Frequency			
	Disturbed	Deep		Shallow
		Undisturbed	Disturbed	Undisturbed
Anemone	4	107	—	—
Tube worm (<i>Filograna implexa</i>)	1	20	—	—
Flounder	12	1	—	—
Bloodstar (<i>Henricia</i> spp.)	1	1	—	—
Sunstar (<i>Crossaster papposus</i>)	45	62	2	—
Sculpin (<i>Myoxocephalus</i> spp.)	7	14	1	2
Ocean pout (<i>M. americanus</i>)	12	7	7	—
Sponge	—	18	—	3
Plant-like animals	14	20	4	22
Scallop (<i>P. magellanicus</i>)	469	92	25	2
Fish (unidentified)	4	8	1	10
Hermit crab (<i>Pagurus</i> spp.)	9	14	25	12
Seastar (<i>Asterias vulgaris</i>)	93	194	23	124
Waved whelk (<i>B. undatum</i>)	3	20	21	17
Crab (<i>Cancer irroratus</i>)	—	—	2	2
Skate	3	4	11	5
Total	160	175	116	105

Filograna implexa at shallow undisturbed site 18, but apparently more plant-like animals at shallow disturbed site 17.

The numerical abundance of benthic megafauna seen in the videos was statistically greater at the deep sites (Fig. 6b) and there were no consistent differences with disturbance level. There were no significant differences in species diversity between sites as measured in the videos (Fig. 6c). Evenness was statistically higher at the shallow sites (Fig. 6d) and again there was no consistent pattern with disturbance level. The difference in evenness means that there were some numerically dominant species at the deep sites and that the lower number of individuals at the shallow sites were more evenly distributed among the taxa in these areas.

Frequencies of individual taxa

The most numerous taxa visible in the videos were anemones, sea scallops and seastars (Table 3A). The interpretation of the log-linear model of individual taxa is complicated by singularities in the model design resulting from zero frequencies in some cells. According to the log-linear model, both depth and disturbance had significant interactions with the species composition. TWINSpan was used to order the taxa into four groups according to their occurrences by depth and disturbance level (Table 3A). The first group of five taxa was seen almost exclusively at the deep sites. Anemones, sunstars and the tubeworm (*Filograna implexa*) were more abundant at the undisturbed sites, whereas floun-

ders were more numerous at the disturbed site (site 13). Group two comprises taxa that occurred at both depths but were more abundant at the deep sites. Within this group, sculpins, sponges and plant-like animals were more abundant at the undisturbed sites; ocean pout and scallops were more numerous at the disturbed sites. The third group contained four taxa that were abundant at both depths. In group three, unidentified fish, and seastars were more abundant at the undisturbed sites, whereas hermit crabs and the waved whelk (*Buccinum undatum*) had no pattern with respect to disturbance level. Group four contained two taxa (*Cancer* crabs and skates) that were more abundant at the shallow sites and were not affected by disturbance level. The inconsistent responses to disturbance shown by crabs, whelks and

Table 3. B. Maximum likelihood analysis of variance table for the saturated log-linear model of frequencies of taxa seen in underwater videos (standardized to a 3.7 km transect).

Source	DF	χ^2	Probability
Depth	1	18.00	0.000
Disturbance	1	0.18	0.668
Depth × disturbance	1	1.32	0.250
Species	15	605.60	0.000
Depth × species	10*	121.29	0.000
Disturbance × species	14*	116.66	0.000
Depth × disturbance × species	7*	33.81	0.000

*Contained 1 or more singularities (i.e., redundant parameters).

Table 4. A. Frequencies of non-colonial taxa seen in underwater photos taken on northern Georges Bank in November 1994.

Taxon	Frequency of individuals standardized to 12 photos per treatment			
	Deep disturbed	Deep undisturbed	Shallow disturbed	Shallow undisturbed
Brittle star (<i>Ophiopholis aculeata</i>)	—	1	—	—
Horse mussel (<i>Modiolus modiolus</i>)	—	15	—	2
Surf clam (<i>Spisula solidissima</i>)	—	2	—	11
Anemone	4	17	—	7
Barnacle (<i>Balanus</i> spp.)	4	28	—	15
Northern cardita (<i>V. borealis</i>)	1	2	—	6
Worm (unidentified)	1	4	—	5
<i>Astarte</i> spp.	7	10	—	17
Waved whelk (<i>Buccinum undatum</i>)	1	1	—	1
Sponge	15	20	—	13
Whelk (unidentified)	9	9	—	6
Nudibranch (<i>Coryphella</i> sp.)	2	3	1	3
Shrimp	4	32	6	12
Crab (<i>Cancer</i> sp.)	—	1	1	—
Smooth velutina (<i>V. velutina</i>)	4	1	—	1
Fish (unidentified)	1	1	—	—
Hermit crab (<i>Pagurus</i> spp.)	16	5	2	3
Sea star (<i>Asterias vulgaris</i>)	2	4	2	2
Sunstar (<i>Crossaster papposus</i>)	1	—	—	1
Toad crab (<i>Hyas</i> spp.)	1	1	—	—
Scallop (<i>Placopecten magellanicus</i>)	1	1	1	—
Tube worm (<i>Thelephus cincinnatus</i>)	45	8	—	—
Tube worm (unidentified)	10	5	1	—
Burrowing anemone	27	4	102	—
Green sea urchin (<i>S. droebachiensis</i>)	4	—	—	—
Total abundance per treatment	160	175	116	105

skates explain the significant three-way interaction in the log-linear model (Table 3B). At the shallow sites, colonies of plant-like animals were seen more frequently at the undisturbed site (site 18) than at the disturbed site (site 17). This is in contrast to Figure 6 where the percent cover of epifauna was greater at site 17 than 18. This apparent inconsistency can be explained by the fact that the frequencies in Table 3 were observed in the entire videotape, while the percent cover was estimated from a subset of video frames.

More organisms could be identified in the still photographs than in the videos, and many could be identified to a lower taxonomic level (Table 4A). A greater number of individuals were observed at the deep sites than at the shallow ones. According to the log-linear model (Table 4B), the species composition depended on both depth and disturbance level ($p < 0.001$). The three-way interaction was insignificant, which indicates that the effect of disturbance on species composition was the same at both depths. Two main groups of taxa were identified with TWINSpan (Table 4A). The first group contains taxa that were more abundant at the undisturbed sites and were virtually absent from the shallow, disturbed site (site 17). These include fragile taxa such as anemones,

worms (unidentified), sponges, nudibranchs and shrimp. Two burrowing mollusk species (*Modiolus modiolus* and *Spisula solidissima*) were seen exclusively at the undisturbed sites. Group two contained taxa that were more abundant at the deep sites. Of these, the smooth velutina, hermit crabs, tube worms, burrowing anemones, and sea urchins were more abundant at the deep, disturbed site (site 13). The remaining taxa did not have a pattern with respect to disturbance level.

Table 4. B. Maximum likelihood analysis of variance table for the log-linear model of frequencies of taxa from underwater photos, standardized to 12 photos per treatment.

Source	DF	χ^2	Probability
Depth	1	0.22	0.636
Disturbance	1	1.41	0.236
Depth × disturbance	1	3.55	0.060
Species	24	161.55	0.000
Depth × species	19*	55.35	0.000
Disturbance × species	19*	77.12	0.000
Depth × disturbance × species	3*	5.69	0.128

Table 5. Summary of two-way ANOVAs of abundant taxa seen in underwater photos taken on northern Georges Bank in November 1994.

Source	Least-squares mean	F statistic	Probability
A. Square root of abundance of encrusting bivalves, <i>Anomia</i> spp.			
Depth		1.54	0.219
Deep	4.121		
Shallow	3.081		
Disturbance level		0.09	0.770
Disturbed	3.724		
Undisturbed	3.478		
Depth × disturbance		3.78	0.056
B. Square root of abundance of the tubeworm, <i>Protula tubularia</i>			
Depth		7.15	0.0096
Deep	1.343		
Shallow	0.243		
Disturbance level		10.55	0.0019
Disturbed	0.125		
Undisturbed	1.461		
Depth × disturbance		6.11	0.0162
C. Square root of abundance of the tubeworm, <i>Spirorbis</i> sp.			
Depth		1.54	0.2197
Deep	10.274		
Shallow	9.190		
Disturbance level		16.80	0.0001
Disturbed	11.524		
Undisturbed	7.940		
Depth × disturbance		4.21	0.0445

Data for three of the most numerous taxa in the still photographs were analyzed separately with two-way ANOVA (Table 5). The encrusting bivalves, *Anomia* spp., were more abundant at the deep sites (Fig. 7), but none of the differences were significant. The tube worm, *Protula tubularia*, was much more abundant at the deep undisturbed sites than at any of the other sites. This marked difference in abundance accounts for the significance of all the terms in the ANOVA (Table 5). The tubeworm, *Spirorbis* sp., was statistically more

abundant at the disturbed sites. This difference was greater at the shallow site, which accounts for the significant depth × dredge interaction in the ANOVA (Table 5).

Discussion

This study demonstrated the usefulness of photography of the sea floor for surveying fish habitat. An earlier report of this work was based on only three photographs per transect. Concerned whether this small sample size might bias our results, we doubled the sample size to six per transect. The present results are qualitatively unchanged from the earlier report, which justifies our approach of randomly selecting a subset of photographs from each transect. Much more detail was visible in the still photographs than in the corresponding videotapes, especially smaller taxa, such as barnacles, nudibranchs and shrimps. Even so, small animals remain hidden in the bushy epifauna. Brittle stars and toad crabs were very numerous in dredge samples collected at sites 10 and 20 (Collie *et al.*, 1997); the fact that we saw only one brittle star and two toad crabs in the photographs (Table 4A) demonstrates the effectiveness of their cryptic coloration. Photography is therefore not a complete substitute for obtaining physical samples of the fauna.

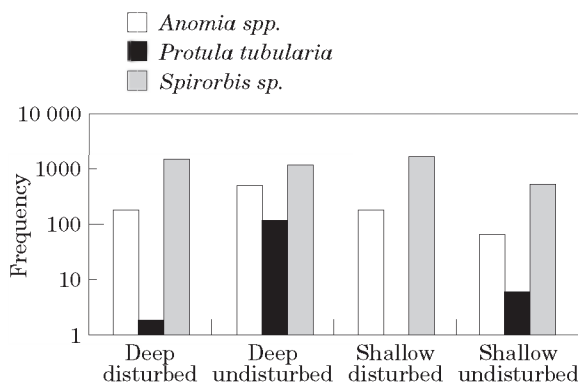


Figure 7. Frequencies of the three most abundant non-colonial animals observed in still photographs taken on northern Georges Bank in November 1994. (These taxa are visible on the gravel particles in Fig. 2c and d.)

The advantages of video were that, by analyzing the entire transect, we were able to enumerate larger, mobile taxa such as flounders and skates (Table 3). Videos are useful for obtaining real-time images of the sea floor, and higher resolution could be obtained with more expensive equipment. Results from the still photos and videos were generally consistent, even though different methods were used to analyze them. The video data were inconsistent between depths (Fig. 6) and therefore did not permit strong tests of the disturbance impact. Langton and Robinson (1990) also found that 35 mm photographs were the most useful for qualitative analysis, although interpretation of the data was greatly enhanced by referring to videotapes and by direct observations from a submersible.

Our results are consistent with the hypothesis that gravel habitats are very sensitive to physical disturbance by bottom fishing and that the primary impact is the removal of emergent, epifaunal taxa (Anon., 1996). The undisturbed sites had significantly higher percent cover of *Filograna implexa* and plant-like animals (Fig. 5). These colonial animals provide a complex, three-dimensional habitat for numerous small, fragile taxa such as shrimps, polychaetes, and brittle stars (Collie *et al.*, 1997). However, other factors in addition to dredging affected the distributions of emergent epifauna. Significant differences in epifaunal cover, numerical abundance and evenness were observed between shallow and deep sites (Fig. 6). The percentage cover of *F. implexa* and plant-like animals was much higher at deep, undisturbed sites 10 and 20 than at the shallow, undisturbed site 18. *Filograna implexa* was more abundant at site 10 and plant-like animals were more abundant at site 20, even though both sites were at the same depth and were apparently undisturbed (Fig. 2a and b). At shallow undisturbed site 18, *F. implexa* tended to grow in the cavities of dead horse mussel (*Modiolus modiolus*) shells rather than on the surface of pebbles as it did at site 10. Colonization by *F. implexa* may be constrained by the tidal currents which are strongest at the shallow sites on the northern edges of Georges Bank (sites 17 and 18) and somewhat lower at the sites on the northeast peak (site 10) (Butman, 1987).

Most of the non-colonial taxa that were observed seemed to be negatively affected by dredging, while some seemed to profit from bottom fishing disturbance. Non-burrowing anemones, shrimps, sponges, nudibranchs, small fish and some tube-worms (e.g. *Protula tubularia*, Fig. 7) were all less frequent at the disturbed sites. These fragile organisms are likely to be destroyed by bottom fishing gear. Burrowing anemones were much more prevalent at disturbed sites than undisturbed sites. We hypothesize that burrowing anemones are not affected by disturbance because their tentacles are easily retracted to safety beneath the surface.

Encrusting bryozoans (Fig. 5) and the small tube worm, *Spirorbis* sp. (Fig. 7), were also consistently more abundant at the disturbed sites. One explanation is that these animals are simply hidden from view by bushy epifauna at the undisturbed sites. However, we controlled for this possibility by removing these obscured cells from the encrusting bryozoans and *Spirorbis* ANOVAs. An alternative explanation is that these taxa are resistant to disturbance and that their abundance is enhanced at disturbed sites by decreased competition for space with the more fragile epifauna. The distributions of non-colonial animals were consistent with our analyses of the dredge samples collected at the same stations (Collie *et al.*, 1997). In both studies, the undisturbed sites were characterized by fragile taxa that are sensitive to fishing disturbance. The horse mussel (*Modiolus modiolus*) has been indicated in several studies as a species that is sensitive to bottom fishing disturbance (Macdonald *et al.*, 1996). The disturbed sites were characterized by scavenger species such as hermit crabs and the waved whelk (*Buccinum undatum*) which are known to be insensitive to disturbance.

All our study sites are located on the gravel pavement habitat and have pebbles as the dominant sediment type. Even though we tried to standardize the sites as much as possible, the sediment distributions were patchy and overall differences in sediment type were apparent among the sites. The slight differences in sediment types between the disturbed and undisturbed sites complicate interpretation of our results. In the videos, the undisturbed sites seemed to have slightly coarser sediments than the disturbed sites (Fig. 3). It is possible that colonial epifauna settle preferentially or have higher growth and survival rates on the large pebbles and cobbles. However, coarser sediments at the undisturbed sites were not apparent in the still photographs; instead the sediments were more heterogeneous, with higher frequencies of sand and cobbles than the disturbed sites (Fig. 4). We consider the sediment classification from the photographs to be more reliable because it was possible to measure the size of sediment particles with the scaled grid. Another consideration is that dredging affects the sediment distribution by exposing sand and small pebbles. Fishermen remove large cobbles and boulders from scallop grounds, which end up with a more homogeneous sediment distribution than undisturbed sites.

In our statistical tests, the main effects of disturbance were significant, but the significant depth \times disturbance interaction terms in several of the ANOVAs make it difficult to generalize our results. The deep sites probably had more species than the shallow sites before any dredging took place, so dredging would naturally have greater effects at depth. To make our data amenable to statistical testing, we classified each site as disturbed or undisturbed. We do not know the exact fishing history

of each site but suspect that there was actually a gradient of disturbance from the least disturbed (site 20) to the most heavily disturbed site (17). For example, there was some evidence of scallop dredging at site 10 in November 1994, but not enough to reduce the percentage cover of *F. implexa*. We suspect that the shallow site 18 had been previously disturbed, as there were no boulders there that would present obstacles to fishing.

In ongoing studies of this area, we are improving the methodology for extracting quantitative information from bottom photographs. A more constant altitude off the bottom can be obtained with a remotely operated vehicle, and paired lasers provide a more precise spatial scale. Computer enhancement of contrast and colour scales can allow more animals to be identified in photographs. The data collected also contain spatial relations of organisms within photographs which may yield important information about benthic microhabitats (Auster *et al.*, 1996).

Fishing disturbance is the most likely explanation for the differences we observed between sites, but a more experimental approach is required to control directly the level of dredging disturbance. A common approach is to fish experimentally undisturbed areas, comparing the results with unfished control areas (Thrush *et al.*, 1995; Kaiser and Spencer, 1996). This approach is best for determining the short-term responses of bottom fishing but it does not address the effects of chronic disturbance that many fishing grounds have experienced. The opposite experiment is to protect previously disturbed areas and monitor the recovery of the benthic community.

Improved gear efficiency and increased fishing effort during the past two decades caused the principal New England groundfish stocks to collapse (Fogarty and Murawski, 1998). In December 1994, the New England Fishery Management Council took emergency action, closing large areas of Georges Bank to bottom fishing. Besides immediately reducing fishing mortality on the groundfish stocks, the closures have an added benefit of protecting benthic habitat and provide an excellent opportunity to monitor the recovery of previously disturbed fishing grounds. Our most heavily disturbed site (site 17) is in an area that was closed to all bottom fishing in December 1994. Based on results from this study (Collie *et al.*, 1997) and previous habitat research (Lough *et al.*, 1989; Valentine and Lough, 1991), this area has been designated a Habitat Area of Particular Concern for juvenile cod.

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References

- Alexander, A. B., Moore, H. F., and Kendall, W. C. 1914. Otter-trawl fishery. Report of the U.S. Commissioner of Fisheries, Appendix VI, 1–97.
- Anonymous. 1996. Report of the Working Group on Ecosystem Effects of Fishing Activities. ICES CM 1996/Assess/Env:1, 126 pp.
- Auster, P. J., and Langton, R. W. 1999. The effects of fishing on fish habitat. American Fisheries Society Symposium, 22: 150–187.
- Auster, P. J., Malatesta, R. J., Langton, R. W., Watling, L., Valentine, P. C., Donaldson, C. S., Langton, E. W., Shepard, A. N., and Babb, I. G. 1996. The impacts of mobile fishing gear on seafloor habitats in the Gulf of Maine (northwest Atlantic): implications for conservation of fish populations. Reviews in Fisheries Science, 4: 185–202.
- Auster, P. J., Stewart, L. L., and Sprunk, H. 1989. Scientific imaging with ROVs: tool and techniques. Marine Technology Society Journal, 23: 16–20.
- Boehlert, G. W. 1996. Biodiversity and the sustainability of marine fisheries. Oceanography, 9: 28–35.
- Bradstock, M., and Gordon, D. P. 1983. Coral-like bryozoan growths in Tasman Bay, and their protection to conserve commercial fish stocks. New Zealand Journal of Marine and Freshwater Research, 17: 159–163.
- Butman, B. 1987. Physical processes causing surficial-sediment movement. In Georges Bank, pp. 147–162. Ed. by R. H. Backus. MIT Press, Cambridge, MA. 593 pp.
- Buzas, M. A., and Gibson, T. G. 1969. Species diversity: benthic Foraminifera in the western North Atlantic. Science, 163: 72–75.
- Collie, J. S., Escanero, G. A., and Valentine, P. C. 1997. Effects of bottom fishing on the benthic megafauna of Georges Bank. Marine Ecology Progress Series, 155: 159–172.
- Collie, J. S., Hall, S. J., Kaiser, M. J., and Poiner, I.R. 2000. A quantitative analysis of fishing impacts on shelf-sea benthos. Journal of Animal Ecology (in press).
- Dayton, P. K., Thrush, S. F., Agardy, M. T., and Hofman, R. J. 1995. Environmental effects of marine fishing. Aquatic Conservation: Marine and Freshwater Ecosystems, 5: 205–232.
- Fogarty, M. J., and Murawski, S. A. 1998. Large-scale disturbance and the structure of marine systems: fishery impacts on Georges Bank. Ecological Applications, 8 (Supplement 1): S6–S22.
- Freese, L., Auster, P. J., Heifetz, J., and Wing, B. L. 1999. Effects of trawling on seafloor habitat and associated invertebrate taxa in the Gulf of Alaska. Marine Ecology Progress Series, 182: 119–126.
- Gislason, H. 1994. Ecosystem effects of fishing activities in the North Sea. Marine Pollution Bulletin, 29: 520–527.
- Graham, M. 1955. Effect of trawling on animals of the sea bed. Deep Sea Research, 3(Suppl): 1–6.
- Hill, M. O. 1979. TWINSpan—A FORTRAN program for arranging multivariate data in an ordered two-way table by classification of individuals and attributes.

- Ecology and Systematics, Cornell University, Ithaca, NY, 90 pp.
- Jennings, S., and Kaiser, M. J. 1998. The effects of fishing on marine ecosystems. *Advances in Marine Biology*, 34: 201–352.
- Jones, J. B. 1992. Environmental impact of trawling on the seabed: a review. *New Zealand Journal of Marine and Freshwater Research*, 26: 59–67.
- Kaiser, M. J., and Spencer, B. E. 1996. The effects of beam-trawl disturbance on infaunal communities in different habitats. *Journal of Animal Ecology*, 65: 348–358.
- Langton, R. W., and Robinson, W. E. 1990. Faunal associations on scallop grounds in the Western Gulf of Maine. *Journal of Experimental Marine Biology and Ecology*, 144: 157–171.
- Lindeboom, H. J., and de Groot, S. J. 1998. The effect of different types of fisheries on the North Sea and Irish Sea benthic ecosystems. Netherlands Institute of Sea Research, Report 1998–1. Den Burg, Texel. 404 p.
- Lough, R. G., Valentine, P. C., Potter, D. C., Auditore, P. J., Boltz, G. R., Neilson, J. D., and Perry, R. I. 1989. Ecology and distribution of juvenile cod and haddock in relation to sediment type and bottom currents on eastern Georges Bank. *Marine Ecology Progress Series*, 56: 1–12.
- Macdonald, D. S., Little, M., Eno, N. C., and Hiscock, K. 1996. Disturbance of benthic species by fishing activities: a sensitivity index. *Aquatic Conservation: Marine and Freshwater Ecosystems*, 6: 257–268.
- National Research Council (NRC). 1995. Understanding marine biodiversity. National Academy Press, Washington, D.C.. 114 pp.
- Poiner, I., Glaister, J., Pitcher, R., Burrige, C., Wassenberg, T., Gribble, N., Hill, B., Blaber, S., Milton, D., Brewer, D., and Ellis, N. 1998. Final report on effects of trawling in the far northern section of the Great Barrier Reef: 1991–1996. CSIRO Division of Marine Research, Cleveland.
- Poiner, I. R., and Kennedy, R. 1984. Complex patterns of change in the macrobenthos of a large sand bank following dredging. *Marine Biology*, 78: 335–352.
- Rijnsdorp, A. D., Buijs, A. M., Storbeck, F., and Visser, E. 1998. Micro-scale distribution of beam trawl effort in the southern North Sea between 1993 and 1996 in relation to the trawling frequency of the sea bed and the impact on benthic organisms. *ICES Journal of Marine Science*, 55: 403–419.
- Sainsbury, K. J. 1988. The ecological basis of multispecies fisheries and management of a demersal fishery in tropical Australia. *In Fish Population Dynamics*, 2nd ed, pp. 349–382. Ed. by J. A. Gulland. John Wiley & Sons, London. 422 pp.
- Sokal, R. P., and Rohlf, F. S. 1981. *Biometry*. W. H. Freeman, San Francisco. 859 pp.
- Thouzeau, G., Robert, G., and Ugarte, R. 1991. Faunal assemblages of benthic megainvertebrates inhabiting sea scallop grounds from eastern Georges Bank, in relation to environmental factors. *Marine Ecology Progress Series*, 74: 61–82.
- Thrush, S. F., Hewitt, J. E., Comings, V. J., and Dayton, P. K. 1995. The impact of habitat disturbance by scallop dredging on marine benthic communities: what can be predicted from the results of experiments? *Marine Ecology Progress Series*, 129: 141–150.
- Tupper, M., and Boutilier, R. G. 1995. Effects of habitat on settlement, growth, and postsettlement survival of Atlantic cod (*Gadus morhua*). *Canadian Journal of Fisheries and Aquatic Sciences*, 52: 1834–1841.
- United States Department of Commerce (USDC). 1996. Magnuson-Stevens Fishery Conservation and Management Act. NOAA Technical Memorandum NMFS-F/SPO-23, 121 pp.
- Valentine, P. C., and Lough, R. G. 1991. The sea floor environment and the fishery of eastern Georges Bank – The influence of geologic and oceanographic environmental factors on the abundance and distribution of fisheries resources of the northeastern United States. U.S. Geological Survey Open-File Report 91-439, 25 pp.
- Watling, L., and Norse, E. A. 1998. Disturbance of the seabed by mobile fishing gear: a comparison to forest clearcutting. *Conservation Biology*, 12: 1180–1197.
- Welleman, H. 1989. Literatuurstudie naar de effecten van de bodemvisserij op de bodem en het bodemleven. RIVO Rapport, MO 89-201, 57 pp.