5. REVIEW OF LITERATURE ON FISHING GEAR EFFECTS

Seventy-three publications were included in the gear-effects literature review. An attempt was made to include all available, relevant, English language scientific publications in order to determine the effects on benthic marine habitat types of the principal commercial fishing gears used in the Northeast Region. Habitat types were defined by the predominant substrate. Gear types that were selected were those that are currently used in the region, or those that are used elsewhere but were judged to have similar effects as gears that are used in the region. Gears that are used strictly in state waters to harvest species that are not federally managed were not included.

This review details individual scientific studies and summarizes what is known about each combination of gear and substrate type. Both peer-reviewed and non-peer-reviewed publications were included, but the emphasis was on the former. Information summarized in this review was based, in all cases, on primary source documents. An attempt was made to include all relevant publications available through early 2002.

This document differs in several important ways from other recent reviews of the gear-effects literature (Jennings and Kaiser 1998; Auster and Langton 1999; Collie *et al.* 2000) and from recent broadscale assessments of the effects of commercial fishing gear on benthic marine habitats and ecosystems (Dayton *et al*. 2002; NRC 2002). Rather than emphasizing general conclusions that apply to combined gear types (*e.g.*, "reduction of habitat complexity by mobile bottom-tending gear"), this document provides detailed summaries, in text and tabular format, of individual studies of relevance to the Northeast Region. The intention was to provide enough information in each summary for the reader to understand where and how the research was conducted and what the principal results were. Each such summary table contains information on location, depth, substrate, effects, recovery, and the methodological approach. No attempt was made to critically evaluate the research approach or the validity of the results, unless there were issues (*e.g.*, a failure to replicate treatment sites, not enough samples) identified as problems by the authors themselves. Most of the studies summarized in this document were also summarized in less detail in an earlier NMFS report that included gear types not used in the Northeast Region (Johnson 2002).

METHODS

The review is organized by combinations of gear and substrate types. Nine of the seventy-three reviewed studies included information for more than one gear type, or for one gear type in more than one substrate or study area, and were therefore summarized in more than a single gear/substrate category. In all, there were 80 descriptions for seven gear types and five substrates (Tables 5.1-5.3). Cases in which the effects of more than one gear type were evaluated in a single study and could not be distinguished were categorized as multiple gears. The same approach was used for studies conducted in mixed substrates that could not be defined as mud, sand, gravel/rock, or biogenic.

Over half (65%) of the descriptions in this document are for otter trawls and scallop dredges, and all but one are for different kinds of mobile bottom-tending gears. Thirty-four of the studies were done in sandy substrate, twelve in mud, seven in different types of biogenic substrate, five in gravel and rocky bottom, and twenty-two in mixed substrate. Most studies were peer reviewed, and most were published after 1990. Geographically, 21 were conducted in the northeastern United States (North Carolina to Maine), 19 elsewhere in North America (United States and Canada), 28 in Europe and Scandinavia, and 12 in Australia and New Zealand.

Individual Studies

Within each gear/substrate subsection, individual studies are described in one to two paragraphs that include the following information, when available:

- citation (authors and date of publication)
- location of study
- depth
- substrate type and/or composition
- detailed information on gear used, especially for otter trawls
- type of study (observational or experimental)
- whether experiments were set up to test for time and location effects
- type(s) of organisms sampled (infauna versus epifauna)
- duration and intensity of fishing (number of tows, duration of each fishing event, total duration of fishing disturbance, frequency of fishing events, etc.)
- timing of sampling or observations (how often, how long before or after fishing, etc.)
- timing and frequency of sampling or observations to determine recovery
- whether study was done in a commercially exploited or unexploited area
- if unexploited, for how long and what gears were excluded

Details that were not generally included were descriptions of sampling gears and procedures, sample processing information (*e.g.,* the mesh size used to sieve grab samples), taxonomic categories used (families, groups of species, individual species), and data analysis procedures (*e.g.,* statistical tests). General conclusions, when they are included, were the own statements of the respective study's author(s); neither speculations regarding the study in question nor any restatements made by the authors regarding anybody else's research were included. Results which are described as "significant" are results that were statistically significant. To avoid confusion, the term was not used in any other context.

Each gear/substrate category also includes a table summarizing the setting (location, depth, and sediment type), general methods, and primary results of each study. The listing of results in these tables is divided into an effects column and a recovery column. Results summarized in the tables include positive and negative results (*e.g.,* increases and decreases in abundance caused by fishing, as well as instances when there were no detectable effects of fishing). Blank cells in the recovery column indicate that the study was not designed to provide information on recovery times. Information in the last column includes the nature of the research (experimental or observational), whether or not the study area was being commercially fished at the time of the study, and how the experimental fishing was conducted (single or multiple tows, discrete or repeated disturbance events, and, if known, the average number of tows to which any given area of bottom was exposed).

Summaries

This section also summarizes results for all studies combined in each gear/substrate category. Each such summary begins with an introductory paragraph that includes general information, such as:

- the number of studies that examined physical and biological effects
- how many studies were done in different geographic areas and depth ranges
- how many studies examined recovery of affected habitat features
- the number of studies performed in areas that were closed to commercial fishing versus areas that were commercially fished at the time of the study
- how many studies involved single versus multiple tows
- how many studies were conducted either during a single discrete time period or during a more prolonged period of time that was intended to simulate actual commercial fishing activity

Physical and biological effects for each gear/substrate category are summarized in separate paragraphs. When necessary, biological effects are presented separately for single disturbance and repeated disturbance experimental studies, and for observational studies.

RESULTS

Otter Trawls

Otter Trawls -- Mud (Table 5.4)

1. Ball *et al.* (2000) sampled benthic macrofauna before and 24 hr after trawling at a heavily fished site within an offshore prawn (*Nephrops*) trawl fishing ground in the Irish Sea and at an unfished "pseudo-control" site near a shipwreck at the same depth (75 m) that had not been fished for about 50 yr. Sediments were sandy silt. No information on the duration of experimental trawling or the type of net used was provided.

Due to few organisms and low biomass, and to the resulting high intersample variance, it was not possible to quantitatively evaluate the short-term effects of trawling at the fished site. There were, however, considerably fewer species and individuals, and lower species diversity and richness, in the commercially trawled area than near the shipwreck.

At the shipwreck site, the number of species, number of individuals, and biomass decreased with increasing distance from the wreck. High intersample variance in biomass estimates near the wreck impeded comparisons with the trawled site. Sixty-nine species found at the wreck site were not found at the experimental fishing site. These included polychaetes, crustaceans, bivalve mollusks, gastropods, and echinoderms. Large specimens of some mollusks and echinoderms were most common near the wreck, whereas only juveniles of these species were sampled in the trawled area.

2. Brylinsky *et al.* (1994) examined physical and biological effects of 18-24 m wide flounder trawls with 180-270 kg doors, 29-cm-diameter rubber rollers, and no tickler chains in an intertidal estuary in the upper Bay of Fundy, Nova Scotia. The study area was commercially fished for flounder by trawlers. Four trawling experiments were conducted at two sites in 6-8 m of water (at high tide) in 1990 and 1991. Repeated tows were made during a single day at each site, but not over the same bottom area. Samples of macrobenthos, meiofauna, and chlorophyll were collected at each site at variable intervals for 1.5-4 mo after trawling. One site had sand overlain with several centimeters of silt; the other site had siltier sediment to a depth of at least 10 cm. The study area is a high-energy environment, owing to the extreme tidal range (average 11 m with a maximum of 16 m) and tidal currents that frequently exceed 2 knots.

Trawl doors made furrows 1-5 cm deep and berms that were visible for at least 2-7 mo. The rollers compressed sediments. The amount of disturbance varied markedly and seemed to be influenced primarily by the kind of sediment and the type of door used, being more pronounced in the finer sediments and when heavier doors were used. Benthic diatoms (measured as chlorophyll *a*) decreased in door furrows at some stations, but recovered within 1-3 mo. No significant effects were observed on macrobenthos, which was dominated by polychaetes. The numbers of nematodes in door furrows were reduced, but only for 1-1.5 mo, and may only have been displaced by the doors. Benthic taxa such as mollusks, crustaceans, and echinoderms that are known to be more susceptible to trawling were not present in the study site.

3. DeAlteris *et al.* (1999) analyzed data from a 1995 sidescan sonar survey to locate and map trawl tracks in shallow sand and mud sediments in lower Narragansett Bay, Rhode Island. At the deeper (14-m) mud-bottom site, trawl doors produced smooth tracks 5-10 cm deep with berms on the inside edge that were 10-20 cm high.

The longevity of hand-dug trenches (dug to simulate tracks left by trawl doors) was monitored using SCUBA divers. The trenches were observed unchanged for the duration of the study (>60 days), and were occupied by Atlantic rock crabs. Natural erosion at this site was predicted to occur <5% of the time.

4. Drabsch *et al.* (2001) used divers to sample benthic infauna before and after experimental trawling in an area of South Australia (Gulf of St. Vincent) where little or no fishing had occurred for 15 yr. Three study sites were used (one in mud and two in sand), with adjacent trawled and control corridors at each site. (See "Otter Trawls -- Sand, 4. Drabsch *et al*. (2001)" for a summary of results at the two sandy study sites.) Two series of 10 adjacent tows were made in a single trawl corridor at the mud treatment site during 1 day in October 1999 using triple prawn trawls with two doors (1x2 m, 200 kg each) and a combined sweep length of about 20 m. Bottom sediments at the mud study site were fine silt sediments and the depth was 20 m.

Trawl doors left tracks, and the footline and net smoothed topographic features and removed 28% of the epifauna (not differentiated between mud and sand substrates). Remaining epifauna in the trawled corridor showed signs of damage. Total infaunal abundance and the abundance of one family of polychaetes (Ctenodrilidae) were significantly reduced 1-wk after trawling. No significant changes were evident for any other taxon.

5. Frid *et al.* (1999) examined the long-term effects of fishing with prawn (*Nephrops norvegicus*) otter trawls by comparing changes over 27 yr on macrobenthic communities at a lightly fished (LF) and a heavily fished (HF) location off the northeastern coast of England (North Sea). Fishing activity within the statistical area that includes both sites was divided into three periods of low (1971-1981), high (1982-1989), and moderate (1990-1997) fishing effort. The depth at the HF site was 80 m, and the substrate was predominantly (>50%) silt-clay. Grab samples were collected at the HF site every year during January. Benthic taxa in the samples were divided into two groups that were predicted to respond negatively (*i.e.*, decreased number of individuals, or "abundance") or positively (*i.e.*, increased abundance) to increased trawling activity, based on published accounts.

The total abundance of taxa in the positive response group conformed to predictions by increasing significantly between the periods of low and high fishing effort, and then declining when fishing effort dropped to moderate levels. The total abundance of taxa in the negative response group did not vary significantly between time periods. Errant polychaetes were the only taxonomic group in the negative response group to increase significantly at high fishing effort. Starfish and brittle stars were more abundant at high fishing effort, but not significantly. Sea urchins, as predicted, decreased in abundance (to zero) at high fishing effort. Sedentary annelids and large bivalve mollusks were taxa in the negative response group that did not decrease in abundance. Benthic macrofaunal abundance at the HF site was low at the beginning of the time series when phytoplankton production was also low, but once fishing effort increased, there was no longer any correlation between the two. (See "Otter Trawls -- Sand, 5. Frid *et al*. (1999)" for a summary of results at the LF site that had a sandy substrate.)

6. Hansson *et al.* (2000) examined the effects of trawling on clay bottom habitats at 75-90 m depths in a Swedish fjord. The benthic infauna was collected 1-5 mo before trawling began at three experimental sites and three control sites, and during the last 5 mo of a 1-yr trawling experiment. All sites were located in an area that had been closed to fishing for 6 yr. The otter trawl that was used was a commercial shrimp trawl with a 14-m ground rope with 20 kg of lead distributed along it, and 125-kg otter boards. Eighty hauls were made at each treatment site during a 1-yr period starting in December 1996, at a frequency of two hauls per week. It was estimated that any given area was passed over 24 times by the trawl during the experiment.

For 61% of the species sampled, abundances tended to be negatively affected by trawling (*i.e.*, abundances decreased more or increased less in the trawled sites compared to the control sites during the experiment). Total biomass decreased significantly at all three trawled sites, and the total number of individuals decreased significantly at two trawled sites, but in both cases significant reductions were also observed at one of the control sites; thus, these changes could not be attributed solely to trawling. Total abundance and biomass at trawled sites was reduced by 25% and 60%, respectively, compared to 6% and 32% in control sites. Individual phyla responded differently to trawling. Echinoderm (mostly brittle star)abundance decreased significantly, polychaete abundance was not affected although some families increased and some families decreased, and amphipod and mollusk abundances were not affected.

7. Mayer *et al.* (1991) examined the immediate effects of a single tow with an otter trawl on mud substrate at a depth of 20 m in a bay on the coast of Maine. The trawl had an 18-m footrope with an attached tickler chain and 90-kg doors. Sediment core samples (to a sediment depth of 18 cm) were taken inside and outside the drag line the day after trawling, and were analyzed for porosity, chlorophyll, pheophytin, total organic matter, protein, extracellular proteolytic activity, and beryllium-7.

Downcore profiles were similar between the dragged and control sites, indicating that trawling did not "plow" the bottom and bury surficial sediments. The trawl doors did produce furrows several centimeters deep, and the chain and net caused a very thin, and inconsistent, planing of surficial features. A high value of beryllium-7 in surficial sediments at the control site, but not at the trawled site, indicated that fine sediments were dispersed laterally, away from the area of dragging.

8. Pilskaln *et al.* (1998) collected large infaunal worms in sediment traps deployed 25-35 m above the bottom in two deep (250-m) basins in the GOM during 1995.

Many more worms were collected in Wilkinson Basin, which is located in a more heavily trawled area in the Gulf, than in Jordan Basin, which is located in a region of the Gulf with very little trawling activity. Higher abundance coincided with seasons of greater trawling activity in the southwestern GOM.

The authors concluded that the worms are dislodged and suspended in the near-bottom water column by trawling because there was no other reason why they would leave their natural habitat in the bottom. They also noted that the resuspension of fine sediment by bottom trawls releases nutrients such as nitrogen and silica from bottom sediments.

9. Sanchez *et al.* (2000) examined the effects of otter trawling in a commercially trawled area with muddy substrate (depth 30-40 m) in the northwest Mediterranean Sea off the coast of Spain. A commercial otter trawl was towed repeatedly during daylight for 1 day (3.5 hr of towing) at one site and during a 23-hr period (7 hr of towing) at a second site in July 1997, so that each trawl wayline was swept entirely either once or twice. Infaunal grab samples were collected prior to fishing and at various times after fishing (up to a maximum of 150 hr) in each trawl wayline and at unfished sampling locations adjacent to each wayline.

A number of taxa (mostly families) were significantly more abundant in the lightly trawled wayline than in the adjacent untrawled area after 150 hr, primarily due to decreased abundance outside the wayline. The total numbers of individuals and taxa were also significantly reduced outside, but not inside, the lightly trawled wayline 150 hr after trawling. There were no differences in the number of taxa or individuals inside and outside the more intensively trawled wayline after 72 hr.

The percentage composition of abundance of major taxa (*i.e.*, polychaetes, crustaceans, and mollusks) was similar in both trawled waylines and in the control locations throughout the experiment, and trawling produced no changes in community structure in either wayline. Sidescan sonar images of the trawl waylines showed furrows left by the trawl doors that remained visible throughout the experiment.

10. Sparks-McConkey and Watling (2001) investigated the effects of trawling on geochemical sediment properties and benthic infauna in Penobscot Bay, Maine. The study site was selected because it was deep (60 m) and bottom sediments were not exposed to storm events or tidal scouring. Sediment particle size was homogeneous spatially and temporally within the study area. There had been no commercial trawling in the area for 20 yr. Trawling was conducted at two stations in December 1997 with a 12-m commercial silver hake net that was modified (increased mesh size and decreased diameter of float rollers) to reduce effects to the seafloor. Four tows were made at each station during 1 day. An attempt was made to tow the same area of bottom each time. Sampling was conducted at the experimental stations and at seven reference stations for a year before trawling, and 5 days, 3.5 mo, and 5 mo after trawling. An underwater video camera was used to verify that post-trawl grab samples were taken in trawl tracks.

Trawling caused immediate and significant reduction in porosity, an increase in the food value of surface sediments (upper 2 cm), and stimulated chlorophyll production, but none of these properties were any different at the trawled stations after 3.5 and 5 mo. Trawling also had immediate and significant effects on benthic infauna, reducing the number of individuals and species, reducing taxonomic diversity, and increasing species dominance. There were no longer any significant differences in any of these parameters after 3.5 mo when mobile species recruited to the benthos. Four polychaete species were significantly less abundant at the trawled stations 5 days after trawling, but three of them were present in equal densities at treatment and control stations 3.5 mo later. Two species of bivalve mollusks were reduced in abundance by trawling, one of them for 3.5 mo. Nemerteans were significantly more abundant at the trawled stations during all three post-trawl sampling dates.

11. Tuck *et al.* (1998) conducted experimental trawling in a sea loch in Scotland that had been closed to fishing for over 25 yr. Trawling was conducted 1 day/mo (for 7.5 hr) for 16 mo in a single treatment site (95% silt-clay, depth 30-35 m) starting in January 1994. Infaunal surveys were completed in the trawled site and a nearby reference site prior to, after 5, 10, and 16 mo of disturbance, and, once trawling ended, after 6, 12, and 18 mo of recovery.

Trawl doors produced furrows in the sediment, which were still evident in sidescan sonar images after 18 mo.

Trawling had no effect on sediment characteristics, but bottom "roughness" in the trawled area increased during the disturbance period and declined during the recovery period.

There were no significant differences in the number of infaunal species in the experimental and reference sites prior to the beginning of the experiment or during the first 10 mo of disturbance, but there were more species in the trawled site after 16 mo of disturbance and throughout the recovery period. In contrast, there were significantly more individuals in the trawled site before trawling began. This difference was maintained after 10 and 16 mo of fishing, and after 6 and 12 mo of recovery, but after 18 mo, there was no difference between the two sites. Taxonomic diversity and evenness indices were significantly lower in the experimental site for the first 22 mo of the experiment, but after 12 mo of recovery there were no longer any differences. Some species (primarily opportunistic polychaetes) increased significantly in abundance in the trawled plot in response to the disturbance, while others (*e.g.,* bivalve mollusks) declined significantly in abundance relative to the reference area. Biomass was significantly higher in the control site before trawling started, but not during the rest of the experiment. Two different measures of community structure were applied. One of them indicated that the two sites became significantly different after only 5 mo of disturbance and remained so throughout the experiment. According to the other one, the treatment site reached a similar condition to the reference site at the end of the recovery period. Trawling effects on epifauna could not be evaluated in this study because organisms were present in very low densities and because the trawl was not equipped with a net, thus any effects on epifauna would have been underestimated.

Summary

Results of 11 studies are summarized. All of the studies were conducted during 1991-2001, five in North America, five in Europe, and one in Australia. One study was performed in an intertidal habitat, one in very deepwater (250 m), and the rest in a depth range of 14-90 m. Eight of them were experimental studies and three were observational. Two studies examined only physical effects, six assessed only biological effects, and three examined both physical and biological effects. One study evaluated geochemical sediment effects.

In this habitat type, biological evaluations focused on infauna: all nine biological assessments examined infaunal organisms, and four of them included epifauna. Habitat recovery was monitored on five occasions. Two studies evaluated the long-term effects of commercial trawling, one by comparing benthic samples from a fishing ground with samples collected near a shipwreck, while another evaluated changes in macrofaunal abundance during periods of low, moderate, and high fishing effort during a 27-yr period. Four of the experimental studies were done in closed or previously untrawled areas and three in commercially fished areas. One study examined the effects of a single tow, and six involved multiple tows. Five studies restricted trawling to a single event (*e.g.,* 1 day) and two examined the cumulative effects of continuous disturbance.

Physical Effects

Trawl doors produce furrows up to 10-cm deep and berms 10-20 cm high on mud bottom. Evidence from three studies (2, 3, 9) indicates that there is a large variation in the duration of these features (2-18 mo). There is also evidence that repeated tows increase bottom roughness (11), fine surface sediments are resuspended and dispersed (7), and rollers compress sediment (2). A single pass of a trawl did not cause sediments to be turned over (7), but single and multiple tows smoothed surface features (4, 7).

Biological Effects -- Single-Disturbance Experimental Studies

Three single-event studies (1, 2, 9) were conducted in commercially trawled areas. Experimental trawling in intertidal mud habitat disrupted diatom mats and reduced the abundance of nematodes in trawl door furrows, but recovery was complete after 1-3 mo (2). There were no effects on infaunal polychaetes (2). In a subtidal mud habitat (30-40 m deep), the benthic infauna was not affected (9). There were no obvious effects on macrofauna at a deeper (75 m) site, but there were fewer organisms and species there than at an unexploited site near a shipwreck (1).

In two assessments performed in areas that had not been affected by mobile bottom gear for many years (4, 10), effects were more severe. Total infaunal abundance (4, 10) and the abundance of individual polychaete (4, 10) and bivalve mollusk (10) species declined immediately after trawling.

In one of these studies (10), there were also immediate and significant reductions in the number of species and species diversity. Other effects included reduced porosity, increased food value, and increased chlorophyll production in surface sediments. Most of these effects lasted <3.5 mo.

In the other study (4), two tows removed 28% of the epifauna on mud and sand substrate (not differentiated), and epifauna in all trawled quadrats showed signs of damage. These results were not reported separately for mud bottom.

Biological Effects -- Repeated-Disturbance Experimental Studies

Two studies of the effects of repeated trawling were conducted in areas that had been closed to fishing for 6 yr (6) and >25 yr (11). In one study (6), multiple tows were made weekly for a year, and in the other (11), monthly for 16 mo.

In one case (6), 61% of the infaunal species sampled tended to be negatively affected, but significant reductions were only noted for brittle stars.

In the other case (11), repeated trawling had no significant effect on the numbers of infaunal individuals or biomass. In this study, the number of infaunal species increased by the end of the disturbance period. Some species (*e.g.,* polychaetes) increased in abundance, while others (*e.g.,* bivalve mollusks) decreased. Community structure was altered after 5 mo of trawling, and (because of mixed results from the analyses) if it did fully recover, then it did not do so until at least 18 mo after trawling ended.

Biological Effects -- Observational Studies

An analysis of benthic sample data collected from a fishing ground over a 27-yr period of high, medium, and low levels of fishing effort showed an increased abundance of organisms belonging to taxa that were expected to increase at higher disturbance levels, whereas those that were expected to decrease did not change in abundance (5). Trawling in deepwater apparently dislodged infaunal polychaetes, causing them to be suspended in near-bottom water (8).

Otter Trawls -- Sand (Table 5.5)

1. Ball *et al.* (2000) sampled benthic macrofauna at a lightly fished inshore prawn trawl fishing ground in the Irish Sea before and 24 hr after trawling and at an unfished (for about 50 yr) "pseudo-control" site near a shipwreck. Sediments at these two sites were muddy sand, and the depth was 35 m. No information on the duration of experimental trawling or the type of net used was provided.

There were no obvious short-term effects of experimental trawling. Chronic effects, as indicated by differences between the fished site and the wreck site before experimental trawling began, were similar in kind, but less pronounced than at the heavily fished, mud-bottom offshore site (see "Otter Trawls -- Mud, 1. Ball *et al.* (2000)"). Mean numbers of species and total numbers of individuals for both infaunal and epifaunal species were higher at the unfished wreck site, as were indices of species diversity and richness. High intersample variance in biomass estimates near the wreck impeded comparisons with the trawled site. Fifty-eight species found at the inshore wreck site were not found at the experimental fishing site. These species included predatory and tube-dwelling polychaetes as well as a number of bivalve mollusks and echinoderms. Other types of polychaetes were more common at the fished site.

2. Bergman and Santbrink (2000) calculated mortality rates for a number of sedentary and relatively immobile megafauna (*i.e.*, >1 cm in maximum dimension) caught or damaged by a flatfish otter trawl at six commercially exploited sites in the southern North Sea during 1992-1995. The substrate at two deeper sites (40-50 m) was silty sand (3-10% silt), and at four shallower sites (<30-40 m) was sand (1-5% silt). At each site, benthic invertebrates were sampled before and 24-48 hr after trawling in four corridors with a dredge that was designed to sample relatively large, relatively low-abundance , infaunal and epifaunal species. The fishing gear was a commercial flatfish trawl that measured 35-55 m between the doors (15-20 m between the wings) when underway, with 20 m of net (32 m with bridles) in contact with the seafloor, 20-cm roller gear, and 8-10 cm mesh in the cod-end. Three corridors were trawled in silty sand substrate and one in sandy substrate. The surface of each corridor was trawled on average 1.5 times.

Mortalities were calculated as the percent reduction from initial density after a single trawl tow, and ranged from <0.5 to 52% for nine species of bivalve mollusks, from 16 to 26% for a sea urchin, from 3 to 30% for a crustacean, and from 2 to 33% for other species. Overall, mortality rates for six species ranged from 20 to 50%, and for 10 other species were < 20%. Significant before-and-after differences were detected on only 11 of 54 occasions. Some species experienced higher mortalities in the silty sand substrate and some in the sandy substrate.

3. DeAlteris *et al.* (1999) used divers to determine that simulated (*i.e.*, dug by the divers) trawl door tracks only lasted 1-4 days at a 7-m deep sandy site in Narragansett Bay, Rhode Island. Natural erosion at this site was predicted to occur on a daily basis, much more rapidly than in deeper water with a mud substrate (see "Otter Trawls -- Mud, DeAlteris *et al*. (1999)" for a summary of the mud-bottom results).

4. Drabsch *et al.* (2001), in addition to sampling a mud-bottom site in South Australia before and after trawling (see "Otter Trawls -- Mud, Drabsch *et al*. (2001)"), also sampled two additional sites (20-m depth) with medium-coarse sand sediments and shell fragments. Trawling effects were evaluated at one of the sites 1 wk after fishing, and at the second site 3 mo after fishing.

Trawl doors left tracks in the sediment, and the footline and net smoothed topographic features and removed epifauna. In contrast to results obtained at the mud-bottom site, trawling at the sand-bottom sites did not significantly affect infaunal abundance. The only significant change to infauna that could be attributed to trawling was a reduction in density of one order of crustaceans (Tanaidaceae) 1 wk after trawling. Three months after trawling, infaunal abundance had declined dramatically in both the treatment and reference sites, and there were no significant differences between them.

5. Frid *et al.* (1999) examined the long-term effects of fishing with prawn otter trawls in the North Sea by comparing changes on macrobenthic communities at an LF sand-bottom site and an HF mud-bottom site during three time periods when fishing effort was either low, moderate, or high (see "Otter Trawls -- Mud, Frid *et al*. (1999)" for results at the HF site). The LF site was located in 55 m of water and had a predominantly sand substrate (20% silt-clay). Benthic taxa collected at the LF site were divided into two groups that were predicted to respond either negatively (decreased abundance) or positively (increased abundance) to increased trawling activity, based on published accounts.

Fluctuations in macrofaunal abundance at the LF site were correlated with the abundance of phytoplankton 2 yr previously, indicating that benthic organisms were more abundant when greater amounts of organic matter were available to stimulate benthic production and vice-versa. There was no correlation with changes in fishing effort and no change in the proportions of organisms in the positive and negative response groups over time.

6. Gibbs *et al.* (1980) sampled benthic epifauna and infauna prior to and immediately after 1 wk of repeated experimental trawling (with a 10-m otter trawl with 1-m x 0.5-m flat otter boards and chain spiders) in a shallow estuary in New South Wales, Australia, during October 1975. The experimental trawling was conducted before the opening of a 6-mo-long prawn fishing season. Additional samples were collected at the end of the season. Grab samples were taken over muddy sand (0-30 % mud-clay) at three sites within the fishing grounds in Botany Bay and at an unfished control site in Jervis Bay, located about 200 km south of Botany Bay.

Trawl footropes lightly skimmed the bottom and disturbed very little sand. Trawling did create a plume of sand, but after repeated trawls, the seafloor was only slightly modified. Community diversity indices were not significantly different among the three study sites and the control site before and immediately after experimental trawling or after the fishing season. The authors therefore concluded that there were no detectable effects of trawling.

7. Gilkinson *et al.* (1998) studied the effects of trawl door scouring on several species of infaunal bivalve mollusks by observing an otter door model deployed in a test tank with a sand bottom, designed to simulate the sediment of the northeastern Grand Banks.

The trawl door created a berm in the sediment (average height 5.5 cm) with an adjacent 2-cm-deep scour furrow. All 42 bivalve mollusks within the scour path were displaced, but only two were damaged.

8. Hall *et al.* (1993) sampled benthic infauna from a fishing ground in the North Sea using distance from a shipwreck as a proxy for changes in trawling intensity. The sediment was coarse sand and the depth was 80 m. The benthic infauna was sampled at intervals along three transects that started 5 m from the wreck and extended to 350 m from the wreck.

Infaunal community structure was closely related to grain size and organic carbon content that varied within concentric rings or linear waves of coarser and finer sand, but not to distance from the wreck. The authors concluded that the observed differences in infaunal abundance did not appear to be consistent with an effect of fishing disturbance, which would most likely not follow the same pattern of fluctuating high and low intensity at increasing distance from the wreck. Epifaunal taxa were not included in this analysis.

9. McConnaughey *et al.* (2000) examined chronic trawling effects on epifauna in a high-energy sandy habitat in the eastern Bering Sea, Alaska. Samples were collected in 1996 just inside and outside an area that had been closed to trawling since 1959, using an otter trawl modified to improve the catch and retention of large epibenthic organisms. The small-mesh net had a 34-m footrope with a tickler chain and a hula skirt, and 1-mt steel V-doors with 55-m paired dandylines (bridles). Each lower dandyline had a 0.6-m chain extension connected to the lower wing of the net to improve bottom-tending characteristics. Sampling sites were selected along the outside edge of the closed area where commercial trawling is intense, and inside the closed area within 1 nmi of the intensely trawled sites. The bottom in the study area was 44-52 m deep, had sand ripples and strong rotary tidal currents, and was well within the depth range affected by storm waves.

Sedentary taxa (*e.g.,* anemones, whelk eggs, soft corals, stalked tunicates, bryozoans, and sponges) were more abundant in the unfished (UF) area than in the heavily fished (HF) area. Differences (*i.e.*, UF>HF) were significant for sponges and anemones. Mixed nonsignificant responses were observed within motile groups (*e.g.,* crabs, starfish, and buccinid whelks) and infaunal bivalve mollusks. Species diversity of sedentary epifaunal taxa was significantly higher in the UF area, owing to the greater dominance of a starfish in the HF area. Attached epifauna (*e.g.,* sponges, anemones, soft corals, and stalked tunicates) had a significantly more patchy distribution in the HF area.

10. Moran and Stephenson (2000) conducted an experimental study of otter trawling effects on an unexploited area with dense macrobenthos at depths of 50-55 m on the continental shelf of northwest Australia. No information on bottom type was provided, but it was presumed to be sand (see Sainsbury *et al.* 1997). A video camera mounted on a sled was used to survey attached epifauna (>20 cm in maximum length) before and after individual trawling events in experimental and control sites. There were four trawling events scheduled at 2-day intervals. During each trawling event, four tows were required to cover the area of each of two experimental blocks so that any unit area of bottom was trawled once. Trawled and control sites were surveyed before and after each trawling event and on alternate days during trawling.

Mean density of benthos declined exponentially (and significantly) with increasing tow numbers, with four tows reducing density by about 50%, and a single tow reducing density by about 15%. This estimated removal rate is much lower than what was estimated by Sainsbury *et al.* (1997) for sponges in the same general location (89%, see below). The authors believe this disparity may be explained by the fact that the trawl used in their study was lighter, with 20-cm disks separated by 30-60 cm long spacers of 9-cm diameter, and may have lifted over some benthic organisms rather than removing them. In addition, sponges are more susceptible to removal than other benthic organisms.

11. Sainsbury *et al.* (1997) reported the results of surveys on the continental shelf (<200 m) in northwestern Australia that documented a shift in the dominance of fish species from those (*Lethrinus* and *Lutjanus*) that occur predominantly within habitats that contain large epibenthic organisms to those (*Nemipterus* and *Saurida*) that favor open sandy habitats, in conjunction with the development of a commercial stern and pair trawling fishery. Five years after trawl closure areas were implemented (in response to these shifts in species dominance), there were increased catch rates of *Lutjanus* and *Lethrinus*, increased abundances of small benthos (<25 cm), and no changes in abundances of large benthos. The abundance of these fishes and of both the large and small benthos continued to decrease in the area left open to trawling.

These results increased the probability placed on a habitat limitation model and decreased the probability of an intraspecific control model (Sainsbury 1991), indicating that changes in species abundance and composition were at least in part a result of the damage inflicted on the epibenthic habitat by demersal trawling gear. Video observations provided by a camera mounted on a trawl showed that during those encounters with the groundline where the outcome was observable, sponges >15 cm were removed from the substrate 89% of the time. The groundline consisted of a 15-cm-diameter rubber roller made from rubber disks packed together and threaded on the groundline, with 14-cm spacers between packs of disks.

Grand Banks, Newfoundland: A number of investigators (see next three summaries) have examined the physical and biological effects of sustained otter trawling in a relatively deep sand habitat (120-146 m) in a 100-nmi^2 area of the Grand Banks, Newfoundland, that was closed to commercial trawling in 1992. Analysis of fishing effort records indicated that it had not been fished intensively since the early 1980s (Kulka 1991). (A 1990 estimate of the intensity of seafloor disturbance by otter trawling in the study area was <8% per year per unit of bottom area, or one set every 12 yr).

Sediments at this site were moderately to well sorted, fine to medium-grained sand. The seafloor is smooth and relatively stable with no evidence of wave- induced ripples. However, interannual variations in grain size and acoustic properties were observed during the study, possibly caused by winter storms (Schwinghamer *et al.* 1998).

Twelve experimental trawl tows (31-34 hr of total trawling) were made in three 13-km long corridors with an Engel 145 otter trawl with 1250-kg oval otter boards and 46-cm diameter rock hopper gear during a 5-day period in late June - early July of 1993, 1994, and 1995. Since the width of the trawl opening (60 m) was considerably less than the width of the disturbance zones created (120-250 m), the average experimental trawling intensity was estimated to be 3-6 sets per year per unit of bottom area.

Physical and biological effects of trawling were evaluated in two of the three experimental corridors. The corridors were sampled just before and just after (within a few hours or days) the experimental trawling ended, as well as 1 yr later. Additionally two reference corridors -- each located parallel to an experimental corridor -- were sampled just before the experimental trawling. Samples were also collected in the reference and experimental corridors in September 1993, 2 mo after trawling.

12. Kenchington *et al.* (2001) analyzed the effects of otter trawling at the Newfoundland study site on benthic infauna and epifauna collected in grab samples in two of the three experimental corridors.

The most prominent feature of the sample data was a significant natural decline in the total number of individuals (or total abundance), the number of species, and the numbers and biomass of several selected species in both the trawled and untrawled corridors between July 1993 and July 1995. The total abundance declined by 50% during the 2-yr period.

There were also significant effects of trawling on the mean total abundance per sample of all taxa and on the individual abundances of 15 taxa (mostly polychaetes), but only in 1994. In that year, immediate declines in abundance for these 15 taxa ranged from 33 to 67%. There were no significant trawling-induced changes in total biomass at any point during the experiment. Likewise, none of the community indices (taxonomic diversity and evenness) showed a significant effect of trawling in any of the years, and the only change in community structure that could be attributed to trawling occurred in 1994. Recovery for species that were affected by trawling in 1994 required <1 yr. Within this time frame, however, the actual recovery period could not be determined.

The authors concluded that there was no consistent, long-term effect that could be attributed to trawling, and that the effects of otter trawling on benthic infauna and infauna in this relatively stable, deepwater sand habitat were limited and short-term. When trawling disturbance was indicated, it appeared to mimic natural disturbance.

13. Prena *et al.* (1999) examined trawl bycatch and the effects of trawling on benthic epifauna, using an Engel 145 otter trawl. The epifauna (and some infauna) were collected with an epibenthic sled in two reference corridors before trawling, and in two experimental corridors before and after trawling (see earlier).

There was a significant reduction in trawl bycatch biomass during the first six sets (15-17 hr) due primarily to a decline in snow crabs, and a relatively constant level of such biomass during the last six sets due to snow crabs migrating into the trawled corridors to feed on dead and damaged organisms.

Epifaunal biomass was lower (by 24%on average) in trawled corridors than in reference corridors in all 3 yr, and remained relatively constant with time, whereas biomass in reference corridors was highly variable from year to year. There were significant trawling and year effects on total epifaunal biomass, and significant trawling effects on mean individual epifaunal biomass, indicating that individuals in the trawled corridors had a smaller average size.

At the species level, the biomass of five of the nine dominant epifaunal species (a sand dollar, brittle star, soft coral, snow crab, and sea urchin) was significantly lower in the trawled corridors than in the reference corridors. There was also a general trend of greater damage to benthic invertebrates in the trawled corridors, especially for three species of brittle star, sea urchin, and sand dollar. There were no significant effects on the abundance of four dominant mollusk species.

14. Schwinghamer *et al.* (1998) sampled surface sediments (top 2 cm) and conducted video and acoustic surveys at the Newfoundland study site before, during, and after trawling in two experimental corridors. Tracks and berms left by the trawl doors increased bottom relief and roughness. In 1993, door tracks 5 cm deep and 1 m wide were still clearly visible in sidescan sonar records after 2 mo, but they were not visible at the beginning of trawling in 1994. Tracks made in 1994 were faintly visible at the beginning of trawling in 1995.

On a small scale, trawling suspended and dispersed sediment, flattened the seafloor, and removed biogenic mounds and organic matter deposited in depressions. Seafloor topography recovered within 1 yr. Sediment grain size varied significantly between corridors and among years, but there was no evidence that it was affected by trawling.

Large, epibenthic organisms (*e.g.,* basket stars, snow crabs, and brittle stars) were readily visible in experimental and reference corridors, but tended to be arranged in linear features parallel to the axis of trawling in the experimental corridors.

The authors concluded that even at a depth of 120-146 m, natural disturbances such as bioturbation and storms might cause more pronounced physical changes to the bottom than those caused by trawling.

Summary

Results of 14 studies are summarized. One of them was described in a 1980 publication; the rest have been published since 1993. Six studies were conducted in North America (three in a single long-term experiment on the Grand Banks), four in Australia, and four in Europe. Ten were experimental studies. Eight of them were done in depths <60 m, one at 80 m, and four in depths >100 m. One study examined just the physical effects of trawling, nine examined just the biological effects, and four examined both. Six of the biological studies were restricted to epifauna, two were restricted to infauna, and five included both epifauna and infauna.

The only experiment that was designed to monitor recovery was the one on the Grand Banks, although surveys conducted in Australia documented changes in the abundance of benthic organisms in an area after 5 yr of fishery closures, and in an area after 15 yr of little or no fishing activity. Two studies compared benthic communities in trawled areas of sandy substrate with those in undisturbed areas near a shipwreck. Six studies were performed in commercially exploited areas, five were performed in closed areas, and two compared closed and open areas; one was done in a test tank.

All the experimental studies examined the effects of multiple tows (up to six per unit area of bottom), and the study in Australia assessed the effects of 1-4 tows on emergent epifauna. Trawling in four studies was limited to a single event (*i.e.*, 1 day to 1 wk), whereas the Grand Banks experiment was designed to evaluate the immediate and cumulative effects of annual 5-day trawling events in a closed area over a 3-yr period.

Physical Effects

A test tank experiment showed that trawl doors produce furrows in sandy bottom that are 2 cm deep, with a berm 5.5 cm high (7). In sandy substrate, trawls smoothed seafloor topographic features (4, 14), and resuspended and dispersed finer surface sediment, but had no lasting effects on sediment composition (14).

Trawl door tracks lasted up to 1 yr in deep water (14), but only for a few days in shallow water (3). Seafloor topography in deep water recovered within a year (14).

Biological Effects -- Single-Disturbance Experimental Studies

Three single-event studies (1, 2, 6) were conducted in commercially trawled areas. In one of these studies (2), otter trawling caused high mortalities of large (>1 cm) sedentary and/or immobile epifaunal species. In another study (6), there were no effects on benthic community diversity. Neither of these studies investigated effects on total abundance or biomass. In the third study (1), there were no obvious effects on macrofauna, but there were fewer organisms and species there than at an unexploited site near a shipwreck.

Two studies (4, 10) were performed in unexploited areas. In one study (10), single tows reduced the density of attached epifauna (>20 cm) by 15%, and four tows reduced it by 50%. In the other study (4), two tows removed 28% of the epifauna on mud and sand substrate, and the epifauna in all trawled quadrats showed signs of damage. (These results were not reported separately for sand bottom.) In this latter study, total infaunal abundance was not affected, but the abundance of one family of polychaetes was reduced.

Biological Effects -- Repeated-Disturbance Experimental Studies

Intensive experimental trawling on the Grand Banks reduced the total biomass of epibenthic organisms and the biomass and average size of a number of epibenthic species (13). Significant reductions in total infaunal abundance and in the abundance of 15 selected taxa (mostly polychaetes) were detected during only 1 of 3 yr, and there were no effects on biomass or taxonomic diversity (12).

Biological Effects -- Observational Studies

Changes in benthic macrofaunal abundance in a lightly trawled location in the North Sea were not correlated with historical changes in fishing effort (5). Changes in infaunal community structure at increasing distances from a shipwreck in the North Sea were related to changes in sediment grain size and organic carbon content (8).

The Alaska study (9) showed that the epifauna attached to sand was more abundant inside a closed area, significantly so for sponges and anemones. A single tow in a closed area in Australia removed 89% of the large sponges in the trawl path (11).

Otter Trawls -- Gravel/Rocky Substrate (Table 5.6)

1. Auster *et al.* (1996) observed bottom conditions during a July 1987 submersible dive at a depth of 94 m near the northern end of Jeffreys Bank, in a gravel area where there were large (>2-m diameter) boulders. A thin layer of mud covered the gravel and boulders, and the rock surfaces supported large numbers of erect sponges, sea spiders, bryozoans, hydroids, anemones, crinoid sea feathers, and ascidians. Smaller mobile fauna, including several species of crustaceans, snails, and scallops, was also abundant.

When the area was resurveyed in August 1993, much of the mud veneer was gone and there was evidence that boulders had been moved. Abundance of erect sponges was greatly reduced, and most of the associated epifaunal species were not present. The authors attributed this disturbance to otter trawling which was occurring in the area during the second survey, and which was conducted in this area only after 1987, when modifications to fishing gear allowed fishermen to trawl rocky, boulder habitat in the GOM.

2. Freese *et al.* (1999) documented the effects of single tows with a bottom trawl in an area that had been exposed to very little or no commercial trawling since the 1970s in the eastern Gulf of Alaska. The trawl was a 42.5-m “Nor’easter” otter trawl with 0.6-m diameter rubber tire groundgear attached to the footrope, and with 0.45-m diameter rockhopper disks and steel bobbins along the wings. Eight tows were made on predominantly pebble substrate (some cobble and boulders were also present) at depths of 206-274 m in August 1996. Quantitative video transects, using a two-man submersible, were made down the center of each trawl path within 2-5 hr after each tow, and in adjacent reference areas.

The trawl moved 19% of the boulders (median size of 0.75 m) it encountered. On less compact substrate, tire gear left a series of furrows that were 1-8 cm deep. On compact substrate (*i.e.*, with a greater percentage of cobble), the tire gear left no furrows, but the trawl removed an overlying layer of silt.

Single tows caused significant decreases in the density of undamaged vase sponges, morel sponges, sea whips, and anemones. Nonsignificant reductions in the density of undamaged organisms were also observed for finger sponges, brittle stars, sea urchins, and one species of sea cucumber. None of the five groups of motile invertebrates showed a significant reduction in density because of trawling. In fact, arthropods and mollusks were more abundant in the trawled areas.

Trawling also caused considerable damage to sponges and sea whips. More than 50% of the vase sponges and sea whips in the trawl transects were either damaged or removed from the substrate. Morel sponges were also damaged, but damage could not be quantified because this species is much more brittle and friable than the vase sponges, and specimens crushed by the trawl were completely torn apart and scattered. Some finger sponges were also knocked over onto the substrate. Brittle stars were also damaged, but reticulate anemones and motile invertebrates were not.

Observations of fishes made during this study showed that rockfish (*Sebastes* spp.) use cobble-boulder and epifaunal invertebrates for cover.

3. Dolah *et al.* (1987) assessed the effects of a single trawl tow on attached sponges and corals in an unexploited area on the coast of Georgia, in the southeastern United States. The bottom (depth 20 m) was smooth rock with a thin layer of sand and an extensive sessile invertebrate growth. The trawl was a 40/54 fly net with a 12.2-m headrope and a 16.5-m footrope equipped with six 30-cm rubber rollers separated by numerous 15-cm diameter rubber disks, and was attached to 1.8x1.2-m China-V doors using 30.5-m leglines.

Densities of three of the most abundant large sponges, three dominant soft corals, and one hard coral were determined by divers before trawling, immediately after trawling, and 12 mo after trawling, both inside and outside the trawl path. Sponges and soft corals <10 cm high were not counted, but all hard corals were counted. In addition, the degree of damage was evaluated.

The trawl damaged some specimens of all species, sponges more notably than corals. Immediately after trawling, undamaged sponges were less abundant, significantly so in two transects that had higher pre-trawl sponge densities. Damage was noted for 31.7% of the sponges that remained in the trawled transects immediately after trawling. Most of the reduction in, and damage to, sponges was for the most abundant species, a barrel sponge. For the other large sponges -- vase sponges and finger sponges -- there were no significant differences in density between sampling periods, although there was some evidence of trawl damage. Twelve months after trawling, sponges in the trawled quadrats were at pre-trawl densities or higher, and all damaged sponges had regenerated new tissue.

Total abundance of soft corals declined in the trawl alley immediately after trawling, and a few damaged specimens were found, but effects were minimal compared to the sponges. There were no differences between pre-trawl and post-trawl density estimates for fan and whip corals. The more abundant stick coral was less abundant immediately after trawling, but had recovered completely 12 mo later.

Divers counted 30% fewer undamaged stony corals in the trawled quadrats immediately after trawling, although the reduction was not significant. Of the seven colonies of stony coral affected by the trawl, four were moderately to heavily damaged, and three were only slightly damaged. Twelve months later, stony corals were more abundant than they were before trawling, and no damage could be detected.

Summary

Three studies of otter trawl effects on gravel and rocky substrate are summarized in this document. All three were conducted in North America. Two were done in glacially affected areas in depths of about 100-300 m using submersibles, and the third was done in a shallow coastal area in the southeastern United States.

One study involved observations made in a gravel/boulder habitat 6 yr apart (*i.e.*, before and after trawling affected the bottom). The other two were experimental studies of the effects of single trawl tows. One of these experimental studies was done in a relatively unexploited gravel habitat, and the other on a smooth rock substrate in an area not affected by trawling.

Two studies examined effects to the seafloor and on attached epifauna and one only examined effects on epifauna. There were no assessments of effects on infauna. Recovery was evaluated in one case for 1 yr.

Physical Effects

Trawling displaced boulders and removed mud covering boulders and rocks (1). Rubber tire groundgear left furrows 1-8 cm deep in less compact gravel sediment (2).

Biological Effects

Trawling in gravel and rocky substrate reduced the abundance of attached benthic organisms (*e.g.,* sponges, anemones, and soft corals) and their associated epifauna (1, 2, 3), and damaged sponges, soft corals, and brittle stars (2, 3). Sponges were more severely damaged by a single pass of a trawl than soft corals, but 12 mo after trawling all affected species, including one species of stony coral, had fully recovered to their original abundance, and there were no signs of damage (3).

Otter Trawls -- Mixed Substrates (Table 5.7)

1. The Canadian Department of Fisheries and Oceans (DFO 1993) conducted a sidescan sonar survey in the Bras D'Or Lakes system in Nova Scotia to document the physical effects of various mobile fishing gears 1 yr after the area was closed to mobile gear. Water depths ranged from 10 to 500 m, and bottom sediments included rich organic mud, clay, pebbly mud, well sorted sand, gravel, and boulders.

Otter doors left parallel marks in the sediments, with spoil ridges or berms faintly visible along their inner margins, and fainter marks between the two door marks apparently produced by the trawl footgear. These marks were seen predominantly in muddy sediments.

2. Engel and Kvitek (1998) compared a lightly fished (LF) and a heavily fished (HF) area off central California with similar sediments (gravel, sand, silt-clay) and depths (180 m) using still photographs and videotapes taken from a submersible in October 1994, and grab samples collected during 1994, 1995, and 1996. There were no differences in sediment composition between the two study sites. They estimated that any square meter of bottom area in the HF area was exposed to 12 times more trawling effort during 1989-1996 than any square meter of bottom area in the LF area.

Results indicated that the HF area had significantly more trawl tracks, shell fragments, and exposed sediment, significantly fewer rocks and biogenic mounds, and significantly less flocculent material. Based on the 1994 video transects, the densities of all six large invertebrate epifauna were higher in the LF area, significantly so for sea pens, starfish, sea anemones, and sea slugs. Based on the grab samples, the number of polychaete species was higher in the LF area in 1994 and 1996, and the densities of nematodes, oligochaetes, and brittle stars were higher in the HF area in all 3 yr (although differences, in most cases, were insignificant). No consistent (or significant) differences were detected for crustaceans, mollusks, or nemerteans. One polychaete species that was the most important prey item for three species of flounder was more abundant in the HF area in all 3 yr, significantly so in 1994 and 1996.

The authors concluded that trawling reduces habitat complexity and biodiversity, while increasing opportunistic infauna and prey important in the diet of some commercially important fish species, but that, since the study lacked controls, there was no way to be sure that the observed differences between the two areas were, in fact, due to differences in trawling intensity.

3. Smith *et al.* (1985) reported that diver observations and videotapes showed minor surface sediment disturbance (<2.5 cm deep) within the sweep path of an otter trawl with 6-ft (1.8-m) doors and 3/8-in (1-cm) footrope chain in Long Island Sound. Sediments in the study area were described as sand with mud and clay.

Much of the observed disturbance was created by turbulence suspending small epifaunal organisms, silt, and flocculent material as the net passed, rather than by direct physical contact of the net with the bottom. Trawl door tracks (<5 cm deep in sand; 5-15 cm deep in mud) were the most notable evidence of trawl passage. These tracks were soon obscured by the effect of tidal currents, but attracted mobile predators. Alteration of existing lobster burrows was minor and appeared easily repairable by resident lobsters. The use of roller gear of unspecified size on mud bottom left shallow scoured depressions; the use of spacers between disks reduced such scouring.

Summary

Three studies of the effects of otter trawls on mixed substrates are summarized. All three were conducted in North America and relied on sidescan sonar and/or observations made by divers or from a submersible.

One study (2) combined submersible observations and benthic sampling to compare the physical and biological effects of trawling in both a lightly fished and heavily fished location in California. Both locations had the same depth and a variety of sediment types. The other two studies were a survey of seafloor features produced by trawls in a variety of bottom types (1), and primarily an examination of the physical effects of single trawl tows on sand and mud bottom (3).

Physical Effects

Trawl doors left tracks in sediments that ranged from <5 cm deep in sand to 15 cm deep in mud (1, 3). In mud, fainter marks were also made between the door tracks, presumably by the footgear (1).

A heavily trawled area had fewer rocks, shell fragments, and biogenic mounds than a lightly trawled area (2).

Biological Effects

The heavily trawled area in California had lower densities of large epifaunal species (*e.g.,* sea slugs, sea pens, starfish, and anemones) and higher densities of brittle stars and infaunal nematodes, oligochaetes, and one species of polychaete (2). There were no differences in the abundance of mollusks, crustaceans, or nemerteans between the two areas. However, since this was not a controlled experiment, these differences could not be attributed to trawling.

Single trawl tows in Long Island Sound attracted predators and suspended epibenthic organisms into the water column (3).

New Bedford-Style Scallop Dredges

New Bedford-Style Scallop Dredges -- Sand (Table 5.8)

1. Auster *et al.* (1996) mapped Stellwagen Bank (GOM) in 1993 (depth 20-55 m) using sidescan sonar, and showed it to be covered by large expanses of sand, gravelly sand, shell deposits, and gravel. Waves produced by large storms from the northeast create ripples in coarse sand measuring 30-60 cm between crests and 10-20 cm high, and deposit large sheets of fine sand with low sand waves 15-35 m between crests. The troughs of these sand waves are filled with shell debris.

Gear tracks produced by trawls and scallop dredges could be distinguished in the sonar images. Examination of gear tracks in sonar images showed that scallop dredges disturb sand ripples and disperse shell deposits.

2. Langton and Robinson (1990) analyzed visual and photographic observations made during submersible transects on an offshore bank in the GOM (Fippennies Ledge) in July 1986 and June 1987. There was little evidence of scallop dredging at the dive site in 1986, but it was heavily dredged sometime between the 1986 and 1987 submersible observations (Langton and Robinson 1988). Depth near the study transects (southeastern end of the ledge) ranged from 80 to 100 m. In the areas of highest sea scallop density, the surficial sediments were usually sand with occasional shell hash and small rocks. Where there were tubes formed by amphipods or polychaetes, the sediment surface was visually a more silty organic sand. Grain size analysis revealed that the upper 5 cm of sediment was uniform throughout the area, and averaged 84% sand, with some gravel.

Dredged areas observed in 1987 were clearly distinguishable from undredged, or not recently dredged, areas. The most obvious result of dredging was a change from organic silty sand to gravelly sand. This was apparently due to the disruption of amphipod tube mats. Occasionally, piles of rock and scallop shells were observed, apparently deposited there when dredges were emptied at the surface.

Densities of three dominant megafaunal species (sea scallops, burrowing anemones, and a tube-dwelling polychaete) declined significantly between 1986 and 1987, apparently because of dredging.

3. Watling *et al.* (2001) evaluated the geochemical and biological effects of scallop dredging in an estuary (Damariscotta River, Maine). The study site was located on an unexploited side of the estuary in a shallow (15 m), silty sand area with a low density of sea scallops. Bottom samples for sediment chemistry, microbiology, and fauna were collected by divers in a control and an experimental plot before and after intensive dredging (23 tows in 1 day) using a 2-m-wide chain-sweep dredge towed at 2 knots. Sampling of benthic macrofauna (primarily infauna) was conducted 4 and 5 mo before dredging, immediately before and after (1 day) dredging, and 4 and 6 mo after dredging, by divers with push cores.

The immediate effects of dredging were the loss of fine material from the top few centimeters of the sediment surface, and a reduction in its food value (significant reductions in enzymatically hydrolysable amino acids and total microbial biomass). There was little discernible difference in the number of macrofauna taxa present after dredging, but the numbers of individuals were greatly (and significantly) reduced. Some taxa (families) showed little difference between the control and treatment site the day after dredging, while others were reduced in abundance. Significant reductions were noted for one family each of polychaetes (Nephtyidae) and amphipods (Photidae).

In the experimental plot, fine sediments still had not been restored 6 mo after dredging, whereas the food value of the sediments had completely recovered after 6 mo. Total macrofaunal abundance was still significantly lower 4 mo afterwards, but after 6 mo there was no longer any significant difference in the number of individuals in the two plots. Some taxa recovered sooner than others.

Summary

Three studies of the effects of New Bedford-style scallop dredges on sand substrate are summarized, and all were performed since 1990. One was conducted in an estuary on the Maine coast (3) and two on offshore banks in the GOM (1, 2). Two of them were observational in nature, but didn't include any direct observations of dredge effects. The other one was a controlled experiment conducted in an unexploited area in which a single dredge was towed repeatedly over the same area of bottom during 1 day.

One study examined physical effects and two examined physical and biological effects. One of them included an analysis of geochemical effects to disturbed silty sand sediments.

Physical Effects

Dredging disturbed physical and biogenic benthic features [sand ripples and waves (1), shell deposits (1), and amphipod tube mats (2)], caused the loss of fine surficial sediment (3), and reduced the food quality of the remaining sediment (3). Sediment composition was still altered 6 mo after dredging, but the food quality of the sediment had recovered by then.

Biological Effects

There were significant reductions in the total number of infaunal individuals in the estuarine location immediately after dredging and reduced abundances of some taxa (particularly one family each of polychaetes and amphipods), but no change in the number of taxa (3). Total abundance was still reduced 4 mo later, but not after 6 mo.

The densities of two megafaunal species (a tube-dwelling polychaete and a burrowing anemone) on an offshore bank were significantly reduced after commercial scallop vessels had worked the area (2).

New Bedford-Style Scallop Dredges -- Mixed Substrates (Table 5.9)

1. Caddy (1968) described diver observations of dredge effects in shallow sea scallop beds in the Northumberland Strait (Gulf of St. Lawrence, Canada). The depth was about 20 m and the sediments ranged in texture from mud to clean sand. Fishing operations were conducted with a 2.4-m-wide, offshore chain-sweep scallop dredge (no teeth) that was modified to reduce its weight by replacing the forward drag bars with chains. The dredge weighed 0.36 mt (800 lb) out of the water. Divers attached to the dredge made direct observations during two 5-min tows that were made at about 2 knots.

The lateral skids, located at each end of the pressure plate produced two parallel furrows approximately 3 cm deep; a series of smooth ridges between them were caused by the rings in the chain belly of the dredge. Dislodged pieces of dead shell were more evident within the drag tracks than on the surrounding bottom.

2. Caddy (1973) used a two-man submersible to observe the effects of a 2.4-m-wide, chain-sweep dredge (no teeth, weight 0.6 mt or 1300 lb out of the water) and a gang of three 0.8-m-wide, Alberton-style, toothed dredges in a previously dredged area of Chaleur Bay in the Gulf of St. Lawrence (Canada). (See "Toothed Scallop Dredges -- Mixed Substrates, 4. Caddy (1973)" for a summary of the toothed-dredge results.) Observations were made inside and outside dredge tracks within 1 hr of each tow. Depth varied from 40 to 50 m, and the substrate was sand overlaid by glacial gravel, 1-10 cm in diameter, with occasional boulders up to 60 cm in diameter embedded in the gravel.

Dredging suspended fine sediments and reduced visibility from 4-8 m to <2 m within 20-30 m of the track, but the silt cloud dispersed within 10-15 min of the tow, coating the gravel in the vicinity of the track with a thin layer of fine silt. The chain-sweep dredge left a flat track that increased in depth from just below the sediment surface to several centimeters deep at the end (tows were 0.8-1.2 km long). Over areas of sand and fine gravel, marks were left by individual belly rings, and the tow bar left a narrow depression in the center of the track. The edge of the track was sometimes marked by an impression left by the lateral skids.

Gravel fragments were less frequent inside the track, and many were overturned. Rocks 20-40 cm in diameter were dislodged every 10-30 m of track. Some boulders were overturned and others were plowed along, leaving a groove several meters long. Empty holes left by some of the rocks were evident.

3. Mayer *et al.* (1991) investigated the effects of scallop dredging at a shallow (8 m) nearshore site on the Maine coast with a mixed mud, sand, and shell hash substrate. The site was dragged with a New Bedford-style, chain-sweep dredge (presumably once, although no information was provided), and core samples were collected before dredging and 1 day after dredging inside and outside the dragged track.

Dredging lowered the substrate by 2 cm and tilled the sediment to a depth of 9 cm, causing finer material (sand and mud) to be injected into the lower 5-9 cm of the sediment profile, and increasing mean sediment grain size to >5 cm. (No statistical tests were performed with these data). Organic matter profiles were strongly affected by dredging. Total organic carbon and nitrogen at the new sediment-water interface were markedly reduced in concentration after dredging, and carbon concentrations in the 5-9 cm sediment depth interval were considerably higher in the dredged site.

A diatom mat on the surface of the sediment was disrupted by the dredge and partially buried. The microbial community of the surface sediments increased in biomass following dredging.

Summary

Three studies have been conducted on mixed glacially derived substrates, two of them over 20 yr ago and one 10 yr ago. All were done in the Northwest Atlantic (one in the United States and two in Canada) at depths of 8-50 m.

Two observational studies examined physical effects and one experimental study examined effects on sediment composition to a sediment depth of 9 cm. The experimental study evaluated the immediate effects of a single dredge tow. None of these studies evaluated habitat recovery or biological effects, although one (3) examined geochemical effects.

Physical Effects

Direct observations in dredge tracks in the Gulf of St. Lawrence documented a number of physical effects to the seafloor, including bottom features produced by dredge skids, rings in the chain bag, and the tow bar (1, 2). Gravel fragments were moved and overturned, and shells and rocks were dislodged or plowed along the bottom (2).

Sampling 1 day after a single dredge tow revealed that surficial sediments were resuspended and lost, and that the dredge tilled the bottom, burying surface sediments and organic matter to a depth of 9 cm, increasing the mean grain size of sediments to >5 cm, and disrupting a surface diatom mat (3). Microbial biomass at the sediment surface increased because of dredging (3).

Toothed Scallop Dredges

Toothed Scallop Dredges -- Sand (Table 5.10)

Port Phillip Bay, Australia: The physical and biological effects of toothed scallop dredges were evaluated at three sites in a large, relatively low-energy, predominantly tidal embayment in southeast Australia in 1991 that had been commercially dredged for *Pecten fumatus* since 1963. Habitat-related objectives of these studies were to test whether dredging alters turbidity and sedimentation patterns in the bay, to evaluate the physical effects of dredging on the seafloor, and to determine the magnitude and direction of changes to the benthic community caused by dredging. These studies were described in four separate publications (see below).

Depths at the three sites were similar (about 15 m), but each site had different sediments and was exposed to different current strengths and wave characteristics. Sediments at the three sites were: 1) fine and very fine sand with 15% silt-clay (St. Leonards); 2) medium fine sand with 7% silt-clay (Dromana); and 3) muddy sand with shell fragments and 30% silt-clay (Portarlington).

Three large (0.36-km^2) experimental plots (one per site) located within larger (20-30 km^2) areas which were closed to dredging in 1991 were dredged repeatedly by a fleet of 5-7 commercial dredge vessels using 3-m-wide "Peninsula"-style box dredges fitted with cutter bars that did not extend below the skids. Experimental dredging intensity at Portarlington (716 tows in 4 days during a 3-wk period) was equivalent, on average, to four tows per unit of area, and duplicated heavy commercial dredging intensity, based on historical levels of fishing effort in the bay. Dredging at the other two sites was less intensive (382 and 459 tows, and an average of two tows per unit of area) and limited to 2- or 3-day periods. The amount of commercial dredging activity in the bay declined dramatically after 1987 (Currie and Parry 1996), so the study sites had been virtually undisturbed for 4 yr when the research was conducted.

Black and Parry (1994[1], 1999[2]) and **Currie and Parry (1996[3], 1999b[4])** evaluated the physical effects of experimental dredging in Port Phillip Bay by using a variety of field sampling techniques at all three sites. Turbidity levels and dredge penetration depths were measured immediately after dredging. Visually apparent changes to the seafloor were assessed by divers with video cameras at various times before and after dredging. The last observations were made at St. Leonards 11 mo after dredging, at Portarlington 7 mo after dredging, and at Dromana 5 days after dredging.

Dredging disturbed the top 1-2 cm of sediment, but sometimes penetrated up to 6 cm in softer sediments. Turbidity plumes extending 1-2 m into the water column were created immediately behind the dredge, reaching turbidity levels within 2-16 sec after dredging which were 2-3 times greater than the turbidity caused by storms. Dredging-related turbidity levels returned to natural storm levels after about 9 min at sites which were 60 and 80 m downcurrent of the nearest boundary of the experimental dredging plots.

Video observations showed that the sediment plume was entrained across the full width of the dredge, mostly by the cutterbar. As the dredge traveled across the rough seafloor, the cutterbar trimmed off the high regions, creating turbulent pulses of sediment. Smaller sediment plumes were also produced by the skids.

Dredging at one of the experimental sites had a graderlike effect on the seafloor, flattening low-relief mounds produced by burrowing callianassid shrimp, and filling in depressions between them. Parallel tracks up to 2.5 cm deep were produced by the dredge skids. The mounds reformed after 6 mo. Flat areas between the mounds were still visible after 6 mo, but 11 mo after dredging there were no visible differences in topography between the control plot and the dredged plot. The tracks were still visible a month after dredging, but not after 6 mo.

At one of the other two sites (*i.e.*, Dromana), small parallel sand ripples in part of the dredged plot were obliterated by dredging, but reformed immediately following a storm that occurred 5 days after the area was dredged. Mounds were reformed 7 mo after dredging, but were still smaller than in the control plot.

Currie and Parry (1996[3], 1999b[4]) evaluated the biological effects of dredging on benthic infauna in Port Philip Bay. At the most intensively sampled site (St. Leonards), grab samples were collected in both a dredged plot and an adjacent control plot on three occasions before dredging, immediately after dredging, and at 3 wk and at 3.5, 5, 8, and 14 mo after dredging. Sampling at the other two sites was intended to evaluate very short-term biological effects, and was limited to the dredged plots: grab samples were taken 8 days before and 2 days after dredging at Dromana, and 10 days before and 1 day after dredging at Portarlington. In addition, a plankton net was attached to the top of the dredge to sample animals thrown up by the dredge during each tow at St. Leonards.

At the St. Leonards site, there was a significant decrease in the number of infaunal species in the dredged plot relative to the control plot 3 wk after dredging that persisted for 14 mo, but there was no effect on the total number of individuals.

In the 3.5 mo following dredging, six of the ten most common benthic species showed significant decreases in abundance of 28-79% on at least one-half of the experimental plot; most species decreased in abundance by

20-30%. At the other two sites (Portarlington and Dromana), two and three of the ten most common species, respectively, were significantly reduced in abundance within 1-2 days after dredging, but reduced sampling intensity limited the statistical power of the tests. Of the six species whose abundance was reduced significantly over the first 3.5 mo at the St. Leonards site, two were affected for 3.5 mo, two for 8 mo, and two for 14 mo. Dredging effects at this site became undetectable for most species following their annual recruitment; most species recruited within 6 mo, but a few still had not recruited after 14 mo.

Species that occurred on or near the sediment surface (*e.g.,* tube-dwelling amphipods) were released into the water column right away, whereas species inhabiting deeper sediments (*e.g.,* burrowing polychaetes) were dislodged as dredging continued. More mobile, opportunistic species inhabiting surface sediments increased in abundance during the 3.5 mo after dredging, perhaps because the removal of other species increased their food supply. Dissimilarity measures between the two plots increased after dredging, reaching a maximum 3 wk after dredging, and suggesting that there were delayed effects on community structure such as increased predation of infaunal organisms that were uncovered by dredging.

Although this research clearly demonstrates that there were biological effects of scallop dredging to benthic habitats in Port Phillip Bay, the reductions in density caused by dredging were small compared to natural changes in population densities during the year (Currie and Parry 1996). Furthermore, changes to infauna caused by dredging in 1991 were smaller than the cumulative changes to infaunal community structure in Port Philip Bay over the preceding 20 yr (Currie and Parry 1999b). Currie and Parry (1999a) also concluded that changes to benthic community structure (species composition) caused by dredging in the bay were small compared with natural differences between study areas.

5. Butcher *et al.* (1981) documented diver observations of scallop dredging in Jervis Bay, New South Wales, Australia, over large-grained firm sand shaped in parallel ridges at depths >13 m. The dredge design was not described, but had teeth that extended up to 5 cm below the leading edge of the dredge.

Dredging flattened sand ridges and produced a sediment plume extending up to 5 m into the water column that settled out within 15 min. Dredge paths were clearly visible, and "old" dredge paths could be seen.

6. Eleftheriou and Robertson (1992) examined the incremental effects of repeated scallop dredge tows in Firemore Bay, a shallow sandy bay in Loch Ewe on the west coast of Scotland in July-August 1985. The depth at the study site was about 5 m, and the sediment was well sorted sand. It was a high-energy environment exposed to wave action. Fishing (divers and beam trawls) took place in the bay during the 1970s and 1980s.

A 1.2-m-wide, Newhaven-style scallop dredge with nine, 12-cm-long teeth was towed 25 times over the same track during a 7-day period (*i.e.*, two tows on day 2, two on day 3, eight on day 4, and thirteen on day 8). The chain bag was removed from the dredge so that all organisms that passed through the mouth of the dredge were returned to the bottom for observation.

Grab samples were collected in the dredge track before and after each set of tows. Qualitative assessments of the epifaunal and large-specimen infaunal community were conducted by divers using still cameras. There was no control (undredged site) in this study, and thus no means to statistically evaluate the effects of location or natural changes on the abundance or composition of the benthic community in the bay that could have occurred during the course of this study.

Dredge teeth penetrated the bottom 3-4 cm. Dredging created furrows, eliminated natural bottom features, and dislodged large shell fragments and small stones. Sediments in this location are well-mixed by wave action to a depth below 3-4 cm, thus the dredge had no effect on the vertical distribution of grain size, organic carbon, or chlorophyll *a*. Grooves and furrows created by the dredge were eliminated shortly after dredging, the length of time depending on wave action and tidal conditions.

Infaunal invertebrates that were adapted to the stresses of a high-energy environment (*e.g.,* amphipods and bivalve mollusks) were not affected in any significant way. Sedentary polychaetes declined in abundance after 12 tows, then increased after 25 tows. Small crustaceans -- mostly cumaceans – increased in abundance after the first two tows and between tows four and twenty-five. There were no significant changes in biomass of the different infaunal taxa.

Organisms such as small infaunal crustaceans, crabs, and starfish were attracted to, and fed on, dead and damaged organisms left behind the dredge. Visual counts of living, damaged, and dead epifaunal organisms before and after each dredging event indicated some damage and mortality to organisms such as sea urchins, starfish, scallops, and crabs. Razor clams were dug up by the dredge and lay partially buried with their valves gaping and large numbers of sand lances (*Ammodytes* spp.) were killed. The plowing effect of the dredge buried, damaged, or chased away organisms such as brittle stars, burrowing anemones, and swimming crabs.

7. Thrush *et al.* (1995) conducted an experimental study of scallop dredging at two sites 14 km apart in the Mercury Bay area of the Coromandel Peninsula in New Zealand in 1991. One site was a commercial scallop fishing ground and the other site was not. The sediment at both sites was coarse sand, but was more poorly sorted and had a large fraction of shell hash at the exploited site. The depth was about 24 m at each site.

At each site, half of a plot measuring 70x20 m was dredged (five parallel tows in 1 day) using a 2.4-m-wide box dredge with 10-cm-long teeth on the lower leading edge of the dredge. Divers collected core samples and made visual observations in the dredged and undredged halves of each plot before dredging, within 2 hr after dredging, and 3 mo after dredging. Results from the two sites were treated separately because the macrobenthic communities were distinctly different. Both sites were dominated by small, short-lived benthic species.

At both sites, the dredge broke down the natural surface features (*e.g.,* emergent tubes and sediment ripples), and the teeth created grooves approximately 2-3 cm deep.

Dredging produced changes in benthic community structure that persisted for 3 mo at both sites. Significant differences in the numbers of individuals and taxa and in the densities of common macrofauna (both infauna and epifauna) were apparent immediately after dredging. The initial community-level responses at both sites were negative; there were significantly lower total densities and numbers of taxa in the dredged half-plots than in the adjacent reference half-plots.

The responses noted 3 mo later were more complex, with differences between the two sites. Effects were more pronounced and more often negative at the previously unexploited site where total density remained significantly lower in the dredged half-plot 3 mo after dredging. Six of the 13 most common taxa at this site were significantly less abundant in the dredged half-plot plot 2 hr after dredging, and five of them (*i.e.*, two phoxocephalid amphipods and three polychaetes) were still less abundant 3 mo later.

In contrast, there was a significant recovery in total density in the dredged half-plot at the exploited site after 3 mo, to the point that the total densities in the adjacent half-plots at that site were the same. Four of the thirteen most common taxa at this site were significantly less abundant 2 hr after dredging, and three of them (*i.e.*, ostracods and two species of bivalve mollusks) still had not recovered 3 mo later. Four taxa that were negatively affected 2 hr after dredging at the exploited site were more abundant in the dredged half-plot than in the control half-plot 3 mo after dredging.

The authors concluded that the differences in the recovery processes at the two sites were likely related to differences in the initial community composition and to differing environmental characteristics.

Summary

Seven studies of the effects of toothed scallop dredges on sandy bottom habitat are summarized in this document, six of them for box dredges in Australia and New Zealand, and one for Newhaven-style dredges in Scotland (6). All of the studies except one (5) were published during the 1990s. Four of the Australian studies (1-4) were done in the same location (Port Phillip Bay), at three sites that had not been disturbed by commercial dredging for 4 yr prior to the beginning of the studies. All were performed in relatively shallow water (5-24 m). Five of these studies were controlled experiments, and two (5, 6) were observational in nature. Three studies (1, 2, 5) examined just physical effects, and four evaluated both physical and biological effects. One study (7) compared effects at commercially exploited and unexploited sites with different benthic communities.

The Australian experimental studies (1-4) simulated commercial dredging activity, whereas the New Zealand study (7) evaluated the effects of multiple side-by-side tows, and the Scottish study (6) examined the incremental effects of multiple tows on the same area of bottom. In all cases, experimental dredging was limited to a single event that never lasted for more than 1 wk. In those studies (3, 4, 7) in which recovery was monitored, it ranged from 3 mo (7) to 14 mo (3, 4).

Physical Effects

Physical effects included sediment plumes (which lasted up to 15 min), the smoothing of the seafloor, tracks made by dredge skids, and furrows up to 4 cm deep created by the dredge teeth (1-7). Dredging disturbed bottom sediments to a maximum depth of 6 cm (1, 2). At a shallow, high-energy site, there was no effect on sediment composition, and dredge tracks were obliterated within a few days (6). At a deeper, less-exposed site, sand ripples that had been smoothed by dredging reformed within 5 days (4), biogenic mounds were restored after 6-7 mo (3, 4), and dredge tracks that were still visible after 1 mo had disappeared after 6 mo (4).

Biological Effects

Biological effects were variable and depended on the degree of natural disturbance, how well individual species were adapted to sediment disturbance, and whether a single dredge tow or multiple tows were made over the same area of bottom.

Two studies conducted at the St. Leonards site in the relatively low-energy, enclosed Port Phillip Bay in Australia showed that the abundance of most infaunal species was reduced by 20-30% during the first 3.5 mo after the area was dredged repeatedly during a 3-day period (3, 4). There were no effects of dredging on the total number of individuals, but there were significantly fewer species in the dredged plot 3 wk after dredging. Dredging significantly reduced the densities of six of the ten most common infaunal taxa, and increased the abundance of more mobile, opportunistic species within the first 3.5 mo of the experiment. (Two and three of the ten most common taxa were significantly reduced in abundance 1-2 days after dredging at two other sites in the bay [4]).

Research at the St. Leonards site also revealed that the surface-dwelling infauna is released into the water column right away, whereas burrowing organisms are released during later dredge tows. Most of the affected species at the St. Leonards site recovered within 8 mo, but some were still less abundant after 14 mo.

At two slightly deeper, open coastal sites in New Zealand, single tows resulted in immediate and significant decreases in the number of macrobenthic individuals and species (7). The immediate effects of dredging at an unexploited site were more pronounced and, for individual taxa, more often negative (significant reductions in six of the thirteen most common taxa) than at the site that was located in a commercial scallop dredging ground (significant reductions in four of 13 taxa). In addition, at the exploited site, total abundance was the same in the dredged and control half-plots 3 mo after dredging, but at the unexploited site, total density was still significantly higher in the control half-plot.

Repeated dredge tows in a very shallow, high-energy location in Scotland significantly increased the abundance of certain species of small infaunal crustaceans, and initially reduced but then increased the abundance of sedentary polychaetes (6). Taxa that are adapted to dynamic environments (*e.g.*, amphipods and bivalve mollusks) were not significantly affected. Dredging also caused considerable damage and mortality to large epifauna and infauna in this study.

Toothed Scallop Dredges -- Biogenic Substrate (Table 5.11)

Hall-Spencer and Moore (2000a) described the effects of scallop dredging on maerl beds, a biogenic substrate which is derived from living calcareous rhodophytes. These beds take hundreds to thousands of years to accumulate because the growth rates of the macroalgae are very slow and are particularly vulnerable to damage from mobile bottom fishing gear (Hall-Spencer and Moore 2000b).

Single tows were made at depths of 10-15 m along three 100-m transects in an area in the Clyde Sea (Scotland) that had been commercially dredged for 40 yr, and as well as along three 100-m transects in an area of the Clyde Sea that had been previously undredged. Tows used a gang of three Newhaven dredges with 10-cm-long, spring-loaded teeth mounted 8 cm apart on a horizontal metal bar that was held off the seafloor by a rubber roller at each end. Immediate effects of dredging were noted and one transect at each site was monitored by divers 2-4 times a year over the following 4 yr.

Video recordings showed, at both sites, that the rollers and chain rings were in contact with the bottom while the dredge teeth projected fully into the maerl substratum (10 cm) and harrowed the seafloor, creating a cloud of suspended sediment. Rocks and boulders <1 m^3 in diameter were dislodged and overturned, and cobbles were often wedged between the teeth and dragged through the sediment. Dredges created 2.5-m-wide tracks along which natural bottom features (*e.g.,* crab pits and burrow mounds) were erased. Sand and silt was brought to the sediment surface, and living maerl was buried. Dredge tracks remained visible for 0.5-2.5 yr depending on depth and exposure to wave action.

Most megafauna on or within the top 10 cm of the maerl was either caught in the dredges or left damaged in the dredge track. Large, fragile organisms (*e.g.,* sea urchins and starfish) were usually broken on impact, whereas strong-shelled organisms (scallops, gastropods) usually passed into the dredge intact. Deep-burrowing species escaped dredge damage. Predatory species (*e.g.,* whelks, crabs, and brittle stars) rapidly aggregated in the dredge track to feed.

Recovery rates for affected benthic species also varied considerably. Species with regular recruitment and rapid growth recovered quickly, as did mobile epibenthic species that migrated into test plots soon after dredging. Slow-growing species and/or infrequently recruiting sessile organisms remained depleted on test plots at the undredged site 4 yr after dredging occurred, whereas the previously dredged macrobenthic community returned to pre-experimental status within 2 yr.

Summary

The immediate physical and biological effects of single dredge tows were evaluated on maerl substrate in Scotland. Recovery was monitored over 4 yr.

Dredging penetrated the seafloor to a depth of 10 cm, suspending sediment, overturning boulders, erasing bottom features, and burying living maerl in dredge tracks. Some dredge tracks were only visible for 6 mo, while others remained visible for 2.5 yr, depending on depth and exposure to wave action.

Most of the megafauna in the top 10 cm of substrate was either caught in the dredge or left damaged in the dredge track. Large, fragile organisms were most vulnerable. Recovery of the epibenthic community was complete at a previously dredged site within 2 yr, but some species at an unexploited site still had not recovered after 4 yr. Slow-growing species, and species that infrequently recruited to the benthos, took much longer to recover than species with regular recruitment patterns and faster growth rates.

Toothed Scallop Dredges -- Mixed Substrates (Table 5.12)

1. **Bradshaw *et al.* (2002)** compared historical and recent benthic sample data from seven sites located south and west of the Isle of Man (in the Irish Sea) exposed to different amounts of fishing effort since the late 1930s. Sample data were available for 1938-1952

when scallop dredging in the area was very limited, and for the 1990s. Some of these data were analyzed earlier by Hill *et al.* (1999).

Analysis of sediment samples indicated that five of the sites were predominantly sand, and two were gravel. No depth information was provided. Fishing disturbance for each site was evaluated in terms of: 1) total fishing effort by a sample fleet during 1981-1993, and that effort's inverse coefficient of variation (*i.e.*, higher values indicate a more even distribution of fishing disturbance from year to year); 2) the number of years since fishing began; and 3) a fishermen's ranked index of total fishing effort at each site since the start of the fishery. Smallscale (*e.g.,* grab) and largescale (*e.g.,* trawls) samples were pooled for each site so that the analysis would include the greatest possible range of infaunal and epifaunal animals.

There was a significant temporal effect across all sites, and at two sites where spatial and temporal replicate samples were available, the historical samples were distinct from the recent samples. Taxa that decreased in abundance between the two time periods included species of brittle stars, hydroids, upright and encrusting bryozoans, encrusting worms, and barnacles. Taxa that increased in abundance between the two time periods included large-bodied tunicates, mobile crustaceans (shrimp, spider crabs, and squat lobsters) and robust scavengers (whelks, hermit crabs, and starfish). Taxa that became more abundant, on average, scored higher in terms of life history characteristics that would increase their ability to survive dredging (highly mobile, deep burrowers, scavengers, mud/sand sediment preference, robust body types, and good regeneration and recolonization powers) than those that became less abundant (sessile, shallow burrowers/nest builders, suspension or filter feeders, shell/stone substrate preference, fragile body types, and poor regeneration and recolonization powers).

For individual sites, mean faunal similarities between the two time periods decreased significantly as the fishermen's index of effort and the number of years since fishing began increased. Similarly, the proportion of species "lost" between the two sampling periods increased significantly as the number of years of fishing increased. Faunal similarities and proportions of lost species between time periods were not significantly related to increased fishing effort, as estimated from fishermen's logbooks. These results suggested to the authors that it was the length of time over which fishing occurred, rather than absolute levels of effort, which was important in structuring benthic communities.

For all sites, there was also no clear evidence of a relationship between changes in taxonomic diversity and fishing effort, although taxonomic distinctness -- probably the best indicator of changes in biodiversity – decreased over time at two of the most heavily fished sites.

2. Bradshaw *et al.* (2000) analyzed density estimates of epibenthic animals made during diver surveys in the undisturbed portion of a 2-km^2 area near the Isle of Man, in the Irish Sea, that was closed to commercial fishing by towed gear in 1989. The entire area adjacent to and inside the closed area had been heavily dredged for 50 yr prior to the closure. Depth in the study area ranged from about 25 to 40 m, and the seafloor was a mixture of gravel, sand, and mud. The diver surveys started in 1989, the year the area was closed, and were repeated in 1990 and then in every other year until 1998.

A number of epifaunal species increased significantly in abundance over the 9-yr period, including brittle stars, a spider crab, scallops, hermit crabs, and one species of starfish. The most significant changes occurred in the fifth, seventh, and ninth years after the area was closed.

3. Bradshaw *et al.* (2001) assessed the effects of scallop dredging on benthic communities inhabiting mixed substrates in the closed area described in the preceding review [Bradshaw *et al*. (2000)]. Two experimental plots inside the closed area were each dredged every 2 mo or so from January 1995 to 1998, using two sets of four, spring-loaded, Newhaven scallop dredges towed 10 times along a single dredge track. Two control plots were established inside the closed area. Three additional plots were located outside the closed area in a commercial scallop dredging ground. Grab samples were collected twice a year starting in 1995 in all seven plots.

After the first 6 mo of experimental dredging, benthic community structure in the experimental plots was more similar to the commercially dredged plots, and less similar to the control plots, than it had been before dredging began. This trend continued over the next 3 yr of the experiment. However, none of these differences were significant, nor were there any clear trends for particular species or groups of species.

Dredging also had no significant effect on total species numbers or richness, but there was evidence that dredging reduced benthic community heterogeneity. Sessile epifaunal organisms were considered to be especially sensitive to dredging disturbance and were analyzed separately; one dataset (March 1998) revealed that encrusting bryozoans, encrusting sponges, and small ascidians were more common in dredged plots, while upright forms such as bryozoans and hydroids were more common in the undredged plots.

4. Caddy (1973) used a two-man submersible to observe the effects of 0.8-m-wide toothed dredges in Chaleur Bay, Gulf of St. Lawrence, in August 1971. A gang of three dredges was attached to a common steel towing bar. The upper and lower edges of each dredge mouth were armed with blunt teeth 4 cm long. Observations were made inside and outside dredge tracks within 1 hr of each tow. Depth varied from 40 to 50 m, and the substrate was sand overlaid by glacial gravel and cobble, 1-10 cm in diameter, with occasional boulders up to 60 cm across embedded in the gravel.

Tracks left by these dredges were shallow with a flat floor. Gravel was sparser inside than outside the track, and dislodged boulders were commonly observed. Tooth marks were seen over sandy bottom. Spoil ridges were left between adjacent dredges, and piles of small rocks were seen at intervals along the track. Small rocks were also "bulldozed" along in front of the dredge.

5. The Canadian Department of Fisheries and Oceans (DFO 1993) conducted a sidescan sonar survey in the Bras D'Or Lakes system in Nova Scotia to document the physical effects of various mobile fishing gears 1 yr after the area was closed to mobile gear. Water depths ranged from 10 to 500 m.

Dredge tracks consisting of a series of parallel furrows made by the dredge teeth were observed in gravelly bottoms and occasionally in silty bottoms. On the older or degraded dredge tracks, the furrows left by the teeth were not always resolved. In a soft bottom area, berms were visible at the outer edges of the dredge track. Similar berms were not seen in harder bottom areas.

6. Kaiser, Hill, *et al.* (1996) compared the immediate effects of beam trawling and scallop dredging on large epibenthic fauna on a heavily fished scallop ground off the southwest coast of the Isle of Man, adjacent to the closed area studied by Bradshaw *et al.* (2001). Three parallel waylines, 500 m apart and 1 nmi long, were established: one was fished 10 times with a 4-m commercial beam trawl fitted with an 80-mm diamond-mesh cod-end, one was left undisturbed, and one was fished 10 times with two gangs of four Newhaven spring-toothed dredges. The benthos in all three waylines was surveyed using a 2.8-m beam trawl with a 40-mm square-mesh cod-end before, and 24 hr after, fishing.

Prior to fishing, there were no significant differences between the epibenthic communities on the three waylines. Both gears greatly reduced the abundance of most species and altered community structure, but there were no significant differences in community structure between the two experimental waylines after fishing. The scallop dredges caught a lower proportion of nontarget species.

7. Kaiser, Ramsay, *et al.* (2000) examined the structure of infaunal and epifaunal benthic communities exposed to either high or low scallop dredging activity, based on fishing effort data, in the Irish Sea between 1986 and 1996. Samples were collected with an anchor dredge, a grab sampler, and a small beam trawl from five sites subjected to low fishing effort, and from five sites subjected to high fishing effort. Only large infaunal organisms (>10 mm) were retained in sediment samples since they were judged more sensitive to physical disturbance. The study area was located south of the Isle of Man, in the Irish Sea, in the center of one of the most heavily fished scallop grounds in Europe, in gravel and coarse sand sediments.

After accounting for habitat effects (caused by variations in median sediment grain size and depth), the only significant response to increased fishing was a higher number of epifaunal organisms. There were no significant effects on the number or diversity of epifaunal species nor on any of the community indices for infauna.

Benthic communities in the heavily fished areas were dominated by higher abundances of smaller-bodied species, whereas the less intensely fished areas were dominated by lower abundances of larger-bodied species. Species with higher mean densities or catch rates in the low-effort sites included a soft coral, two species of sea urchin, a bivalve mollusk, and two gastropods. Species that were more abundant in the high-effort sites included three species of brittle star and a sea urchin.

8. Veale *et al.* (2000) compared samples of epibenthic organisms collected with a gang of four Newhaven type spring-toothed scallop dredges in 1995 on 13 commercial fishing grounds in the Irish Sea that had been exposed to different amounts of fishing effort during the preceding 60 yr. The dredges were equipped with short teeth (76 mm) and small belly rings (57 mm). Annual estimates of fishing effort were available from detailed, high-resolution fishermen's logbooks. Depths ranged from 20 to 67 m, and sediment types were generally coarse sand and gravel, overlain with pebbles, cobbles, and dead shell.

Of all environmental parameters examined (including depth and bottom hardness and texture), a combination of long- and short-term fishing effort best explained the observed differences in dredge bycatch assemblages across sampling sites. Species diversity and richness, total number of species, and total number of individuals all decreased significantly with increasing fishing effort. Total abundance, biomass, and production, and the production of most of the major individual taxa investigated, decreased significantly with increasing effort. Species that were more abundant at the high-effort sites included starfish, soft corals, spider crabs, and the crab *Cancer pagurus*. Spider crabs and soft corals were also more abundant at the medium-effort sites.

Summary

This section summarizes the results of eight studies that assessed the effects of toothed scallop dredges on mixed glacially derived substrates. All but one (4) of these studies were done since 1993. Six of them were conducted in the Irish Sea and two in eastern Canada. The Canadian studies (4, 5) examined physical effects to the seafloor, and the Irish Sea studies evaluated effects on benthic infauna and epifauna.

Two of the Irish Sea studies (2, 6) were experimental. One study (1) compared benthic sample data collected at sites exposed to variable amounts of historical fishing effort, and another (3) involved diver surveys in a closed area. One of the two experimental studies (6) evaluated the effects of a discrete scallop dredging and beam trawling event on large epifauna in a commercially exploited area, and the other (2) examined the incremental effects of repeated, bimonthly tows over a 3-yr period in a closed area.

Physical Effects

Physical effects of scallop dredging in mixed substrates included furrows made by the teeth, shallow, flat tracks with spoil ridges or berms at the edges, dislodged boulders, and the “bulldozing” of small rocks by the dredge (4, 5). No information on recovery times was available.

Biological Effects

In the closed area study (3), 6 mo of experimental dredging (total of 30-40 tows per dredge track with eight dredges on three or four different occasions) following a 6-yr period with no dredging altered benthic community structure, but not significantly. There were no trends in the abundance of individual species or number of species, but there was evidence of reduced benthic community heterogeneity. Three years after dredging began, upright species were less abundant, and encrusting species were more abundant. (These changes may have occurred earlier, but this could not be verified). A number of epifaunal species increased significantly in abundance in the closed area 5-9 yr after the area was closed (2).

Experimental dredging in commercial fishing grounds in the Irish Sea altered the community structure of large epifaunal populations (6), while areas exposed to 10 yr of high fishing effort were characterized by significantly higher numbers of epifaunal organisms (7). Chronic exposure to high fishing effort did not significantly affect infaunal communities, and there were no significant effects of increased scallop dredging activity on the number of epifaunal species or species diversity, but there was a shift from benthic communities dominated by greater numbers of larger species to fewer numbers of smaller species (7).

Sites exposed to low fishing activity during the late 1930s to early 1950s, and high fishing activity during the 1990s, were characterized by fewer “disturbance-vulnerable” species and more “disturbance-tolerant” species (1). Furthermore, faunal differences and the percentage of species “lost” between the low- and high-effort time periods increased as the number of years since fishing began increased. Overall, there was no clear evidence of reduced species diversity between the two time periods.

Invertebrate bycatch collected in dredges at high-effort sites was composed of significantly fewer species and individuals than at low and medium-effort sites, and total abundance, biomass, and production, and the production of individual taxa declined significantly with increasing fishing effort (8).

Other Nonhydraulic Dredges

Other Nonhydraulic Dredges -- Biogenic Substrate (Table 5.13)

1. Fonseca *et al.* (1984) conducted research near Beaufort, North Carolina, in 1982 to determine the effects of small, hand-pulled, bay scallop dredges on eelgrass. Two, 65-cm-wide, lightweight dredges (no teeth on the dredge foot) were fixed to a single tow bar. Two study sites were selected, an exposed site with compacted silty sand sediments (19.8% silt-clay), and a protected site where sediments were less compact and had a slightly higher silt-clay content (22.3%). Three small quadrats at each site were dredged 15 times, three were dredged 30 times, and three were not dredged at all.

There was a significant decrease in both the number of eelgrass shoots and the biomass of eelgrass leaves with increasing dredging effort at each site. Both shoot number and leaf biomass were reduced to zero at the soft bottom site after 30 dredge pulls, but the hard-bottom site lost more biomass than the soft-bottom site because the initial biomass there was higher. The proportional reduction in shoot number was greater at the soft-bottom site.

The authors concluded that intensive scallop dredging for bay scallops with this gear or with the heavier dredges that are pulled by powerboats has the potential for immediate as well as long-term reduction of eelgrass nursery habitat.

2. Langan (1998) conducted a study in 1994 to determine the effects of dredge harvesting on an eastern oyster population and its associated benthic community in the Piscataqua River, which divides the states of New Hampshire and Maine. An oyster bed approximately 18 acres in size in the river channel is divided nearly equally by the border between the two states. Maine allowed commercial harvesting of oysters, but New Hampshire did not, for many years prior to the study. The dredge used on the Maine side of the river was 30 in (76 cm) wide, weighed approximately 27 kg, had blunt 8-mm teeth, and had a chain-mesh bag. Commercial dredging on the Maine side of the river (with one dredge, about twice a week) had continued for 5 yr prior to the study. A limited number of benthic samples were collected by divers on each side of the river on one sampling occasion. Turbidity was measured during a single dredge tow.

No significant differences were found in the number, species richness, or diversity of epifaunal or infaunal invertebrates between the two areas. The concentration of suspended sediment in near-bottom water during the dredge tow was slightly more than double the ambient level 10 m behind the dredge, and dropped off to the ambient level 110 m behind the dredge.

3. Lenihan and Peterson (1998) conducted a study in the Neuse River estuary in North Carolina to determine if the loss of eastern oysters from the river was in part due to the lowering of oyster reefs by oyster dredges. Eight, 1-m-tall, oyster-shell reefs were constructed in two depths (3 and 6 m). Nineteen months later, four of the eight reefs were dredged by a commercial dredge vessel for 1 wk until the catch of market-sized oysters in each haul declined to near zero and remained constant. The height of harvested and unharvested reefs was measured 3 days before dredging started and 2 days after dredging stopped.

Dredging reduced the mean height of the 1-m reefs by 29±6 cm. Unharvested reefs lost only 1±1 cm of height over the 1-wk duration of the experiment.

4. Riemann and Hoffmann (1991) assessed the effects on the water column of mussel dredging in a shallow eutrophic sound (Limfjord) in Denmark that had a mean depth of 7 m and a maximum depth of 15 m. Suspended particulate matter, oxygen, and nutrient (phosphorus and ammonia nitrogen) levels were measured at a number of stations throughout the water column at a dredged and a control site before dredging, immediately afterwards, and 30 and 60 min later. No information on sediment type was given. Dredging was performed for 15 min with a 2-m-wide mussel dredge weighing about 100 kg.

Average suspended particulate matter increased significantly immediately after dredging, but returned to pre-dredge levels 60 min later. Particulate matter also increased markedly on a day with high wind velocity. Oxygen decreased significantly immediately after dredging, particularly near the bottom. Average ammonia content also increased after dredging, but large horizontal variations prevented detailed interpretation of these increases.

Summary

Four studies are summarized. Three studies were conducted on the U.S. Atlantic coast, and one was conducted in Denmark. All studies were performed in shallow water, two in rivers and two in coastal waters with a maximum depth of 15 m. Two studies evaluated biological effects, one examined physical effects, and one examined geochemical effects in the water column. Three studies were experimental and one was observational.

Physical and Biological Effects

These studies showed that dredging lowered the height of oyster reefs (3) and, in a shallow enclosed fjord, temporarily increased water column turbidity and lowered dissolved oxygen concentrations, especially near the bottom (4). There were no detectable effects after 5 yr of oyster dredging on benthic invertebrate abundance, species richness, or diversity (2). Repeated tows with hand-hauled bay scallop dredges significantly reduced eelgrass biomass (1).

Hydraulic Clam Dredges

Hydraulic Clam Dredges -- Mud (Table 5.14)

Hall and Harding (1997) evaluated the effects of experimental suction dredging on intertidal infaunal communities in Auchencairn Bay, on the north side of the Solway Firth, on the west coast of Scotland. Sediments were 60-90% silt-clay in the inner bay and 25-60% silt-clay in the middle and outer bay. Commercial dredging for the cockle *Cerastoderma edule* in the bay was prohibited 4.5 mo before experimental dredging began. Core samples were collected in control plots prior to each dredge tow, and in experimental plots immediately after, and 1, 4, and 8 wk after each dredge tow.

Dredge tracks could not be seen after the first day. The total number of infaunal individuals and species increased in both plots over time, but were significantly lower in the experimental plots than in the control plots immediately after dredging and after 4 wk. Species diversity also increased significantly over time, but was not significantly different in the two plots at any point during the experiment. Three of the five dominant species were significantly reduced by dredging over the course of the study. By the end of the study (8 wk), much of the difference between dredged and control sites had been lost.

Summary

Results of a single experimental study are summarized. It examined the physical and biological effects of individual suction dredge passes in an intertidal mud habitat, and monitored recovery for 8 wk.

Dredging produced dredge tracks that disappeared after 1 day. There were significant reductions in the total number of infaunal individuals and species that lasted 4 wk, and three out of five dominant species were reduced in abundance during the entire 8-wk duration of the experiment. However, infaunal community structure recovered nearly completely by the end of the experiment.

Hydraulic Clam Dredges -- Sand (Table 5.15)

1. Hall *et al.* (1990) studied the physical and biological effects of a commercial escalator dredge used to harvest razor clams (*Ensis* spp.) in a shallow sea loch (Loch Gairloch) on the west coast of Scotland in November 1989. The depth at the study site was 7 m, and the sediment was fine sand. The study site was located near a recently dredged area, but was not exploited itself. Experimental and control plots were visually inspected and sampled by divers immediately after dredging and 40 days later. Each experimental plot was dredged intensively for approximately 5 hr in order to simulate commercial fishing activity.

After dredging, the experimental plots were criss-crossed by shallow trenches (0.5 m wide and 0.25 m deep) interspersed with larger holes (up to 3.5 m wide and 0.6 m deep) that were presumably produced when the dredge remained stationary for a brief period. Sediment in the holes and trenches was "almost fluidized," and sediment in the fished area had a significantly higher median particle size than sediment in the control plots. After 40 days, however, none of these features remained.

The number of infaunal species and individuals were reduced in the experimental plots immediately after dredging (significantly, for individuals), but there were no detectable differences between experimental and control plots 40 days later. There were no significant differences in the abundance of individual species in the control and experimental plots on either sampling occasion.

The authors concluded that dredging caused a short-term, nonselective reduction in the numbers of all infaunal species and that recovery from physical effects was accelerated by a series of winter storms and considerable sediment disturbance in the study area. No attempt was made to assess the mortality of: 1) large polychaetes and crustaceans that were observed to be retained on the wire-mesh conveyor belt or that fell off the end of the belt, or 2) ocean quahogs that were often cracked by the dredge.

2. Kaiser, Edwards, *et al.* (1996) investigated the effects of suction dredging for cultivated manila clams (*Tapes philippinarum*) [since reclassified and renamed as Japanese littleneck clam (*Venerupis philippinarum*)] on a muddy sand intertidal flat in southeastern England during December 1994. Samples of benthic infauna and sediment were collected prior to, 3 hr after, and 7 mo after harvest in one cultivated plot and in nearby control locations.

There were significantly higher densities of infaunal organisms in the cultivated plot versus the control plots prior to dredging, but no differences in the number of species or in four indices of taxonomic diversity. During dredging, large amounts of fine sand were resuspended by the dredge, exposing the underlying clay. Immediately after dredging, there were significant reductions in the mean numbers of infaunal species and individuals in the cultivated plot, resulting in levels that were statistically the same as in the control plots. Crustaceans and bivalve mollusks were particularly affected. Seven months later there were no significant differences between the benthic community in the harvested plot and in the control plots, and the proportion of fine sand in the harvested plot had increased significantly, indicating that recovery from the effects of clam cultivation and harvesting was complete.

3. MacKenzie (1982) sampled the benthic invertebrate assemblages of three ocean quahog beds with contrasting fishing histories located about 65 km east of Cape May, New Jersey, in the MAB, during October 1978. One bed had never been fished, one had been actively fished for 2 yr, and one had been fished for about a year but then abandoned 4-5 mo prior to this study. All three beds were in very-fine-to-medium sand sediments in 37 m of water. Commercial dredging was conducted with cage dredges in this area. Sampling was limited to a total of 30 grab samples from all three sites.

No significant differences were found in numbers of invertebrate individuals or species, nor in species composition, between the recently abandoned and never dredged sites, or between the actively dredged and never dredged sites. Hydraulic dredging thus did not appear to have any lasting effect on the invertebrate populations in these beds. Comparison of samples from the recently abandoned and never dredged sites also indicated that hydraulic jetting of the bottom re-sorts bottom sediments, leaving shell fragments on the surface and coarser sediments at the bottom of dredge tracks.

4. Maier *et al.* (1995) assessed the effects of escalator dredges in four muddy sand tidal creeks in South Carolina by comparing pre- and post-dredging turbidity levels and benthic infaunal assemblages. Turbidity was monitored 2 wk before, during, and 2 wk after dredging at one location, and during and immediately after dredging at another. Infaunal samples were collected 3 wk before and 2 wk after dredging in a creek that had been commercially dredged 5 yr prior to the study, and in a creek that had never been dredged before.

Turbidity was elevated near the dredge and immediately downstream while it was operating, but the sediment plumes only persisted for a few hours. Sampling failed to detect any significant changes in the abundance of dominant infaunal taxa, or in the total numbers of individuals, after dredging.

5. Medcof and Caddy (1971) utilized divers and a submersible to compare the physical effects of a hydraulic cage dredge in shallow-water (7-12 m) sand inlets in southern Nova Scotia, Canada.

On sand and sand-mud habitats, hydraulic dredges left smooth tracks with steeply cut walls that averaged 20 cm deep, and then slowly filled in by slumping. The hydraulic dredge raised a sediment cloud that seldom exceeded 0.5 m high and usually settled within 1 min. Dredge tracks were still easily recognizable after 2-3 days.

6. Meyer *et al.* (1981) observed the effects of a small (1.2-m-wide) hydraulic clam cage dredge in an Atlantic surfclam bed located near Rockaway Beach on the south shore of Long Island, New York. The study was conducted in 1977, 3 yr after the area was closed to commercial clamming. The sediment in the study area was fine-to-medium sand covered with a 7.5-cm-thick layer of silt, and the maximum water depth was 30 m. The study area was exposed to strong bottom currents that caused considerable movement of sand. As part of a larger study to evaluate gear performance, the effects of dredging on bottom substrate and fauna were assessed by divers during, immediately after, and 2 and 24 hr after, a single 2-min tow.

The dredge formed trenches that were initially rectangular, as wide as the dredge, and over 20 cm deep. Mounds of sand 15-35 cm wide and 5-15 cm high were formed on either side of the trench. The dredge raised a cloud of silt 0.5-1.5 m high, which settled within 4 min. Slumping of the trench walls began immediately after the tow and became more apparent with time. Two hours after dredging, slumping of the trench walls had rounded the depression. After 24 hr, the dredge track was less distinct, appearing as a series of shallow depressions, and was difficult to recognize.

The dredging attracted predators, with lady and Atlantic rock crabs preying on damaged clams, and with starfish, horseshoe crabs, and moon snails attacking exposed but undamaged clams. By 24 hr after dredging, the abundance of predators appeared to have returned to normal, and the most obvious evidence of dredging was whole and broken clam shells without meat.

7. Pranovi and Giovanardi (1994) studied the effects of a 2.7-m-wide hydraulic cage dredge in 1.5-2 m depths in the Venice Lagoon (Italy, Adriatic Sea). Divers collected samples of sediment and benthic organisms from experimentally dredged and control areas at two sites located inside and outside a commercial fishing ground immediately after experimental dredging and every 3 wk for 2 mo. A single tow was made at each site.

The dredge created 8-10 cm deep furrows, one of which was clearly visible 2 mo later. In this study, sediment grain size was not significantly affected by dredging, although portions of the fishing ground which had been predominantly silt and clay 15 yr earlier had a considerably higher sand content at the time of the study. Hydraulic dredging in this area often cracks the shells of bivalve mollusks.

Inside the fishing ground, total numbers and biomass of benthic infauna and epifauna were significantly reduced in the experimental plot immediately following dredging. Densities, especially of small species and epibenthic species, recovered 2 mo later, but biomass did not. Inside the fishing ground, there were also fewer species in the dredged area than in the control area immediately after, and 3 and 6 wk after, dredging, but no differences 2 mo afterwards. Outside the fishing ground, immediately after passage of the dredge, there were no significant faunal differences between dredged and undredged areas.

8. Tuck *et al.* (2000) examined in March 1998 the effects of hydraulic dredging on the seafloor and benthic community in a shallow (2-5 m) site that is located in the Outer Hebrides (Sound of Ronay) on the west coast of Scotland, and that was closed to commercial dredging. Sediments in the study area consisted of moderately well sorted medium or fine sand, and tidal currents reached speeds as high as 3 knots. Divers collected core samples and made observations and video recordings before, during, and immediately after dredging inside and outside six dredge tracks, and then returned to re-examine the site 5 days and 11 wk after dredging. The dredge was a commercial dredge that is used to harvest razor clams and that employs a hollow blade that protrudes 0.3 m into the sediment and that has holes to direct pressurized water forward into the sediment.

Immediately after dredging, the track had distinct vertical walls and a depth similar to the dredge blade. However, once the dredge was hauled, the sidewalls collapsed and the tracks had a flat-bottomed "V" shape. The sediment within the base of the tracks was fluidized to a depth of approximately 0.3 m and within both sidewalls to approximately 0.15 m. The tracks were still clearly visible after 5 days, but less pronounced, and the depth of fluidized sediment remained the same. After 11 wk, the tracks were no longer visible, but 0.2 m of sand was still fluidized. Immediately after fishing, there was significantly less silt in the sediments inside the tracks than outside, but there was no difference after 5 days.

Numerically, the infauna at the study site was dominated by polychaetes. There was a significant decrease in the proportion of polychaetes, and an increase in amphipods, in the dredge tracks within 5 days of dredging, but not after 11 wk. Bivalve mollusks -- other than razor clams -- were not affected by dredging. Within a day of dredging, the total number of species and individuals was significantly lower in the dredge tracks, but there was no difference after 5 days. Dredging had an immediate positive and negative effect on the abundance of a number of individual species. For some species, the effect persisted for 5 days, but no effects were detected 11 wk after dredging. Owing to the strong currents, there was a very sparse epifauna in the area; the only observed effect of dredging was the attraction of crabs into the area to scavenge on material disturbed by the dredge.

Summary

Results of eight hydraulic dredge studies in sandy substrates are summarized. Five studies examined the effects of "cage" dredges of the type used in the Northeast Region of the United States (3, 5-8), two examined the effects of escalator dredges, and one examined the effects of suction dredges. Three of them were published prior to 1990, and five since then. Four were performed in North America, one in the Adriatic Sea, and three in the United

Kingdom. One study was conducted on the U.S. continental shelf at a depth of 37 m, five in shallower nearshore waters (1.5-12 m), and two in intertidal environments. Three studies were observational in nature (3, 5, 6), and five were controlled experiments (1, 2, 4, 7, 8).

Three studies (2, 3, 7) compared effects in commercially dredged and undredged areas, and four (1, 4, 6, 8) were conducted in previously undredged areas. Six studies examined the effects of individual dredge passes (2, 4-8), one evaluated the effects of repeated passes in the same area during a short period of time (1), and one compared infaunal communities in an actively dredged, a recently abandoned, and an never dredged location (3). Seven studies examined physical and biological effects, and one was limited to physical effects (5). All of the biological studies examined effects to infauna. Recovery was evaluated in four cases for periods ranging from 40 days to 7 mo (1, 2, 7, 8).

Physical Effects

Hydraulic clam dredges created steep-sided trenches 8-30 cm deep that started deteriorating immediately after they were formed (1, 5-8). Trenches in a shallow, inshore location with strong bottom currents filled in within 24 hr (6). Trenches in a very shallow, protected, coastal lagoon were still visible 2 mo after they were formed (7).

Hydraulic dredges also fluidized sediments in the bottom and sides of trenches (1, 8), created mounds of sediment along the edges of the trench (6), resuspended and dispersed fine sediment (1, 2, 4-6, 8), and caused a re-sorting of sediments that settled back into trenches (3). In one study (8), sediment in the bottom of trenches was initially fluidized to a depth of 30 cm, and in the sides of the trench to 15 cm. After 11 wk, sand in the bottom of the trench was still fluidized to a depth of 20 cm. Silt clouds only last for a few minutes or hours (4-6).

Complete recovery of seafloor topography, sediment grain size, and sediment water content was noted after 40 days in a shallow sandy environment that was exposed to winter storms (1).

Biological Effects

Some of the larger infaunal organisms (*e.g.,* polychaetes and crustaceans) retained on the wire mesh of the conveyor belt used in an escalator dredge, or that drop off the end of the belt, presumably die (1). Benthic organisms that are dislodged from the sediment, or damaged by the dredge, temporarily provided food for foraging fish and invertebrates (6, 8). Predator densities returned to normal within 24 hr in one study (6).

Hydraulic dredging caused an immediate and significant reduction in the total number of infaunal organisms in three studies (1, 2, 8), and in the number of both infaunal and epifaunal organisms in a fourth study (7). There were also significant immediate reductions in the number of species of infauna in two cases (2, 8), and in the number of species and biomass of both infauna and epifauna in a third case (7).

In one study using a hydraulic cage dredge, polychaetes were the most affected in the short term (7); in another study using a suction dredge, crustaceans and bivalve mollusks were the most affected in the short term (2). Two studies of the effects of escalator dredging failed to detect any reduction in the abundance of individual taxa (1, 4). In one of them (4), dredging did not reduce the number of infaunal organisms. Evidence from the study conducted off the New Jersey coast indicated that the number of infaunal organisms and species, and the species composition, were the same in actively dredged and never dredged locations (3).

Recovery times for infaunal communities were estimated in four studies. Three of these studies (1, 7, 8) were conducted in very shallow (1.5-7 m) water, and one (2) in an intertidal environment. Total infaunal abundance and species diversity had fully recovered only 5 days after dredging in a location where tidal currents reach maximum speeds of 3 knots (8). In the latter study, all species which had been initially reduced due to dredging had recovered after 11 wk. In another study, total abundance recovered 40 days after dredging (when the site was first revisited) at a site exposed to winter storms (1). Total infaunal abundance, but not biomass, recovered within 2 mo at a commercially exploited site, but not at a nearby unexploited site (7). Full recovery at the intertidal site was noted when it was first revisited 7 mo after it was suction dredged (2). Actual recovery times at this site and at one of the exposed subtidal sites (1) may have been much quicker than 7 mo and 40 days.

Hydraulic Clam Dredges -- Mixed Substrates (Table 5.16)

Murawski and Serchuk (1989) used manned submersibles to observe effects of hydraulic dredging on sand, mud, and gravel bottom habitats in a number of offshore locations in the MAB between Delaware Bay and Long Island (water depths not reported).

They reported that hydraulic cage dredges penetrate deeper into the sediments and, on a per-tow basis, result in greater short-term disruption of the benthic community and underlying sediments than do scallop dredges (no data were provided). In coarse gravel, the sides of hydraulic dredge trenches soon collapsed, leaving little evidence of dredge passage. There was also a transient increase in bottom-water turbidity. In finer-grained, hard-packed sediments, tracks persisted for several days after dredging.

Nonharvested benthic organisms (*e.g.,* sand dollars, crustaceans, and polychaetes) were substantially disrupted by the dredge. Sand dollar assemblages appeared to recover quickly, but short-term reductions in infaunal biomass were considered likely. Numerous predatory fish (*e.g.,* red hake, spotted hake, and skates) and invertebrates (Atlantic rock crabs and starfish) were observed consuming broken quahogs in and near dredge tracks. Densities of crabs and starfish were estimated to be two-and-a-half times higher in dredge tracks than in nearby undredged areas within 1 hr of experimental tows, and >10 times higher 8 hr after dredging. Presumably, the benthic infauna "tilled up" by the dredge was also being consumed, since not all predators observed foraging in the dredge paths were eating damaged shellfish.

Summary

An in situ evaluation of hydraulic dredge effects in sand, mud, and coarse gravel in the MAB indicated that trenches fill in quickly -- within several days in fine sediment, and more rapidly than that in coarse gravel. Dredging dislodged benthic organisms from the sediment, attracting predators.

Hydraulic Clam Dredges -- Biogenic Substrate (Table 5.17)

1. Godcharles (1971) experimentally evaluated the physical effects of escalator dredging in seagrass (*Thallasia testudinum* and *Syringodium filiforme*) beds, *Caulerpa* algae beds, and bare sand bottoms (depth not given) in Tampa Bay, Florida, in 1968. Dredging was conducted with a commercial dredge at six sites. Water jets penetrated sediments to a maximum depth of 45 cm and left trenches that varied from 15 to 45 cm deep.

Trenches were deeper in shallow areas where propeller wash scoured loose sediments from trenches and prevented redeposition of suspended sediments. The proportion of fine sediment in some trenches decreased immediately after passage of the dredge. Virtually all attached vegetation in the path of the dredge was uprooted, leaving open bottom areas.

Trenches in grass beds remained visible the longest (up to 86 days), while those in sandy areas filled in immediately. Most fluidized sediments hardened within 1 mo, but some spots were still soft 500 days after dredging. Differences in silt-clay content between tracks and undisturbed areas became negligible after a year, but seagrasses had still not recolonized disturbed areas. New algal growth was noted in some dredged areas after 86 days, and after 1 yr, dredge tracks were completely covered.

2. Orth *et al.* (1998) assessed damage to submerged aquatic vegetation caused by escalator dredges in Chincoteague Bay, Virginia, during 1996, 1997, and 1998.

They reported a large number of circular "scars" in the vegetation, with 70-100% seagrass cover outside the scarred areas, and an abrupt reduction to 15% or less at the scar edge. The percent cover of seagrass was low across the scar except for an abrupt increase in cover at the center, where seagrass had not been disturbed.

There were no measurable differences in percent cover estimates in the scarred portions of areas that were dredged during the 3 yr of observation, indicating that revegetation was proceeding very slowly. There were two factors that the authors believed were delaying revegetation: an increase in depth of 10-20 cm in the dredge tracks, and large holes inside the unvegetated portions of the scars made by organisms such as foraging cownose rays. The authors concluded that even the most lightly effected areas would require a minimum of 5 yr to fully recover.

Summary

Two studies were performed in the southeastern United States in shallow, subtidal, vegetated habitats. One study was a controlled experiment that compared the effects of escalator dredges in vegetated (seagrass and algae) and unvegetated areas; the other study evaluated damage to seagrass beds caused by commercial escalator dredging.

In the experimental study (1), water jets penetrated sand substrate to a maximum depth of 45 cm, created trenches up to 30 cm deep, uprooted vegetation, and decreased the proportion of fine sediments in dredge tracks. Recovery times were extremely variable. In some cases, trenches were visible for only 1 day, and in other cases for 3 mo. In most cases, sediments hardened within 1 mo, but in some tracks, sediments were still fluidized 500 days after dredging. After 1 yr, sediment composition in dredge tracks had returned to normal, but seagrass had not recolonized disturbed areas.

In the observational study (2), there were no signs of recovery of seagrass in commercially dredged areas 3 yr after dredging.

Pots and Traps

Pots and Traps -- Mixed Substrates (Table 5.18)

Eno *et al.* (2001) evaluated the effects of crab and lobster pots on attached epibenthic megafauna (sponges, bryozoans, ascidians, soft corals, and tube worms) at three locations in Great Britain: one each off Scotland, Wales, and England.

Off the west coast of Scotland (Badentarbet Bay), the effects of dropping pots onto sea pens were observed by divers in a soft-mud, pot fishing ground for Norway lobster (*Nephrops* sp.) in 1995. In addition, three experiments were conducted to assess sea pen survival and recovery following dragging, uprooting, and smothering by lobster pots. In one experiment, divers dragged pots over marked areas of the seafloor and recorded the fate of sea pens for 3 days after the disturbance. In the second experiment, groups of sea pens removed from the seafloor by the pots were relocated to an undisturbed location, and their behavior and survival were observed over a 4-day period. In the third experiment, 60 pots were dropped onto individual or small groups of sea pens and then removed after 24 or 48 hr to simulate the effects of smothering that would occur during commercial operations.

Video observations at the Scottish site showed that the pressure wave created by pots as they sink to the bottom was sufficient to bend sea pens away from the pot just before contact. Results of the three experiments revealed that all sea pens were able to fully recover from pot impact. Furthermore, all sea pens recovered from the effects of dragging within 24-72 hr. Uprooted sea pens reinserted themselves into the sediment, providing the peduncle gained contact with the mud surface. Following smothering for either 24 or 48 hr, it took 72-96 and 96-144 hr, respectively, for all three species of sea pen to fully recover an upright position.

At five coastal sites in Lyme Bay, southwest England, SCUBA divers assessed the immediate effects of pot hauling in different habitats at depths of 14-20 m in September and October 1995. Habitats varied from exposed limestone slabs and bedrock covered by sediment, to large boulders with mixtures of various rocky substrates interspersed with coarse sediment. A variety of fragile epifaunal species, including a sea fan and Ross coral, were present. Two lines of three pots were deployed at each site. Divers videorecorded pots as they landed on the seafloor, and as they were hauled back, and then videorecorded back along the path of each pot after its removal.

There were very few signs of effect on epifaunal species at any of the five sites. Gorgonians (soft corals) were frequently seen to bend under the weight of pots, then spring back once the pots had passed. When pots were hauled back along the bottom, a track was left in the sediments.

At Greenala Point, Wales, and in Lyme Bay, the effects of potting on selected epibenthic species were quantified by diver observations at sites with rocky substrates, water depths <23 m, and fragile epifaunal species. Common epifaunal species included a sea fan and a colonial emergent bryozoan. A commercial pot fishery for crabs (*Cancer pagurus*) and lobsters (*Homarus gammarus*) was carried out in these two locations. Each location was divided into two control and two experimental plots. Pots were set in the experimental plots and hauled every 2 or 3 days for 4 wk, such that at least 30 pots and 10 anchor weights landed in each experimental plot over the course of the study.

At the Greenala Point site, the abundance of four sponge species increased significantly in the experimental plots after 4 wk of potting, but not in the control plots. At the Lyme Bay site, one species of sponge, an ascidian, and a bryozoan increased significantly in abundance in the experimental plots only.

Summary

Observations and experiments were carried out in a single study conducted at three coastal locations in Great Britain to evaluate the effects of crab and lobster pot fishing on attached epibenthic megafauna. Sea pens underneath pots were bent over and some were uprooted when pots were dragged over mud sediments, but they fully recovered within 72-144 hr after pots left on the bottom for 24 or 48 hr were removed. When pots were dragged over the bottom they left tracks, but 4 wk of simulated commercial pot fishing had no negative effect on the abundance of attached benthic epifauna. In fact, seven taxa (five sponges, an ascidian, and a bryozoan) increased in abundance after 4 wk of fishing..

Multiple Gear Types

Multiple Gear Types -- Sand (Table 5.19)

1. Almeida *et al.* (2000) surveyed the southern half of Closed Area II on Georges Bank in June 1999, 4.5 yr after that area was closed to gear used to catch groundfish (bottom trawls, scallop dredges, longlines, and gill nets). This portion of the closed area ranges in depth from slightly <50 m to slightly >90 m, the substrate is sand, and there are sand ripples and bedforms in the shallower, northwest, "high-energy" portion of the survey area where bottom tidal currents are stronger. These features are generally absent from the deeper (>65 m), "low-energy," southeast portion of the survey area. Still photographs and video imagery were used to assess the relative abundance of seven microhabitats at a series of paired stations just inside and outside the closed area boundary.

No significant differences were found for any microhabitat type except for the emergent sponge epifauna (*e.g., Suberites ficus* and *Polymastia* sp.) microhabitat type that was more abundant inside the closed area.

2. Kaiser, Spencer, *et al.* (2000) sampled infauna and epifauna with a 2-m beam trawl and an anchor dredge along the south Devon coast in England of three high-fishing-effort areas open to all fishing (otter trawl, beam trawl, scallop dredge, and pots), in two medium-fishing-effort areas open to mobile gear for 6 mo out of the year and to pots year-round, and in one low-fishing-effort area only open to pots. Sampling within each of the six areas was distributed among three sites. At each trio of sites, sediments followed a gradient from fine sand to medium sand to coarse-medium sand. Fine-sand sites (inshore) were located in 15-17 m depths. The medium sand and coarse-medium sand sites (offshore) were located in 53-70 m depths.

For epifauna, there were significant habitat effects (*i.e.*, depth and substrate) on the numbers of species and individuals, and on two indices of species diversity, but there were no significant fishing effort effects (high versus low) on any of these parameters. In general, however, as fishing disturbance increased, less mobile, larger-bodied, and more fragile epifaunal species decreased in abundance, while mobile, more resilient species increased in abundance. Areas closed to draggers had higher abundances of emergent fauna (*i.e.*, soft corals and hydroids) that increased habitat complexity.

For infauna, there were significant habitat effects (*i.e.*, depth and substrate) on the number of species and on one index of species diversity between the two offshore sites, but no consistent fishing effort effects across all three sites, and only one significant fishing effort effect (on species diversity) between the two deeper offshore sites (*i.e.*, greater effect at the coarse-medium sand sites). Infaunal biota in the three different habitats were affected to different extents by increasing levels of fishing. In particular, the deeper, medium-coarse sand habitat seemed most severely affected by fishing. Several infaunal species in this habitat had significantly lower biomasses and abundances.

Areas subjected to low fishing effort were dominated by epifaunal and infaunal species with relatively high biomass, whereas areas subjected to high fishing effort had fewer high-biomass species and greater abundances of smaller-bodied species.

Summary

The results of two observational studies of multiple gear types on sand habitats (at depths that varied from 15 to >90 m) are summarized. A recent study in U.S. waters on eastern Georges Bank (1) compared the amount of cover provided by different habitat types inside and outside an area closed to trawls, dredges, longlines, and gill nets for 4.5 yr. Another recent study (2) compared sandy shallow and deepwater sites on the south coast of England that were exposed to low, medium, and high levels of fishing effort by mobile and fixed gears.

On Georges Bank, the only significant difference was a higher abundance of emergent sponges inside the closed area (1). On the south coast of England, low-effort areas that were closed to trawls and dredges had more emergent epifauna (soft corals and hydroids) and were dominated by relatively high-biomass epifauna and infauna, whereas high-effort areas fully exposed to fixed and mobile gears had higher abundances of small-bodied organisms (2). Deep (53-70 m), coarse-medium sand, offshore sites were more affected by fishing than deep, medium sand, offshore sites, or shallow (15-17 m), fine-sand, inshore sites (2).

Multiple Gear Types -- Gravel/Rock (Table 5.20)

1. Collie *et al.* (1997) sampled two relatively shallow (42-47 m) and four relatively deep (80-90 m) gravel sites in U.S. and Canadian waters on the northern edge of eastern Georges Bank during two cruises in 1994. Bottom substrates at the sites were predominantly pebble-cobble with or without encrusting organisms, with some overlying sand. The sites were classified as disturbed (D) or undisturbed (U) by bottom-tending mobile gear based on the number of dredge and trawl tracks in sidescan sonar images, the presence or absence of large boulders and epifauna in bottom photographs, and 1993 records of scallop dredging effort in TMSs of latitude and longitude in U.S. waters on the bank. There were three U sites and one D site in deep water, and one U and one D site in shallow water.

Quantitative samples of epibenthic organisms (>10 mm) were collected with a 1-m-wide naturalist dredge fitted with a 6.4-mm square-mesh liner. Organisms such as colonial sponges, bryozoans, hydroids, and the tube-dwelling polychaete *Filograna implexa* that were not quantitatively sampled by the dredge were excluded from analysis.

There were significant effects of fishing and depth combined on total density, biomass, and an evenness diversity index based on abundance, as well as some evidence of a gradient in abundance, biomass, and species diversity from deep undisturbed sites (high values) to shallow disturbed sites (low values). However, because of the significant depth effects and depth-disturbance interactions, fishing disturbance alone was not a significant factor.

Cluster analysis identified a group of six species that were abundant at U sites, rare or absent at D sites, and not affected by depth. This group included two species of shrimp, a tube-dwelling polychaete, a nemertean, horse mussels, and a bloodstar. Six other species groups were defined by either depth or some combination of depth and disturbance level, or included species that were ubiquitous.

2. Collie *et al.* (2000), in a follow-up publication, analyzed video images and still photographs recorded at five of the six study sites surveyed in the two 1994 research cruises to George Bank (*i.e.*, one of the deep U sites was not included).

In the videotapes, the U sites at both depths had slightly coarser sediments (higher frequency of pebble-gravel than sand-gravel); in the still photos, there was a higher frequency of sand and cobble in U sites and a lower frequency of pebbles. Bottom photos showed a high percent cover of colonial hydroids and bryozoans at one of the deep U sites, and of the rock encrusting polychaete *Filograna implexa,* at both deep U sites. In contrast, at the D sites, the gravel was free of epifaunal cover, and few animals were visible. Statistical analysis confirmed that the

U sites had a significantly higher percent cover of *Filograna implexa*. However, cover provided by this species was also significantly greater in deeper water than in shallow water.

Emergent hydroids and bryozoans were significantly more abundant at the deep U sites than they were at the shallow U site. Overall, the percent cover of all emergent epifauna was significantly higher at the deep sites, but there was no significant disturbance effect.

Summary

Two recent observational studies of mobile gear effects on sediments and epifauna in gravel bottom habitat on the northern edge of eastern Georges Bank (42-90 m) are summarized. Study sites were distinguished by depth and the presence or absence of fishing disturbance. Sediments in undisturbed sites were slightly coarser with more sand and cobble. There were significantly more organisms, higher biomass, and greater species diversity at the undisturbed sites in both depths, but there were also significantly higher values in disturbed and undisturbed deep sites than in disturbed and undisturbed shallow sites.

Percent cover of an encrusting colonial polychaete was also significantly higher at the deep sites and at the undisturbed sites. Emergent hydroids and bryozoans were significantly more abundant in deep undisturbed sites, and at shallow disturbed sites. Overall, emergent epifauna was more abundant in deep water, but there was no significant disturbance effect.

Multiple Gear Types -- Mixed Substrates (Table 5.21)

1. Auster *et al.* (1996) used a remotely operated vehicle (ROV) in July 1993 to compare conditions inside and outside an inshore area (depth 30-40 m) in the GOM that was closed to mobile fishing gear in 1983. On sand-shell bottom, video transects indicated that habitat complexity was provided mostly by sea cucumbers attached to shell and other biogenic debris, and by bottom depressions created by mobile fauna. Both of these habitat features were significantly less common outside the closed area, a difference that was attributed to the incidental exploitation of sea cucumbers and the harvest of lobsters, sea scallops, crabs, and white hake -- all animals that produce depressions.

On cobble-shell bottom, habitat complexity was provided mostly by emergent epifauna (*i.e.*, hydroids, bryozoans, sponges, and serpulid worms) and sea cucumbers. These species were less common outside the closed area. Their reduced abundance was attributed to removal by mobile fishing gear.

Cleared swaths in epifaunal cover were observed at the border of the closed area and were presumed to be caused by scallop dredges and trawl doors.

Auster *et al.* (1996) also conducted sidescan sonar surveys and ROV observations of Stellwagen Bank (GOM) in 1993 (depth 20 -55 m). The sonar images showed that showed large expanses of sand, gravelly sand, shell deposits, and gravel. The authors reported that waves produced by large storms from the northeast create ripples in coarse sand that measure 30-60 cm between crests and 10-20 cm in height, and deposit large sheets of fine sand with low sand waves 15-35 m between crests. The troughs of these sand waves are filled with shell debris (mostly ocean quahogs). Examination of the sonar images also showed scallop dredge and trawl tracks that disturbed sand ripples and dispersed shell deposits.

The ROV observations on Stellwagen Bank's crest (32-43 m deep) indicated that aggregations of emergent hydrozoans were missing, and that benthic microalgal cover was disturbed in gear tracks. Observations on the crest of the bank in July 1994 showed that an ascidian species was widely distributed, but was not present in otter trawl tracks.

2-4. Reise (1982), Riesen and Reise (1982), and Reise and Schubert (1987) compared invertebrate surveys in the Wadden Sea (Netherlands) made between 1869 and 1986. Bottom sediments in these areas currently range from mud to coarse sand and some pebbles. The area is made up of tidal flats, shallow subtidal banks, and channels that reach depths of 23 m. Surveys were completed using oyster dredges and grabs.

During the time period encompassed by the various surveys, abundant oyster reefs were overexploited, seagrass beds were lost to a natural epidemic, and *Sabelleria* reefs were destroyed by heavy trawl gear. The area is now dominated by soft sediments and mussel beds, which prior to 1920 were restricted to very shallow water. Comparisons show that 28 mollusk and amphipod species (including eight associated with oyster beds, eight with *Sabelleria*, and seven with seagrasses) have declined in abundance. Twenty-three species (many of them polychaetes) that were missing or rare in earlier surveys were common in 1986. The epifauna was more abundant in the 1920s, and the infauna was more abundant in the 1980s.

5. Thrush *et al.* (1998) tested 10 predictions regarding the effects of increasing fishing pressure on benthic communities in the Hauraki Gulf, New Zealand. Core, grab, and suction dredge samples were taken from 18 stations exposed to varying levels of commercial fishing effort by otter trawls, Danish seines, and toothed scallop dredges. Additional data were obtained from video images using an ROV, and from sediment samples collected by divers. Sediments ranged from sand (<1% silt and clay) to mud (nearly 50% silt-clay) and depths from 17 to 35 m.

After accounting for the effects of location, depth, and sediment characteristics (grain size and organic matter content), 15-20% of the variability in macrofauna (>0.5 mm) community composition was attributed to fishing pressure.

Most of the predictions were supported by analysis of the core-sample data; fewer predictions were supported by other sample types. Three predicted results of increasing fishing pressure were confirmed at $P<0.05$: decreased density of large epifauna (video transects), decreased species diversity and richness (core samples), and decreased density of echinoderms (cores). Four additional predictions were confirmed at $P<0.10$: decreased number of individuals (grabs), increased density of small opportunistic species (cores), decreased density of long-lived surface dwellers (cores), and increased density of deposit feeders (cores). The large members of the epifauna were also less abundant in grab samples collected from more heavily fished sites ($P<0.10$).

Results, in some cases, were not consistent among sample types. Species diversity and richness, for example, were not even identified as significant model variables in the grab sample data, nor was the number of individuals in the core samples, and deposit feeders collected in grab samples were significantly less abundant at sites exposed to increased fishing pressure.

Two predictions were contradicted by the results of this study: the ratio of polychaetes to mollusks (in cores) decreased rather than increased with greater fishing pressure, and the ratio of small to large individuals, for one common species of sea urchin, increased rather than decreased (also in cores). Further, scavengers (large, mobile benthic organisms such as crabs and starfish) were predicted to increase with increasing fishing pressure, but there was no evidence from this study that they responded either positively or negatively to changes in fishing intensity.

6. Valentine and Lough (1991) used sidescan sonar and a submersible to describe the effects of scallop dredges and bottom trawls on sand and gravel habitats on eastern Georges Bank. They noted that the most evident signs of disturbance occurred on gravel pavement where they observed long, low mounds of gravel that presumably had been produced by trawling and dredging. In some areas, the seafloor was covered by trawl and dredge tracks.

Gravel areas that were not accessible to bottom-tending mobile gear (due to the presence of large boulders) had a biologically diverse community with abundant attached organisms. Conversely, the attached epifaunal community was sparse, and the bottom was smoother, in areas that had been disturbed by dredging and trawling.

Summary

Six observational studies of the effects of multiple gear types on mixed substrates are summarized. Surveys were conducted in the GOM inside and outside an inshore area closed to mobile fishing gear, and in an offshore area that was disturbed by mobile fishing gear (1). A series of three publications examined long-term (100+ yr) changes in benthic habitats and communities in the Wadden Sea, some of which were attributed to fishing (2-4). A study in New Zealand (5) tested 10 predictions of how increasing fishing activity affects benthic communities by comparing benthic samples and underwater video footage from areas exposed to varying degrees of commercial fishing effort. A sixth study (6) examined areas on eastern Georges Bank that were affected by mobile bottom gear.

Significant increases were observed in the abundance of sea cucumbers and emergent epifauna, and in the number of bottom depressions created by organisms such as lobsters, sea scallops, and crabs, on sand-cobble-shell substrate inside the GOM closed area (1). Sidescan sonar and ROV surveys of Stellwagen Bank revealed evidence that otter trawls and New Bedford-style scallop dredges disturb sand waves and ripples, disperse shell deposits, remove emergent epifauna, and disturb microalgal cover (1). Disturbed sand and gravel areas of Georges Bank were characterized by trawl and dredge tracks, sparse epifauna, mounds of gravel presumably produced by fishing gear, and smoother bottom (6). In the New Zealand study (5), there were four significant effects of increased fishing activity by bottom trawls, Danish seines, and toothed scallop dredges in mud and sand substrates that were consistent across all sampling methods. These effects were reduced density of large epifauna, echinoderms, and long-lived surface-dwelling organisms, and an increased density of small, opportunistic species. The loss of biogenic reefs and changes in benthic community composition (fewer mollusk and amphipod species and more polychaete species) in the Wadden Sea were in part attributed to fishing activity (2-4).

Table 5.1. Number of studies included in this review, by gear and substrate type. (PR = peer-reviewed; NPR = non-peer-reviewed.)

Gear	Substrate	1990-2002			Pre-1990			Total
		PR	NPR	Total	PR	NPR	Total	
Otter Trawls	Mud	9	2	11	0	0	0	11
	Sand	10	2	12	1	0	1	13
	Gravel/Rock	2	0	2	1	0	1	3
	Mixed	1	1	2	0	1	1	3
	All	22	5	27	2	1	3	30
NB Scallop Dredges	Sand	3	0	3	0	0	0	3
	Mixed	1	0	1	2	0	2	3
	All	4	0	4	2	0	2	6
Toothed Scallop Dredges	Sand	6	0	6	0	1	1	7
	Biogenic	1	0	1	0	0	0	1
	Mixed	6	1	7	1	0	1	8
	All	13	1	14	1	1	2	16
Hydraulic Clam Dredges	Mud	1	0	1	0	0	0	1
	Sand	4	1	5	2	1	3	8
	Biogenic	0	1	1	0	1	1	2
	Mixed	0	0	0	0	1	1	1
	All	5	2	7	2	3	5	12
Other Dredge	Biogenic	2	1	3	1	0	1	4
Multiple Gears	Sand	2	1	3	0	0	0	3
	Gravel/Rock	2	0	2	0	0	0	2
	Mixed	2	1	3	3	0	3	6
	All	7	1	8	3	0	3	11
Lobster Pots	Mixed	1	0	1	0	0	0	1
Total	**All**	**53**	**11**	**64**	**11**	**5**	**16**	**80**

Table 5.2. Number of studies included in this review, by substrate type. (PR = peer-reviewed; NPR = non-peer-reviewed.)							
Substrate	**1990-2002**			**Pre-1990**			**Total**
	PR	NPR	Total	PR	NPR	Total	
Mud	10	2	12	0	0	0	12
Sand	25	4	29	3	2	5	34
Gravel/Rock	4	0	4	1	0	1	5
Biogenic	3	2	5	1	1	2	7
Mixed Substrate	11	3	14	6	2	8	22
Total	**53**	**11**	**64**	**11**	**7**	**18**	**80**

Table 5.3. Number of studies included in this review, by geographical area. (PR = peer-reviewed; NPR = non-peer-reviewed.)					
Gear	**Northeast Region**	**Other North America**	**Europe and Scandinavia**	**Australia and New Zealand**	**Total**
Bottom Otter Trawl	7	10	8	5	30
New Bedford Scallop Dredge	4	2	0	0	6
Toothed Scallop Dredge	0	2	8	6	16
Hydraulic Clam Dredge	2	5	5	0	12
Other Dredge	3	0	1	0	4
Multiple Gears	5	0	5	1	11
Lobster Pot	0	0	1	0	1
Total	**21**	**19**	**28**	**12**	**80**

Table 5.4. Effects of otter trawls on mud substrate habitat: summary of published studies. (S = statistically significant; citations in bold print are peer-reviewed publications.)

No.	Reference	Location	Depth	Sediment	Effects	Recovery	Approach
1	Ball *et al.* 2000	Irish Sea	75 m	Sandy silt	Reduced infaunal and epifaunal richness, diversity, number of species, and individuals in fishing ground compared to wreck site, but no obvious effects on macrofauna 24 hr after trawling.		Experimental trawling in heavily fished prawn fishing ground, unfished area near a shipwreck used as control.
2	**Brylinsky *et al.* 1994**	Bay of Fundy, Nova Scotia, Canada	Intertidal	Silt and coarse sand overlain with silt	Door tracks in sediment, rollers compressed sediment; S decrease in nematodes and benthic diatoms in door tracks, no effects on larger infaunal organisms (mostly polychaetes).	Furrows visible 2-7 mo; nematodes recovered in 1-1.5 mo, diatoms in about 1-3 mo.	Four trawling experiments (repeated tows during a single day) at two locations in a trawled area, effects evaluated for 1.5-4 mo.
3	DeAlteris *et al.* 1999	Narragansett Bay, Rhode Island, USA	14 m	Mud	Doors produced tracks 5-10 cm deep and adjacent berm 10-20 cm high.	No changes in hand dug trenches for >60 days.	Diver observations.
4	**Drabsch *et al.* 2001**	Gulf of St. Vincent, South Australia	20 m	Fine silt	Trawl door tracks, smoothing of topographic features; S decrease in total infaunal abundance and one group of polychaetes, damaged epifauna.		Experimental trawling (two tows per unit of area in 1 day) in area with no trawling for 15 yrs (one site); effects evaluated after 1 wk.
5	**Frid *et al.* 1999**	Northeast England (North Sea)	80 m	Silt-clay	S increase in total number of individuals in taxa predicted to increase at high fishing effort and number of errant polychaetes; no effect of increasing effort on total number of individuals expected to decrease, but S decline in sea urchins.		Related changes in benthic fauna in a heavily trawled location to low, high, and moderate fishing activity and to changes in phytoplankton production over 27 yr.
6	**Hansson *et al.* 2000**	Fjord on the west coast of Sweden	75-90 m	Clay	Abundance of 61% infaunal species negatively affected and S reductions in abundance of brittle stars during last 5 mo of disturbance period; S reductions in total biomass at 3 of 3 trawled sites and 1 of 3 control sites, and in number of individuals at 2 of 3 trawled sites and 1 of 3 control sites; abundance of polychaetes, amphipods, and mollusks not affected.		Experimental trawling for 1 yr (two tows per wk, twenty-four tows per unit of area) in area closed to fishing for 6 yr (three treatment and three control sites); effects evaluated during last 5 mo of experiment.
7	**Mayer *et al.* 1991**	Maine coast, USA	20 m	Mud	Dispersal of fine surface sediment; doors made furrows several cm deep; some planing of surface features, but no plowing of bottom or burial of surface sediments.		Experimental trawling (single tow); examined immediate effects on sediment composition and food value to sediment depth of 18 cm.
8	**Pilskaln *et al.* 1998**	Gulf of Maine, USA	250 m	Mud	Greater abundance of suspended infaunal polychaetes in more heavily trawled area.		Deployed sediment traps in fishing grounds 25-35 m above substrate.
9	**Sanchez *et al.* 2000**	Coast of Spain, Mediterranean Sea	30-40 m	Mud	Door tracks in sediment; no change in number of infaunal individuals or taxa, or in abundance of individual taxa; no changes in community structure.	Door tracks still clearly visible after 150 hr.	Experimental trawling in trawled area at two sites swept once and twice in a single day; effects evaluated after 24, 72, 102, and 150 hr.

Table 5.4 (cont.). Effects of otter trawls on mud substrate habitat: summary of published studies. (S = statistically significant; citations in bold print are peer-reviewed publications.)

No.	Reference	Location	Depth	Sediment	Effects	Recovery	Approach
10	**Sparks-McConkey and Watling 2001**	Penobscot Bay, Maine, USA	60 m	Mud	S decline in porosity, increased food value, and increased chlorophyll production of surface sediments; S reductions in number of infaunal individuals and species, species diversity, and abundances of 6 polychaete and bivalve species, S increase in nemerteans.	All geochemical sediment properties and all but one polychaete/bivalve species recovered within 3.5 mo, nemerteans still more abundant after 5 mo.	Experimental trawling (four tows in 1 day) in untrawled area; pre-trawl sampling of sediments and infauna for a year; recovery monitored for 5 mo.
11	**Tuck *et al.* 1998**	West coast of Scotland	30-35 m	Fine silt	Tracks in sediment, increased bottom roughness; no effect on sediment characteristics; S increase in number of infaunal species at end of 16 mo disturbance period and during 18 mo recovery period; no change in biomass or number of individuals at end of recovery period; S increase in polychaetes, S decrease in bivalves; mixed results of analyses of community structure, S reduction in diversity during first 22 mo.	Door tracks still evident after 18 mo; bottom roughness recovered after 6 mo; nearly complete recovery of infaunal community within 12 mo, complete after 18 mo.	Experimental trawling for 1 day/mo (one and a half tows per unit of area) for 16 mo in area closed to fishing for >25 years; recovery monitored after 6, 12, and 18 mo.

Table 5.5. Effects of otter trawls on sand substrate habitat: summary of published studies. (S = statistically significant; citations in bold print are peer-reviewed publications.)

No.	Reference	Location	Depth	Sediment	Effects	Recovery	Approach
1	Ball *et al.* 2000	Irish Sea	35 m	Muddy sand	Lower number of infaunal and epifaunal species and individuals, and lower species diversity and richness, compared to wreck site.		Experimental trawling in a heavily fished fishing ground; unfished area near a shipwreck used as control.
2	Bergman and van Santbrink 2000	Southern North Sea (Dutch coast)	<30-50 m	Silty sand and sand	High (20-50%) mortalities for six sedentary and/or immobile megafaunal (>1 cm) species, <20% for 10 others, from a single pass of the trawl; S effects on 11 of 54 occasions.		Experimental trawling (one- and-a-half tows per unit of area) in commercially trawled area; effects assessed after 24-48 hr.
3	**DeAlteris *et al.* 1999**	Narragansett Bay, Rhode Island, USA	7 m	Sand	No tracks found.	Hand dug trenches not visible after 1-4 days.	Diver observations.
4	**Drabsch *et al.* 2001**	Gulf of St. Vincent, South Australia	20 m	Coarse sand with shells	Trawl door tracks; smoothing of topographic features; removal of, and damage to epifauna; no S effects on total infaunal abundance; S reduction in density for one order of crustaceans 1 wk of trawling.		Experimental trawling (two tows per unit area) in area with no trawling for 15 yr; effects assessed after 1 wk (site one) and 3 mo (site two).
5	**Frid *et al.* 1999**	Northeast England (North Sea)	55 m	Sand	Total abundance of benthic macrofauna increased as phytoplankton abundance increased; no correlation with fishing effort.		Related changes in benthic fauna in a lightly trawled location to low, high, and moderate fishing activity, and to changes in phytoplankton production over 27 yr.
6	**Gibbs *et al.* 1980**	Botany Bay, New South Wales, Australia	Shallow estuary	Sand with 0-30% silt-clay	Sediment plume; no consistent effects on benthic community diversity; very little disturbance of seafloor.		Sampling before, immediately after, and 6 mo after 1 wk of experimental trawling in a fished location; control area located 200 km away.
7	**Gilkinson *et al.* 1998**	Test tank to simulate Grand Banks of Newfoundland		Sand	Trawl door created 5.5-cm berm adjacent to 2-cm furrow; bivalves displaced, but little damage.		Observed effects of commercial otter door model in test tank.
8	**Hall *et al.* 1993**	North Sea	80 m	Coarse sand	Abundance of infauna related to changes in sediment type and organic content, not distance from shipwreck.		Sampled infauna at increasing distance from a shipwreck (proxy for increasing fishing effort).
9	**McConnaughey et al. 2000**	Eastern Bering Sea, Alaska	44-52 m	Sand with ripples	Reduced abundance (S for sponges and anemones); more patchy distribution; S decrease in species diversity of sedentary epifauna; mixed responses of motile taxa and bivalves.		Compared abundance of epifauna caught in small-mesh trawl inside and outside an area closed to trawling for almost 40 yr.

Table 5.5 (cont.). Effects of otter trawls on sand substrate habitat: summary of published studies. (S = statistically significant; citations in bold print are peer-reviewed publications.)

No.	Reference	Location	Depth	Sediment	Effects	Recovery	Approach
10	**Moran and Stephenson 2000**	Northwest Australia	50-55 m	Not given, presumed to be sand	Single tow reduced density of macrobenthos (>20 cm) by 15%, 4 tows by 50%.		Video surveys before and after four experimental trawling events (one tow per unit area) at 2-day intervals in unexploited area.
11	**Sainsbury et al. 1997**	Northwest Australia	<200 m	Calcareous sands	Decreased abundance of benthic organisms and fish associated with large epifauna; removal of attached epifauna (single tow removed 89% of sponges >15 cm).	Increased catch rates of fish associated with large epifauna and small (<25 cm) benthos within 5 yr; recovery of large epifauna takes >5 yr.	Compared historical survey data (before and after fishing started) to data collected in area that remained open to commercial trawlers and to area closed for 5 yr.
12	**Kenchington *et al.* 2001**	Grand Banks, Newfoundland	120-146 m	Fine to medium grain sand	S short-term reductions in total abundance and abundance of 15 infaunal and epifaunal taxa (mostly polychaetes) in only 1 of 3 yr; no short-term effects on biomass or taxonomic diversity; no long-term effects.	Benthic organisms that were reduced in abundance in 1994 had recovered a yr later.	Experimental trawling (3-6 tows per unit of area) in closed area 1, 2, and 3 yrs after closure; lightly exploited for >10 yrs; effects evaluated within several hours or days after trawling and after 1 yr.
13	**Prena et al. 1999**	Grand Banks, Newfoundland	120-146 m	Fine to medium grain sand	24% average decrease in epibenthic biomass; S reductions in total and mean individual epifaunal biomass, and biomass of five of nine dominant species; damage to echinoderms.		Experimental trawling (3-6 tows per unit of area) in closed area 1, 2 and 3 yr after closure, lightly exploited for >10 yr.
14	**Schwinghamer et al. 1998**	Grand Banks, Newfoundland	120-146 m	Fine and medium grain sand	Tracks in sediment; increased bottom roughness; sediment resuspension and dispersal; smoothing of seafloor and removal of flocculated organic material; organisms and shells organized into linear features.	Tracks last up to 1 yr; recovery of seafloor topography within 1 yr.	Experimental trawling (3-6 tows per unit area) in closed area 1, 2 and 3 yr after closure, lightly exploited for >10 yr.

Table 5.6. Effects of otter trawls on gravel/rock substrate habitat: summary of published studies. (S = statistically significant; citations in bold print are peer-reviewed publications.)

No.	Reference	Location	Depth	Sediment	Effects	Recovery	Approach
1	**Auster *et al.* 1996**	Jeffreys Bank, Gulf of Maine	94 m	Gravel/boulder with thin mud veneer.	Gravel base exposed; boulders moved; reduced abundance of erect sponges and associated epifaunal species; changes attributed to trawling.		Submersible and video observations in same location in 1987 and 1993.
2	**Freese *et al.* 1999**	Gulf of Alaska	206-274 m	93% pebble, 5% cobble, 2% boulder.	Boulders displaced; groundgear left furrows 1-8 cm deep in less compact sediment; layer of silt removed in more compact sediment; S reductions in abundance of sponges, anemones, and sea whips; damage to sponges, sea whips and brittle stars.		Video observations from a submersible 2-5 hr after single trawl tows in area exposed to little or no commercial trawling for about 20 yr.
3	**Dolah *et al.* 1987**	Georgia, SE U.S. coast	20 m	Smooth rock with thin layer of sand and attached epifauna.	Damage to sponges and corals, mostly to sponges; S reductions in density of undamaged barrel sponges in high-density transects; no S effects on densities of vase sponges, finger sponges, or stony corals.	Full recovery of damaged organisms and density within 12 mo.	Experimental study using diver counts of large sponges and corals before, immediately after, and 12 mo after, a single tow of a “roller” trawl in an unexploited area.

Table 5.7. Effects of otter trawls on mixed substrate habitat: summary of published studies. (S = statistically significant; citations in bold print are peer-reviewed publications.)

No.	Reference	Location	Depth	Sediment	Effects	Recovery	Approach
1	DFO 1993	Bras d'Or Lakes, Nova Scotia, Canada	10–500 m	Mud, sand, gravel, and boulders	Trawl doors left parallel marks (furrows and berms), fainter marks from footgear, primarily in mud.		Sidescan sonar survey after area was closed to mobile gear for 1 yr.
2	**Engel and Kvitek 1998**	California, USA	180 m	Gravel, sand, silt, and clay	S fewer rocks and biogenic mounds, S less flocculent material, and S more exposed sediment and shell fragments in HF area; lower densities of large epibenthic taxa in HF area (S for sea pens, starfish, anemones, and sea slugs); higher densities of nematodes, oligochaetes, brittle stars and one species of polychaete in HF area; no differences between areas for crustaceans, mollusks, or nemerteans.		Used a submersible and grab samples (3 yr) to compare lightly trawled and heavily trawled commercial fishing sites with same sediments and depth.
3	Smith *et al.* 1985	Long Island Sound, New York, USA	Not given	Sand and mud	Tracks in sediment (<5 cm in sand, 5-15 cm in mud); attraction of predators; suspension of epibenthic organisms.	Tracks "naturalized" by tidal currents.	Video and diver observations.

Table 5.8. Effects of New Bedford-style scallop dredges on sand substrate habitat: summary of published studies. (S = statistically significant; citations in bold print are peer-reviewed publications.)

No.	Reference	Location	Depth	Sediment	Effects	Recovery	Approach
1	**Auster *et al.* 1996**	Stellwagen Bank, Gulf of Maine, USA	20-55 m	Coarse sand	Smoothing of sand ripples and low sand waves; dispersal of shell deposits in wave troughs.		Examined gear tracks in sidescan sonar images.
2	**Langton and Robinson 1990**	Fippennies Ledge, Gulf of Maine, USA	80-100 m	Gravelly sand with some gravel, shell hash, and small rocks	Coarser substrate; disruption of amphipod tube mats; piles of small rocks and scallop shells dropped from surface; S reductions in densities of tube dwelling polychaete and burrowing anemone.		Submersible observations made 1 yr apart, before and after commercial dredging of area.
3	**Watling *et al.* 2001**	Damariscotta River, Maine, USA	15 m	Silty sand	Loss of fine surficial sediments; lowered food quality of sediment; reduced abundance of some taxa; no changes in number of taxa; S reductions in total number of individuals 4 mo after dredging.	No recovery of fine sediments, full recovery of benthic fauna and food value within 6 mo.	Experimental study (23 tows in 1 day); effects on macrofauna (mostly infauna) evaluated 1 day and 4 and 6 mo after dredging in an unexploited area.

Table 5.9. Effects of New Bedford-style scallop dredges on mixed substrate habitat: summary of published studies. (S = statistically significant; citations in bold print are peer-reviewed publications.)

No.	Reference	Location	Depth	Sediment	Effects	Recovery	Approach
1	**Caddy 1968**	Northumberland Strait, Gulf of St. Lawrence, Canada	20 m	Mud and sand	Drag tracks (3 cm deep) produced by skids; smooth ridges between them produced by rings in drag belly; dislodged shells in dredge tracks.		Diver observations of physical effects of two tows.
2	**Caddy 1973**	Chaleur Bay, Gulf of St. Lawrence, Canada	40-50 m	Gravel over sand, with occasional boulders	Suspended sediment; flat track, marks left by skids, rings, and tow bar; gravel fragments less frequent (many overturned); rocks dislodged or plowed along bottom.		Submersible observations of tow tracks made <1 hr after single dredge tows.
3	**Mayer *et al.* 1991**	Coastal Gulf of Maine, USA	8 m	Mud, sand, and shell hash	Lowered sediment surface by 2 cm, injected organic matter and finer sediment into lower 5-9 cm; increased mean grain size in upper 5 cm; disruption of surface diatom mat; increased microbial biomass at sediment surface.		Experimental study, compared dredged and undredged sites before and 1day after a single dredge tow.

Table 5.10. Effects of toothed scallop dredges on sand substrate habitat: summary of published studies. (S = statistically significant; citations in bold print are peer-reviewed publications.)

No.	Reference	Location	Depth	Sediment	Effects	Recovery	Approach
1,2	**Black and Parry 1994, 1999**	Port Phillip Bay, SE Australia (three sites)	15 m	Sand (7-30% silt-clay)	Sediment plume; maximum depth of disturbance 4-6 cm into bottom; cutterbar trims off high regions of seafloor.	Turbidity returned to normal storm levels within 9 min.	Experimental dredging for 2-4 days (two to four tows per unit area) in three areas with no commercial dredging for 4 yrs.
3,4	**Currie and Parry 1996, 1999b**	Port Phillip Bay, SE Australia (St. Leonards site)	15 m	Fine/very fine sand	Flattening of low-relief biogenic mounds; depressions filled in; parallel tracks produced by skids; S fewer species after 3 wks; most species 20-30% less abundant 3.5 mo after dredging; S reduced abundance of 6 of 10 most common infaunal species within first 3.5 mo (S increase for one species); no effect on total number of individuals; surface-dwelling organisms released into water column right away, burrowing organisms as dredging continued; increased abundance of more mobile, opportunistic species within first 3.5 mo.	Mounds reformed after 6 mo; tracks visible after 1 mo, but not after 6 mo; most species recovered within 8 mo, but some had not after 14 mo.	Experimental dredging for 3 days (2 tows per unit of area) in an area with no commercial dredging for 4 yr; recovery of infauna monitored at 5 intervals during 14 mo; seafloor changes at 8 days and at 6 and 11 mo.
4	**Currie and Parry 1999b**	Port Phillip Bay, SE Australia (Dromana site)	15 m	Medium-fine sand	Removal of small, parallel sand ripples; S reductions in abundance of three of ten most common infaunal species within 2 days.	Ripples reformed after 5 days following storm.	Experimental dredging for 2 consecutive days (2 tows per unit of area) in an area with no commercial dredging for 4 yr; effects on infauna evaluated after 2 days, seafloor changes after 5 days.
		Port Phillip Bay, SE Australia (Portarlington site)	15 m	Muddy sand with shell fragments	Flattening of biogenic mounds; S reductions in abundance of 2 of 10 most common infaunal species within 1 day.	Mounds reformed 7 months after dredging, but were still smaller than in undredged area.	Experimental dredging for 4 days (four tows per unit area) in an area (Portarlington) with no commercial dredging for 4 yrs; effects on infauna evaluated after 1 day, seafloor changes after 7 mo.
5	Butcher *et al.* 1981	Jervis Bay, New South Wales, Australia	>13 m	Sand	Sediment plume up to 5 m off bottom, flattening of sand ridges.	Sediment plume settled out within 15 min.	Diver observations.
6	**Eleftheriou and Robertson 1992**	Firemore Bay, Loch Ewe, Scotland	5 m	Well-sorted sand	Dredge eliminated natural bottom features; teeth created 3-4 cm deep furrows; no effect on sediment characteristics; damage or mortality of larger epifauna, razor clams, and sand lance, attraction of predators; increase in some species of small infaunal crustaceans; initial reduction in polychaetes followed by increase; no effect on taxa adapted to dynamic environment (*e.g.*, amphipods, bivalves).	Grooves and furrows no longer visible shortly after dredging, duration depended on wave and current action.	Evaluation of incremental effects of dredging (25 tows in 1 wk) at a single site (no control).
7	**Thrush *et al.* 1995**	Mercury Bay, New Zealand	24 m	Coarse sand	Breaking down of surface sediment features; grooves 2-3 cm deep created by teeth; S declines in abundance of 6 of 13 most common taxa at unexploited site, and 4 of 13 most common taxa at exploited site; S reductions in total number of individuals and taxa at both sites.	General recovery of macrobenthic abundance at previously exploited site after 3 mo, but not at unexploited site.	Experimental dredging (5 parallel tows in 1 day) at a previously exploited and an unexploited site with different benthic communities; biological effects evaluated within 2 hr and 3 mo after dredging.

Table 5.11. Effects of toothed scallop dredges on biogenic substrate habitat: summary of published studies. (S = statistically significant; citations in bold print are peer-reviewed publications.

Reference	Location	Depth	Sediment	Effects	Recovery	Approach
Hall-Spencer and Moore 2000a	Clyde Sea, Scotland	10-15 m	Live bottom (maerl) with some cobble and boulders	Disturbance of seafloor to 10 cm; overturned boulders; suspended sediment; erasure of bottom features and burial of living maerl in dredge tracks; most megafauna in top 10 cm either caught in dredge or left damaged in dredge track (large, fragile organisms more vulnerable); rapid aggregation of predatory species in track.	Dredge tracks remained visible for 0.5-2.5 yrs; some recovery rates of large epibenthic species variable, some recovering quickly, but others at unexploited site had not recovered 4 yr after dredging; macrobenthic community at previously exploited site recovered within 2 yr.	Observations of the effects of single dredge tows at a previously dredged and undredged site; immediate effects and recovery (after 4 yr) evaluated by divers using video cameras.

Table 5.12. Effects of toothed scallop dredges on mixed substrate habitat: summary of published studies. (S = statistically significant; citations in bold print are peer-reviewed publications.)

No.	Reference	Location	Depth	Sediment	Effects	Recovery	Approach
1	**Bradshaw *et al.* 2002**	Isle of Man, Irish Sea	Not given	Sand and gravel	More vulnerable taxa less abundant in recent samples, less vulnerable taxa more abundant; faunal differences and proportion of species "lost" between time periods increased significantly as number of years since fishing began increased; no effect of increases in total effort; no clear evidence over all sites for reduced species diversity.		Recent benthic sample data collected at 7 sites exposed to varying amounts of fishing effort compared with data collected 50-60 yr ago, when scallop fishing was very limited.
2,3	**Bradshaw *et al.* 2000, 2001**	Isle of Man, Irish Sea	25-40 m	Gravel, sand, and mud	6 mo of experimental dredging in closed area altered community structure, no trends in abundance of individual species; no S effects on number of species, but community heterogeneity was reduced; encrusting species were more abundant and upright species less abundant in dredged plots than in control plots after 3 yr.	S increases in abundance of several epifaunal species in undredged portion of closed area 5-9 yr after closure.	Continuous experimental dredging (10 tows every 2 mo for 3 yr) in an area closed to commercial fishing for 6 yr; semi-annual grab sampling inside and outside closed area, and biannual diver surveys of epibenthic animals in closed area.
4	**Caddy 1973**	Chaleur Bay, Gulf of St. Lawrence, Canada	40-50 m	Gravel over sand, with occasional cobble and boulders.	Shallow, flat tracks; tooth marks in sand; boulders dislodged and small rocks "plowed" by dredge; spoil ridges at edges of track.		Submersible observations and photographs of tow tracks made <1 hr after dredging.
5	DFO 1993	Bras d'Or Lakes, Nova Scotia, Canada	10-500 m	Gravel and mud	Furrows left by dredge teeth; berms at outer edges of dredge track.		Sidescan sonar survey 1 yr after area was closed to mobile gear.
6	**Kaiser, Hill *et al.* 1996**	Irish Sea, southwest of Isle of Man	Not given	Not given, assume mixed substrates	Reduced abundance of most large epibenthic species; same effects on community structure as beam trawls, but lower bycatch.		Experimental study of effects of dredging (10 tows) and beam trawling on large epifauna; sampling with small-mesh (40mm) beam trawl both before and 24 hr after fishing.
7	**Kaiser, Ramsay *et al.* 2000**	Irish Sea	Not given	Coarse sand and gravel	S more epifaunal organisms in areas exposed to high fishing effort, no effects on infauna or on diversity or number of epifaunal species; shift from communities dominated by more larger-bodied to fewer smaller-bodied organisms.		Compared benthic communities in areas exposed to 10 yr of low and high fishing effort.
8	**Veale *et al.* 2000**	Irish Sea	20-67 m	Coarse sand or gravel, often overlain with pebbles, cobbles and dead shell.	S decreases in epibenthic species diversity and total number of species and individuals with increasing fishing effort; total abundance, biomass, and production and production of most taxa S decreased with increasing effort.		Compared dredge bycatch from fishing grounds exposed to varying amounts of fishing effort during previous 60 yr.

Table 5.13. Effects of other nonhydraulic dredges on biogenic substrate habitat: summary of published studies. (S = statistically significant; citations in bold print are peer-reviewed publications.)

No.	Reference	Location	Depth	Sediment	Effects	Recovery	Approach
1	**Fonseca *et al.* 1984**	Beaufort, North Carolina, USA	Very shallow, subtidal	Silty sand with eelgrass	S reduction in number of eelgrass shoots and leaf biomass with increased dredging intensity at each of two sites, one hard bottom and one soft bottom.		Experimental study with lightweight toothless dredge; two levels of disturbance.
2	Langan 1998	Piscataqua River, Maine-NH, USA	Not given	Oyster bed	No detectable differences in the number of benthic invertebrates, species richness, or diversity; turbidity of near-bottom water doubled 10 m behind dredge.	Turbidity returned to normal 110 m behind dredge.	One-time sampling of benthic invertebrates in dredged and undredged sides of the river; turbidity measured during a single dredge tow.
3	**Lenihan and Peterson 1998**	Neuse River, North Carolina, USA	3 and 6 m	Oyster reefs	Dredging lowered mean height of 1 m reefs by ~30%.		Experimental study where 4 of 8 oyster-shell reefs were dredged for 1 wk to remove all market-sized oysters; sampled 3 days before and 2 days after dredging..
4	**Riemann and Hoffmann 1991**	Limfjord, Denmark	Mean depth 7 m, maximum 15 m	Not given (presumed mussel bed)	S increase in suspended particulate matter; S reduction in oxygen immediately after dredging, especially near the bottom.	Turbidity returned to normal within 1 hr.	Water column sampling of physical and chemical attributes with a 2-m mussel dredge before and after dredging (maximum 1 hr) at an experimental and a control site.

Table 5.14. Effects of hydraulic clam dredges on mud substrate habitat: summary of published studies. (S = statistically significant; citations in bold print are peer-reviewed publications.)

Reference	Location	Depth	Sediment	Effects	Recovery	Approach
Hall and Harding 1997	Auchencairn Bay, Solway Firth, Scotland	Intertidal	Mud	Dredge tracks; S reductions in number of infaunal species and individuals persisted for 4 wk; 3 of 5 dominant species reduced in abundance throughout experiment (8 wk).	Nearly complete recovery of infaunal community after 8 wk, but some effects remained; dredge tracks not seen after first day.	Experimental study of the effects of single suction dredge passes in a commercially harvested area; recovery monitored 1, 4, and 8 wk after dredging.

Table 5.15. Effects of hydraulic clam dredges on sand substrate habitat: summary of published studies. (S = statistically significant; citations in bold print are peer-reviewed publications.)

No.	Reference	Location	Depth	Sediment	Effects	Recovery	Approach
1	**Hall *et al.* (1990)**	Loch Gairloch, Scotland	7 m	Fine sand	Shallow trenches (25 cm deep) and large holes; sediment "almost fluidized"; median sediment grain size S higher in fished area; S reductions in numbers of infaunal organisms; no effect on abundance of individual species; some mortality (not assessed) of large polychaetes and crustaceans retained on conveyor belt or returned to sea surface.	Complete recovery of physical features and benthic community after 40 days; filling of trenches and holes accelerated by winter storms.	Experimental study in unexploited area to evaluate effects of simulated commercial escalator dredging activity; recovery evaluated after 40 days.
2	**Kaiser, Edwards *et al.* (1996b)**	SE England	Intertidal	Muddy sand	Resuspension and loss of fine sand from sediment surface; S reductions in total number of infaunal species and individuals.	Complete recovery of sediments and benthic community within 7 mo.	Experimental study; effects of suction dredging for cultivated clams evaluated after 3 hr and 7 mo.
3	**MacKenzie, 1982**	East of Cape May, New Jersey, USA	37 m	Very fine to medium sand	Resorting of sediments (coarser at bottom of dredge track); no effect on number of infaunal individuals or species, nor on species composition.		Comparison of actively fished, recently fished, and never fished areas on the continental shelf; dredging conducted with hydraulic cage dredges.
4	Maier *et al.* 1995	South Carolina, USA	Tidal creeks	Muddy sand	Turbidity plumes; no S effects on abundance of dominant infaunal taxa or total number of individuals.	Turbidity plumes persisted for a few hours.	Before and after study of commercial escalator dredging effects in four tidal creeks. Turbidity monitored 2 wk before, during, and 2 wk after dredging at one location, and during and immediately after dredging at another. Infaunal samples collected 3 wk before and 2 wk after dredging in a creek that had been commercially dredged 5 yr prior to the study and in a creek that had never been dredged before.
5	Medcof and Caddy 1971	Southern Nova Scotia, Canada	7-12 m	Sand and sand-mud	Smooth tracks with steep walls, 20 cm deep; sediment cloud.	Sediment plume lasted 1 min; dredge tracks still clearly visible after 2-3 days.	SCUBA and submersible observations of the effects of individual tows with a cage dredge.
6	**Meyer *et al.* 1981**	Long Island, New York, USA	11 m	Fine to medium sand, covered by silt layer	>20-cm-deep trench; mounds on either side of trench; silt cloud, attraction of predators.	Trench nearly indistinct, and predator abundance normal, after 24 hr; silt settled in 4 min.	SCUBA observations during and following a single tow with a cage dredge in a closed area; effects evaluated after 24 hr.
7	**Pranovi and Giovanardi 1994**	Venice Lagoon, Adriatic Sea, Italy	1.5-2 m	Sand	8-10 cm deep trench; S decrease in total abundance, biomass, and diversity of benthic macrofauna in fishing ground; no S effects outside fishing ground.	After 2 mo, dredge tracks still visible; densities (especially of small species and epibenthic species) in fishing ground recovered, biomass did not.	Experimental dredging with a cage dredge (single tows) in previously dredged and undredged areas in coastal lagoon; recovery monitored every 3 wk for 2 mo.
8	**Tuck *et al.* 2000**	Sound of Ronay, Outer Hebrides, Scotland	2-5 m	Medium to fine sand	Steep-sided trenches (30 cm deep); sediments fluidized up to 30 cm; S decrease in number of infaunal species and individuals within a day of dredging; S decrease in proportion of polychaetes and S increase in proportion of amphipods 5 days after dredging; S increases in abundance of some species and S decreases in abundance of other species.	Trenches no longer visible but sand still fluidized after 11 wk; species diversity and total abundance recovered within 5 days; proportions of polychaetes and amphipods, and abundances of individual species, returned to pre-dredge levels after 11 wk.	Experimental dredging with cage dredge (individual tows at 6 sites) in area closed to commercial dredging, effects evaluated 1 day, 5 days, and 11 wk after dredging.

Table 5.16. Effects of hydraulic clam dredges on mixed substrate habitat: summary of published studies. (S = statistically significant; citations in bold print are peer-reviewed publications.)

Reference	Location	Depth	Sediment	Effects	Recovery	Approach
Murawski and Serchuk 1989	Mid-Atlantic Bight, USA	Not given	Sand, mud, and coarse gravel	Trench cut; temporary increase in turbidity, disruption of benthic organisms in dredge path; attraction of predators.	Trenches filled quickly in coarse gravel, but took several days in fine sediments.	Submersible observations following hydraulic cage dredge tows.

Table 5.17. Effects of hydraulic clam dredges on biogenic substrate habitat: summary of published studies. (S = statistically significant; citations in bold print are peer-reviewed publications.)

No.	Reference	Location	Depth	Sediment	Effects	Recovery	Approach
1	Godcharles 1971	Tampa Bay, Florida, USA	Not given	Open sand, sand with seagrass, and sand with algae	Water jets penetrate to 45 cm, create trenches 15-45 cm deep; uprooted vegetation; decreased proportion of fine sediment in some dredge tracks.	Trenches lasted longer (up to 86 days) in grass beds, filled in immediately in open sand; most sediments hardened within 1 mo, some spots still soft 500 days after dredging; sediment composition returned to normal after 1 yr, but seagrass still had not recovered; new algal growth after 86 days, complete after a year.	SCUBA observations and sediment sampling before and after experimental escalator dredging in undisturbed sand, seagrass, and algae bottom habitats; recovery monitored for 16+ mo.
2	Orth *et al.* 1998	Chincoteague Bay, Virginia, USA	Not given	Seagrass beds	Circular "scars" left by dredges; loss of grass and large holes in dredge track.	No revegetation 3 yr after disturbance; recovery estimated to take at least 5 yr in lightly disturbed areas, longer in heavily disturbed areas.	Field observations of commercial escalator dredging effects over a 3-yr period.

Table 5.18. Effects of pots and traps on mixed substrate habitat: summary of published studies. (S = statistically significant; citations in bold print are peer-reviewed publications.)

Reference	Location	Depth	Sediment	Effects	Recovery	Approach
Eno *et al.* 2001	Badentarpet Bay, west coast of Scotland	Not given	Soft mud	Bending and smothering of sea pens underneath pots; uprooting of some sea pens when pots are dragged over bottom.	Sea pens recover from effects of pot dragging within 24-72 hr, re-assume upright posture within 72-144 hr of pot removal, and re-root as long as "foot" remains in contact with bottom.	Diver observations and experiments to assess effects on, and recovery of, sea pens following dragging, uprooting, and smothering by lobster pots left on bottom for 24 or 48 hr.
Eno *et al.* 2001	Greenale Pt., Wales, and Lyme Bay, southwest England	14-20 m	Varied – from bedrock to boulders to coarse sediment – and interspersed.	Soft corals bent by pots, but spring back; pots leave tracks in bottom when hauled; increased abundance of 4 species of sponges, an ascidian, and a bryozoan in experimental plots after 4 wk, no changes in abundance of other epibenthic species.		Diver observations and experiments to assess effects of 4 wk of simulated commercial pot fishing on attached epifauna at two study sites.

Table 5.19. Effects of multiple gears on sand substrate habitat: summary of published studies. (S = statistically significant; citations in bold print are peer-reviewed publications.)

No.	Reference	Location	Depth	Sediment	Effects	Recovery	Approach
1	Almeida *et al.* 2000	Eastern Georges Bank, USA	<50->90 m	Sandy	Microhabitat associated with two species of sponges more abundant inside closed area; no S differences for six other microhabitat types.		Analysis of still photos and video imagery inside and outside area closed to trawls, dredges, longlines, and gill nets 4.5 yr after it was closed.
2	**Kaiser, Spencer *et al.* 2000**	South Devon coast, England	15-70 m	Fine, medium, and coarse sand	No S effect of high fishing effort on numbers of infaunal or epifaunal species or individuals; in high-effort areas there were: 1) a lower reduced abundance of larger, less mobile, and emergent epifauna; 2) a higher abundance of more epifauna; and 3) fewer high-biomass species of epifauna and infauna; infauna in deeper coarse-medium sand habitat most affected by fishing.		Compared benthic communities in areas of high, medium, and low fishing effort by fixed and mobile gears; each area with three sites (shallow, fine sand, deep medium sand, and deep coarse-medium sand).

Table 5.20. Effects of multiple gears on gravel/rock substrate habitat: summary of published studies. (S = statistically significant; citations in bold print are peer-reviewed publications.)

No.	Reference	Location	Depth	Sediment	Effects	Recovery	Approach
1,2	**Collie *et al.* 1997, 2000**	Northern edge, eastern Georges Bank, U.S. and Canada	42-90 m	Pebble-cobble "pavement" with some overlying sand	S higher total densities, biomass, and species diversity in undisturbed sites, but also in deeper water (*i.e.*, effects of fishing could not be distinguished from depth effects); 6 species abundant at U sites, rare or absent at D sites; percent cover of tube-dwelling polychaetes, hydroids, and bryozoans S higher in deepwater, but no disturbance effect.		Benthic sampling, video, and still photos in 2 shallow (42-47 m) and 4 deep (80-90 m) sites disturbed (D) and undisturbed (U) by trawls and scallop dredges.

Table 5.21. Effects of multiple gears on mixed substrate habitat: summary of published studies. (S = statistically significant; citations in bold print are peer-reviewed publications.)

No.	Reference	Location	Depth	Sediment	Effects	Recovery	Approach
1	**Auster *et al.* 1996**	Coastal Gulf of Maine, USA	30-40 m	Sand-shell	S more sea cucumbers and bottom depressions inside closed area.		ROV and video observations inside and outside an area closed to mobile gear for 10 yr.
1	**Auster *et al.* 1996**	Coastal Gulf of Maine, USA	30-40 m	Cobble-shell	S more emergent epifauna inside closed area.		ROV and video observations inside and outside an area closed to mobile gear for 10 yr.
1	**Auster *et al.* 1996**	Stellwagen Bank, Gulf of Maine, USA	20-55 m	Sand with gravel and shell	Disturbed sand ripples and sand waves; dispersed shell deposits; absence of epifauna and reduced microalgal cover in trawl and dredge tracks.		Sidescan sonar survey and ROV observations.
2,3,4	**Reise 1982; Riesen and Reise 1982; Reise and Schubert 1987**	Wadden Sea, The Netherlands	<23 m	Mud, coarse sand, and some pebbles	Loss of oyster and *Sabellaria* reefs; decrease in abundance of 28 species (mollusks and amphipods); 23 "new" species (many of them polychaetes).		Compared benthic surveys conducted during time period when oysters were overexploited and trawl fishery developed on *Sabellaria* reefs (1869-1986).
5	**Thrush *et al.* 1998**	Hauraki Gulf, New Zealand	17-35 m	Mud and sand	S reductions in density of large epifauna, echinoderms, and long-lived surface dwellers; S increases in density of small, opportunistic species; some predictions contra-indicated by results; 15-20% variability in macrofaunal community composition attributed to fishing pressure.		Tested 10 predictions of the effects of increasing fishing intensity on benthic community structure by comparing samples and video images from 18 stations exposed to varying degrees of commercial fishing pressure by bottom trawls, Danish seines, and scallop dredges.
6	Valentine and Lough 1991	Eastern Georges Bank		Sand and gravel	Trawl and dredge tracks in sediments; sparse epifauna, gravel mounds, and smoother bottom in disturbed areas.		Sidescan sonar and submersible observations of area presumed to be disturbed by trawls and scallop dredges.