# Effects of Trawling and Dredging on Seafloor Habitat

Committee on Ecosystem Effects of Fishing: Phase 1—Effects of Bottom Trawling on Seafloor Habitats

Ocean Studies Board

Division on Earth and Life Studies

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# Executive Summary

Fishing has a variety of effects on marine habitats and ecosystems, depending on the spatial extent of fishing, the level of fishing effort, and the type of gear. Expansion of U.S. domestic fisheries after passage of the Magnuson-Stevens Fishery Conservation and Management Act of 1976 fueled advances in gear and navigation technology that greatly increased the geographic extent of these effects. However, declining fish stocks have reduced fishing activities in some areas over the past decade. After passage of the Sustainable Fisheries Act in 1996, which required that fishery management plans address the effects of fishing on habitat, attention focused on how fishing affects the seafloor. The primary fisheries involved in the controversy are trawl and dredge fisheries, which tow gear over seafloor habitats and communities. A complete consideration of the effects of fishing on ecosystems would require evaluation not only of trawl and dredge gear, but also of stationary gear (traps, pots, longlines, gillnets) and other kinds of towed gear (pelagic trawls) on target and nontarget species.

As a first step in evaluating the ecosystem effects of fishing, the National Marine Fisheries Service (NMFS) asked the Ocean Studies Board of the National Academy of Sciences to study the effects of bottom trawling and dredging on seafloor habitats. Specifically, NMFS asked the committee to undertake the following tasks: 1) summarize and evaluate existing knowledge on the effects of bottom trawling on the structure of seafloor habitats and on the abundance, productivity, and diversity of bottom-dwelling species in relation to gear type and trawling method, frequency of trawling, bottom type, species, and other important characteristics; 2)summarize and evaluate knowledge about changes in seafloor habitats associated with trawling and with the cessation of trawling; 3) summarize and evaluate research on the indirect effects of bottom trawling on non-seafloor species; 4) recommend how existing information could be used more effectively in managing trawl fisheries; and 5) recommend research to improve understanding of the effects of bottom trawling on seafloor habitats.

During the study, the committee held public meetings in several regions with participation by fishery scientists and managers, the fishing industry, and environmental groups. Discussions often centered on concerns that habitat protection initiatives would become avenues for the reallocation of resources among stakeholders, including various sectors of the fishing industry, recreational fishing groups, and conservation organizations. Resolution of these allocation considerations to meet ecological and socioeconomic goals often has been contentious.

The policy context for addressing the effects of fishing on habitat is found in the essential fish habitat (EFH) provisions specified by the 1996 Sustainable Fisheries Act amending the Magnuson-Stevens Fishery Conservation and Management Act. The amended act requires regional fishery management councils to describe and identify EFH for each fish stock managed under a fishery management plan, to minimize to the extent practicable adverse effects on such habitat caused by fishing, and to identify other actions to encourage habitat conservation and enhancement. Instead of amending individual fishery management plans, most regional councils developed a single,

overarching EFH amendment. The Secretary of Commerce approved most of the revised plans, but some environmental groups have mounted legal challenges regarding the adequacy of some EFH amendments. A major complaint was that the regional councils did not sufficiently address the effects of fishing gear on benthic habitats.

Gaps in existing knowledge of the distribution of benthic life stages of fishes and other species and of the physical and biological characteristics of the seafloor made it difficult for the regional councils to develop criteria for designating EFH. Similarly, the councils struggled with the requirement to assess the effects of bottom trawling and dredging because of insufficient data on the spatial scale and extent of bottom fishing. The councils also lacked guidelines for generalizing the results of research on specific gears and habitats. These problems relate to the committee’s task to recommend ways of using existing information in the management of the habitat effects of trawl and dredge fisheries.

A complete assessment of the ecosystem effects of trawling and dredging requires three types of information:

1. gear-specific effects on different habitat types (obtained experimentally);
2. frequency and geographic distribution of bottom tows (trawl and dredge fishing effort data); and
3. physical and biological characteristics of seafloor habitats in the fishing grounds (seafloor mapping).

This report summarizes current data in these three areas and describes how the low spatial resolution and availability of the fishing effort and habitat mapping data restrict a full evaluation of the ecosystem effects of trawling and dredging.

Under the first category of information, many experimental studies have documented the acute, gear-specific effects of trawling and dredging on various types of habitat. The results confirm predictions based on the ecological principle that stable communities of low mobility, long-lived species will be more vulnerable to acute and chronic physical disturbance than will short-lived species in changeable environments. Trawling and dredging can reduce habitat complexity by removing or damaging the biological and physical structures of the seafloor. The extent of the initial effects and the rate of recovery depend on the habitat stability. The more stable biogenic (i.e., of biological origin), gravel, and mud habitats experience the greatest changes and have the slowest recovery rates. In contrast, less consolidated coarse sediments in areas of high natural disturbance show fewer initial effects. Because those habitats tend to be populated by opportunistic species that recolonize more rapidly, recovery is faster as well. Significant alterations to habitat can cause changes in the associated biological communities, potentially altering the composition and productivity of fish communities that depend on seafloor habitats for food and refuge.

The second category of information, the geographic distribution and frequency of trawling and dredging, suffers from limitations in the spatial resolution of the data and in regional variation in reporting methods. For example, trawling effort data are averaged over reporting areas that range 25–2420 $km^2$, depending on the region. Although the data are imperfect, a few generalizations emerged from the analysis presented in this report. Based on estimates of the spatial extent and intensity of trawl and dredge fishing effort, bottom trawling takes place over large areas of the continental shelf and slope. The level of effort varies greatly among regions. The highest intensity of effort, based on rough estimates of the number of times a reporting area is swept (Table 4.1), occurs in the fishing grounds of the Gulf of Mexico and New England regions. In contrast, bottom trawling in the mid-Atlantic, Pacific, and North Pacific regions is relatively light, with less than one tow per year in many reporting areas. Even in heavily trawled regions, effort is not evenly distributed. As a consequence, some areas may be trawled several times per year while other areas may be trawled infrequently if at all. Throughout the 1990s and into 2001 there were significant reductions in the intensity and spatial extent of bottom trawling. Those reductions reflect effort reductions, area closures, and gear restrictions instituted by managers in response to problems with declining fish stocks, bycatch, or interactions with endangered species.

The spatial distribution of different habitat types in trawled (or dredged) areas is the third category of information that must be integrated with the other two to assess the effects of trawling and dredging on ecosystems. Experimental studies on specific gear types in a few well-defined habitats provide small-scale estimates of ecological disturbance, but for most areas only coarse maps are available on habitat distribution.

The mismatch in the spatial scales of experimental results, habitat maps, and trawl effort reporting data

makes it difficult to assess the ecosystem-level effects of trawling and dredging. Although fisheries managers collect data continuously, limitations in resources and time require them to assess effects in the absence of complete information. In this context, comparative risk assessment provides a promising approach to evaluate the effects of bottom trawling and dredging. This method brings together the various stakeholders to identify risks to seafloor habitats and to rank management actions within the context of current statutes. Because risk assessment requires full use of all available information on seafloor habitats, fishing methods, and effort distribution there is an immediate need to integrate the available data in a readily available format.

## RECOMMENDATIONS

Although there are still habitats, gears, and geographic regions that have not been adequately studied and characterized, there is an extensive literature on the effects of fishing on the seafloor. It is both possible and necessary to use this existing information to more effectively manage the effects of fishing on habitat. The following recommendations fall into three categories: 1) interpretation and use of existing data; 2) integration of management options; and 3) policy issues raised by existing legislation. These recommendations are intended to build upon the strengths of existing approaches to management rather than completely transform them.

## *Interpretation and Use of Existing Data*

### Recommendation

**Fishery managers should evaluate the effects of trawling based on known responses of specific habitat types and species to disturbance by different fishing gears and levels of fishing effort, even when region-specific studies are not available.** The lack of area-specific studies on the effect of trawling and dredging gear is insufficient justification to postpone management of fishing effects on seafloor habitat. The direct responses of benthic communities to trawling and dredging are consistent with ecological predictions based on disturbance theory. Predictions from common trends observed in other areas provide useful first-order approximations of fishing effects for use in habitat management. As more site-specific information becomes available on the fine scale distribution of fishing effort and habitat distribution, those estimates should be revised.

### Recommendation

**NMFS and its partner agencies should integrate existing data on seabed characteristics, fishing effort, and catch to provide geographic databases for major fishing grounds.** Management decisions about how fishing affects habitat can be improved by the simultaneous and consistent presentation of all available data on the characteristics of the seabed and fishing effort. There are data that describe seabed types and habitats and the location and intensity of fishing for much of the U.S. continental shelf. Available data sets collected by different agencies currently exist in different formats, at variable levels of resolution, in separate archives. Their integration into a single geographic information system will help managers evaluate regional needs for habitat conservation.

## *Integration of Management Options*

### Recommendation

**Management of the effects of trawling and dredging should be tailored to the specific requirements of the habitat and the fishery through a balanced combination of the following management tools.**

- *Fishing effort reductions*. Effort reduction is the cornerstone of managing the effects of fishing, including, but not limited to, effects on habitat. Both of the other management tools (gear restrictions or modifications and closed areas) also can require effort reduction to achieve maximum benefit. The success of fishing effort reduction measures will depend on the resilience and recovery potential of the habitat.
- *Modifications of gear design or gear type*. Gear restrictions or modifications that minimize bottom contact can reduce habitat disturbance. Shifts to different gear types or operational modes can be considered, but the social, economic, and ecological consequences of gear reallocation should be recognized and addressed.
- *Establishment of areas closed to fishing*. Closed areas are necessary to protect a range of vulnerable, representative habitats. Closures are particularly useful for protecting biogenic habitats (corals, bryozoans, hydroids, sponges, seagrass beds) that are disturbed by even minimal fishing effort. Because area closures could displace effort to open fishing grounds, effort reductions could be necessary in some cases to reduce habitat effects.

The optimal combination of these management approaches will depend on the characteristics of the ecosystem and the fishery—habitat type, resident seafloor species, frequency and distribution of fishing effort, gear type and usage, and the socioeconomics of the fishery. Each characteristic should be considered during development of management plans for mitigating the impacts of fishing on the seafloor.

**Recommendation**

**The regional fishery management councils should use comparative risk assessment to identify and evaluate risks to seafloor habitat and to prioritize management actions within the context of current statutes and regulations.** Risk assessment, in general, is a scientifically informed way of clarifying public debates over environmental policy by making explicit the environmental consequences of particular policy choices. Comparative risk assessment provides the following advantages for the task of benthic habitat protection:

- It can be used even in the absence of scientific certainty because it relies on a combination of available data, scientific inference, and public values.
- It provides simultaneous analysis of a wide range of risks to benthic habitats. Mobile bottom gear is only one of many factors that contribute to the degradation of benthic habitats. Other factors might include pollution, drilling and natural disturbance.
- It enables stakeholder involvement in the decisionmaking process.

## *Policy Issues Raised by Existing Legislation*

**Recommendation**

**Guidelines for designating EFH and habitat areas of particular concern (HAPC) should be established based on standardized ecological criteria.** The underlying aim of the EFH concept is valuable, and it appropriately emphasizes the need to place management of exploited fishes within the context of managing the total ecosystem. The current designation of EFH, however, does not require the use of consistent criteria for the assignment of habitat to each life stage of the species covered by fishery management plans. Instead, the regional councils develop the criteria, often based on data availability. Current EFH designations typically are too extensive to form a practical basis for managing fisheries. Although this approach could help mitigate some threats to habitat, it provides little guidance for evaluating the consequences of trawling and dredging. EFH designations should be based on a clear understanding of the population biology and spatial distribution of each species.

An HAPC constitutes a subset of EFH based on the ecological value of the area, its susceptibility to perturbation, and whether it is rare or stressed (National Marine Fisheries Service, 1997). HAPCs require the strongest safeguards to ensure habitat protection because their value in the life cycle of exploited fish populations has been documented. Nevertheless, no such protection is afforded in the current policy structure. HAPC should be clearly and narrowly defined, specific guidelines should be set for determining permissible activities, and a schedule for reviewing the effectiveness of the designation should be developed.

**Recommendation**

**A national habitat classification system should be developed to support EFH and HAPC designations.** Efforts to inventory and construct regional or national habitat maps require a classification system with common designations. Such a system would facilitate tracking of changes over time and would provide a basis for determining functional links between seafloor ecosystems and fisheries production. A classification system would assist in ranking different habitats according to the resilience of their biological communities and associated fisheries; estimating habitat vulnerability; and managing habitat impacts based on the generalized results of research conducted in other geographic areas.

## FUTURE RESEARCH

Many gaps were identified in current understanding of the consequences of fishing on the seafloor. The following recommendations are intended to direct research toward filling these gaps. They have been organized into three primary areas of research—gear effects and modification, habitat evaluation, and management—with some overlap between categories.

### *Gear Effects and Modification*

Fishermen's knowledge and experience should be used to study gear impacts and to develop new gear technology. Their active engagement in research will help ensure that mitigation strategies are practical, enforceable, and acceptable to the fishing community. Further research on gear effects will be required to develop a predictive capability to link gear type and effort to bottom disturbance, fish production, and recovery times in particular habitats. New research is needed in the following areas:

- identification of the forces that injure and dislodge a range of benthic organisms;
- development of fishing gear that is less damaging to habitat and that helps meet other conservation goals, such as bycatch reduction and maintenance of biological communities; and
- determination of the relationship between fish production and bottom disturbance, especially for areas that continue to support fish despite chronic disturbance by fishing gear.

### *Habitat Evaluation*

Most previous research has addressed habitat disturbance on a small spatial scales. The focus has been on short-term, acute disturbance, and on animal communities rather than ecosystem processes (productivity, nutrient regeneration). Closed areas should be used as control sites to study the chronic effects of seabed disturbance by trawl or dredge gear. Future research should examine:

- cumulative effects of trawling on sites that have been trawled repeatedly;
- repeated disturbances by fishing gears to determine the dose-response relationship as a function of gear, recovery time, and habitat type;
- recovery dynamics, with estimates of large-scale effects at current fishing intensities;
- acute and chronic effects of trawling in deeper water (>100 m); and
- recovery rates in stable and structurally complex habitats for which the return time will be measured in years to decades.

Evaluation of the indirect effects of bottom trawling and dredging will require experimentation, modeling, and comparison of different habitat types to analyze trends in benthic production and community structure relative to trends in fisheries production. This evaluation should include:

- effects of habitat fragmentation on biological communities and the productivity of exploited fish stocks;

- rates and magnitude of sediment resuspension, nutrient regeneration, and responses of the plankton community in relation to gear-induced disturbance; and
- long-term trend data on benthic production versus fisheries production.

## *Management*

Productive interactions among stakeholders and policymakers should be enhanced through increased participation in research on the effects of fishing on the seafloor and development of alternative gears and practices. Interactions can be facilitated through user group funding of research and by collaborative research projects that involve scientists and fishermen.

Development of better quantitative data for risk analysis will require research on the habitats and population dynamics of nontarget species, specifically:

- adequate baselines for particular habitats and regions, to document the effects of various fishery practices;
- testable hypotheses about how communities in different habitat will respond to fishing;
- quantitative models to predict fishing effects in areas that have not been studied; and
- mortality estimates for nontarget species.

NMFS should establish protocols for studying existing trawl and dredge area closures to evaluate ecological, social, and economic effects of habitat management strategies. This will aid assessment of management alternatives in other locations. Aggregation and analysis of existing information on habitats, fishing effort, and efficacy of various management measures will help the regional fishery management councils meet their mandate to protect EFH. Research that will facilitate management decisions include:

- analysis of community structure and life history parameters to validate the use of frequency

  dependent distribution approaches for designating EFH and HAPC; and
- collection and analysis of data on the social and economic characteristics of trawl, dredge, and nonmobile gear fisheries to assess the tradeoffs among various management alternatives.

## CONCLUSION

Integration of available data on the effects of trawling and dredging, fishing effort, and the distribution of seafloor habitats can provide a starting point for practical initial evaluations that will inform management decisions. Management measures should be assessed regularly to provide better information about how various restrictions affect fish stocks and habitats and to determine the socioeconomic effects on the fishing industry and fishing communities.

However, existing data are not sufficient to optimize the spatial and temporal distribution of trawling and dredging to protect habitat and sustain fishery yields. Resolution of the different, and at times conflicting, ecological and socioeconomic goals will require not only a better understanding of the relevant ecosystems and fisheries, but also more effective interaction among stakeholders.

# Effects of Trawling and Dredging

“Habitat alteration by the fishing activities themselves is perhaps the least understood of the important environmental effects of fishing” (National Research Council, 1994).

The use of mobile fishing gear has become a source of concern because of the size of the affected fishing grounds, the modification of the substrate, disturbance of benthic communities, and removal of nontarget species. The long-term viability of some fish populations could be threatened if essential fish habitat is degraded. Also, because of declines in many traditional fisheries, efforts to find under-exploited fish populations have increased interest in exploiting less accessible, previously unfished areas. These efforts have been facilitated by the development of new gear and navigational aids. Extensive new regions of the continental shelf, slope, submarine canyons, and seamounts have been exposed to the effects of bottom trawling and dredging. Expansion of fishing into new territory could lead to the loss of habitats that might have provided as refuge for heavily exploited species.

Since the publication of the 1994 National Research Council report, there has been additional research on the effects of fishing gear, especially trawls and dredges, on marine benthic habitats. The magnitude depends on gear configuration, on the subtle modifications various operators make to their gear and on the many and varied habitats fished. Given the inherent difficulty of studying offshore habitats and the problems associated with determining causation under shifting environmental conditions (current, temperature variation, natural migration, storm activity), not all questions regarding the effects of fishing on the seafloor have been answered—nor are they likely to be in the near future. Evaluating the effects of bottom trawling on benthic communities is complicated by the sparseness of data on species abundance and composition before intensive bottom fishing began. This is important because recent analyses of the few existing historical data sets suggest that larger bodied organisms (fish and benthos) were more prevalent before intensive bottom trawling began (Frid and Clark, 2000; Greenstreet and Hall, 1996). Existing studies necessarily indicate changes relative to recent conditions, not changes relative to the less disturbed ecosystem. There has been an increase in the understanding of fishing gear and habitat interactions that can be used for making decisions about habitat management.

Any fishing gear will affect the flora and fauna of a given location to some degree, but the magnitude and duration of the effect depends on several factors, including gear configuration, towing speed, water depth, and the substrate over which the tow occurs. Variations in substrate include differences in sediment type, bed form (sand waves and ripples, flat mud), and biologic structure (shell, macroalgae, vascular plants, sponges, corals, burrows) (Auster and Langton, 1999). What are the ecologic consequences of these fishing effects? What are the short- and long-term effects on populations, community structure, and interspecific dynamics? Is the disturbance caused by fishing less than what occurs naturally? Are some species threatened with local extinction?

In considering the consequences of trawling and dredging it is important to distinguish between the direct and indirect effects of the activity. Direct effects can be summarized as follows:

- Mortality. Population mortality occurs either as part of the catch (landings plus discards) or incidentally either by killing benthic and demersal species or making them more vulnerable to scavengers and other predators.
- Increased food availability. Discarded fish, fish offal, and dead benthic organisms become food for scavenging species.
- Loss of habitat. Some fishing gears cause the disturbance or destruction of seafloor habitat.

Indirect effects are the downstream consequences of a direct effect. Reductions in the total biomass of target fish, along with the direct effects noted above, could be expected to affect predators, prey, competitors of a target species, and overall seafloor community structure. Indirect effects also encompass potential changes in the flow of materials and energy through ecosystems and shifts in the balance among the processes of primary production, primary consumption, and secondary production.

Human activities such as trawling can be considered a disturbance to environments, and their effects are often compared with natural disturbances that occur in the same ecosystems. It is important to ask whether human disturbances represent selective pressures at novel spatial or temporal scales or are just slight changes in the scale of existing natural disturbance. Natural disturbances can occur with different periodicities, spatial effects, and patterns of recovery (e.g., Lake, 1990; Pickett and White, 1995). Periodic disturbances can be considered pulse events, and a population or community assemblage might respond in several ways. If the disturbance is not too intense, and if the interval between disturbances is long relative to the attributes of the community, or if the system is resilient, the community could return to its previous state. Ecological disturbance theory also suggests that, even if each individual pulse disturbance does not have a large acute effect, there could be a threshold of intensity or a cumulative level beyond which persistent changes in the ecosystem occur. Resilience is the degree to which an ecosystem's long-standing composition, structure, and function can recover from disturbance (Holling, 1973). The disturbance paradigm predicts that short-lived, highly motile or dispersing species with high reproduction rates will recover from disturbance faster than will long-lived, sessile, low-dispersing species (Pickett and White, 1995).

The following sections are based on the results of previous studies and reviews. They summarize commonly observed effects of fishing on the seafloor with respect to gear type, the nature of the seafloor habitat, frequency of disturbance (natural and from fishing gear), and rates of recovery to the pretrawling or predredging state.

## DIRECT EFFECTS ON SPECIES AND HABITAT STRUCTURE

### *Research Approaches*

Studies of the effects of mobile fishing gear on benthic habitat have used observation and experiment. Observational studies compare the benthic habitat in trawled areas with the habitat in lightly trawled or untrawled places. One difficulty with this approach is finding habitats that are similar in all respects other than the degree of fishing. In any given region, benthic areas inhabited by commercial concentrations of fish and shellfish, not closed by regulation, will be trawled or dredged at some frequency. Quantifying how much trawling has occurred in lightly trawled areas can be impractical given the limited scale of benthic studies. It is difficult to assess how much trawling actually occurs in an area solely from effort data collected in most fisheries. A full evaluation of the effects of trawling and dredging on habitat will require higher resolution effort data to translate the results of smallscale experimental studies to effects at the ecosystem level.

Experimental studies generally use the before/after control/impact design. In this approach, an experimental area is trawled and compared before and after trawling (before/after comparison) and with a site that has not been trawled recently (control/impact comparison). This design often involves direct sampling of fauna, video observations, and sonar scans of the control and disturbed sites. The primary limitation of this design is that it is based on the assumption that the control and experimental sites are equivalent. A study by Lindegarth et al. (2000) suggests multiple evaluation sites are needed to assess the effect of trawling on benthic habitat. The authors showed that the interpretation of experimental studies varies depending on the control and treatment sites compared. Although the need for multiple control sites and replicate trawling is acknowledged within the scientific community, application is limited by ship time, funding constraints, and existing and shifting management regimes.

### *Research Summary*

The effects of mobile bottomfishing gear on benthic habitats depend on the susceptibility of the habitat and on the type gear used. Table 3.1 provides examples of observed effects of different gear in various habitats as catalogued in recent literature reviews (e.g., Auster and Langton, 1999; Barnette, 1999; Jennings and Kaiser, 1988). The extensive primary literature, many review articles, and a meta-analysis of 57 published studies (Collie et al., 2000b), reveal several generalities about the response of seafloor communities to trawling and dredging. These generalities, highlighted in bold text, are discussed below.

**Trawling and dredging reduce habitat complexity.** The direct effects of trawling and dredging include loss of erect and sessile epifauna, smoothing of sedimentary bedforms and reduction of bottom roughness, and removal of taxa that produce structure. Trawl gear can crush, bury, or expose marine flora and fauna and reduce structural diversity (Auster and Langton, 1999). On Florida’s Oculina Banks, for example, trawl fisheries for rock shrimp and trawl and dredge fisheries for calico scallops have been implicated in the reduction of 1–2 m diameter *Oculina varicosa* tree corals to 2–3cm rubble (Koenig et al., 2000). If the interval between trawls is shorter than the recovery time, the original benthic structure and species populations might not have the opportunity to recover to pretrawl conditions (Watling and Norse, 1998). Most research bears out the paradigm of variable environments inhabited by short-lived species recovering more rapidly than stable

TABLE 3.1 Examples of Mobile Fishing Gear Effects on Habitat (Based on Reviews by Auster and Langton, 1999, and Barnette, 1999)

| Gear | SAV | Sand | Hardbottom/ Biogenic | Muddy Sand | Gravel |
|---|---|---|---|---|---|

| | | | | | |
|---|---|---|---|---|---|
| **Scallop dredge** | Increased dredging resulted in significant reductions in biomass and number of shoots (1) | Smoothed bedforms; reduction of epifaunal coverage; shell aggregate dispersal (2, 3, 4) | • Single passage can kill 70% of the living maerl in the dredge path. Flora and megafauna to a depth of 10 cm are damaged.<br>• Dredge tracks remain visible for 2.5 years in maerl habitats.<br>• Maerl is a "living sediment" that is slow to recover from disturbance due to extremely low growth rates (5) | A gradient of increasing large epifaunal cover correlated with decreasing fishing effort (4) | • Undredged sites had higher numbers of organisms, biomass, species richness, and species diversity than dredged sites. Undredged sites had bushy epifauna, dredged sites were dominated by hard-shelled mollusks, crabs, and echinoderms (6, 7)<br>• Suspended fine sediment and buried gravel below the sediment water interface (3)<br>• Smoothed bedforms; hydrozoan cover removed; reduced densities of shrimp (2) |
| **Oyster dredge** | Gear modified for clam harvest reduction in coverage; loss of rhizomes; extended recovery time; sediment suspension; smothering of SAV (8) | | Reduction in height of oyster reefs, increased susceptibility to hypoxia (9) | | |
| **Gear** | SAV | Sand | Hardbottom/ Biogenic | Muddy Sand | Gravel |
| **Otter trawl** | Reduction in coverage; loss of rhizomes; sediment suspension; smothering of SAV (10) | • Reduction of epifaunal coverage; smoothed bedforms; compression of sediments; sediment suspension (fines); reduction in depth of oxygenated sediments (4, 11, 12)<br>• Roller gear produced depressions; chain gear caused damage or loss of epifaunal coverage (11, 13)<br>• Well buried boulders removed and displaced from sediment; trawl doors smoothed sand waves; penetrated seabed 0–40 mm (14) | • Reduced density and size of bryozoan colonies in trawled areas vs. closed areas (15)<br>• Trawled areas showed mussel beds of lower structural complexity and less attached epibenthos compared with untrawled areas (16) | Reduction of epifaunal coverage; smoothed bedforms; compression of sediments; sediment suspension (fines); reduction in depth of oxygenated sediments (4, 14, 17) | |
| **Beam trawl** | | Trawl removed high number of the hydroidTubularia(17) | | | 50% reduction in density of epifauna such as hydroids and soft coral (18) |
| **Rollerrigged trawl** | | | Damage or loss of sponge and coral cover (11, 19, 20) | | • Significant reductions in density of structural |

|  |  |  |  |  |
|---|---|---|---|---|
|  |  |  |  | components of habitat (21)<br>• No differences in densities of small sponges; 20% of boulders moved or dragged (22) |
| **Roller frame bait shrimp trawl** | Minimal SAV degradation; mostly from propeller scars (23, 24) |  | • Damage, loss of sponge and coral cover (25)<br>• 30–80% damage to coral; declines in groups of large and small benthos in trawled areas (26) |  |

NOTE: SAV refers to submerged aquatic vegetation.
SOURCE CODE: 1=Fonseca et al., 1984; 2=Auster et al., 1996; 3=Caddy, 1973; 4=Thrush et al., 1998; 5=Hall-Spencer and Moore, 2000; 6=Collie et al., 2000b; 7=Collie et al., 1997; 8=Moore and Orth, 1997; 9=Lenihan and Peterson, 1998; 10=Guillen et al., 1994; 11=Sainsbury et al., 1997; 12=Schwinghamer et al., 1998; 13=Smith et al., 1985; 14=Bridger, 1970; 15=Bradstock and Gordon, 1983; 16=Magorrian, 1996; 17=de Groot, 1984; 18=Kaiser and Spencer, 1996b; 19=Moore and Bullis, 1960; 20=Van Dolah et al., 1987; 21=Engel and Kvitek, 1998; 22=Freese et al., 1999; 23=Futch and Beaumariage, 1965; 24=Meyer et al., 1999; 25=Berkeley et al., 1985; 26=Tilmant, 1979.

communities composed of sessile, long-lived species, which sustain longer term damage.

**Repeated trawling and dredging result in discernable changes in benthic communities.** Many studies report that repeated trawling and dredging causes a shift from communities dominated by species with relatively large adult body size toward dominance by high abundances of small-bodied organisms (Auster et al., 1996; Engel and Kvitek, 1998; Jennings et al., 2001; Kaiser et al., 2000; Kaiser and Spencer, 1996b; Watling and Norse, 1998). Intensively fished areas are likely to remain permanently altered, inhabited by fauna that readapted to frequent physical disturbance. In some habitats these differences will be profound, in others they will be rather subtle (Kenchington et al., 2001). Species richness (the number of species per unit area) and evenness (the relative abundance of resident species)—two measures of species diversity— can decline in response to bottom fishing, but not all communities show reduced diversity. For example, if bottom fishing reduces the abundance of a dominant species, the disturbed community might have higher evenness and hence lower species diversity (Collie et al., 1997). Untrawled, silty habitat in the Aegean Sea had lower species diversity than did similar, trawled, silty habitat. Measurements of species diversity is not always a reliable indicator of disturbance because a change in the structure of the benthic community can increase or decrease overall species diversity.

**Bottom trawling reduces the productivity of benthic habitats.** It has been hypothesized that the shift to communities of smaller, fast-growing species after removal of larger, slow-growing species by trawling could maintain benthic productivity and support predacious fish. However, Jennings et al. (2001) found a 75 percent reduction in total infaunal productivity between unfished and heavily trawled areas. Although productivity per unit biomass was higher in heavily trawled areas because of the shift to smaller organisms, overall productivity was lower because of the loss of biomass.

The effects of mobile fishing gear are cumulative, and depend on trawling frequency. Repeated trawling (or dredging) can exceed a threshold above which a disturbance can result in observable, long-term ecological effects. Even shallow, high-energy areas that often experience natural disturbances can be affected if the frequency and seasonality of the trawling disturbances are different from those of natural events (e.g., Auster and Langton, 1999). Small-scale fishing disturbances can be masked by larger scale natural events (Kaiser and Spencer, 1996b). A three-year study by Tuck et al. (1998) compared the benthic infauna at sites that were trawled regularly and at untrawled control sites. After five months of trawling, they observed changes only in the relative abundances of different species, but after 16 months total species richness began to decline in the trawled sites. Unfortunately, most research has focused on acute effects, quantifying changes to benthic habitat after only a limited number of trawl passes over a short period. These acute studies do not document long-term changes attributable to repeated trawling and dredging. More long-term studies are needed to assess the full range of consequences in areas that are trawled or dredged regularly.

**Fauna that live in low natural disturbance regimes are generally more vulnerable to fishing gear disturbance.** According to ecologic disturbance theory, initial responses and rates of recovery from trawling should reflect the stability of the substrate in a particular habitat and the character of the benthic community that it supports (Figure 3.1) (Lake, 1990; Pickett and White, 1995). Habitats consisting of unconsolidated sediments that experience high rates of natural disturbance can have more subtle responses to trawling than will habitats characterized by boulders or pebbles (Tuck et al., 2000; Kenchington et al., 2001). Animals that live in unconsolidated sediments in high natural disturbance regimes are adapted to periodic sediment resuspension and smothering like that caused by mobile bottom gear. In contrast, epifaunal communities that stabilize sediments, reef-forming species, or fauna in habitats that experience low rates of natural disturbance have been observed to be particularly vulnerable. Individual studies support the generalizations summarized in Figure 3.1, but a quantitative meta-analysis was less conclusive (Collie et al., 2000a). Responses in sand habitats were usually less negative than in the other habitats, but a consistent ranking of impacts with respect to *a priori* expectations by habitat did not emerge. However, the outcome of the meta-analysis could be confounded by limitations in the available data and by interactions among the factors (gear type, habitat type).

Fishing gears can be ranked according to effects on benthic organisms. Intertidal dredging (with gear that causes the direct removal of sediments, shells, and rocks) has more marked initial effects than either scallop dredging or intertidal raking, which in turn cause greater damage than beam and otter trawling (Collie et al., 2000a). Otter trawls have been evaluated more often than have other types of gear, because of their widespread use (Barnette, 2001; Collie et al., 2000a). This ranking is consistent with the degree of bottom contact and sediment penetration of the different gears.

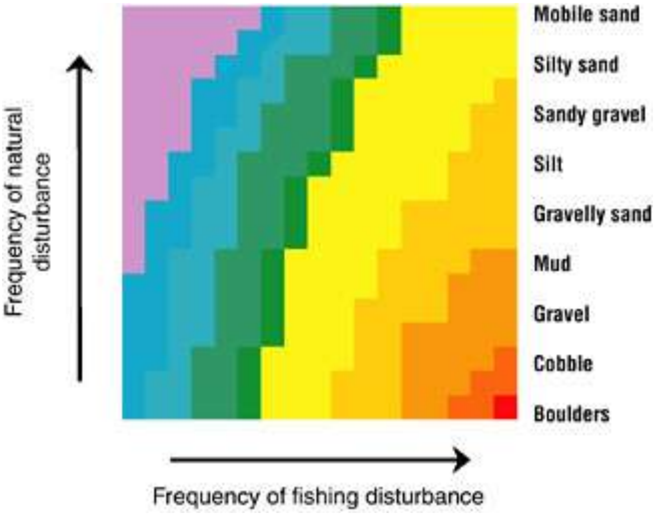

FIGURE 3.1 Conceptual model of fishing disturbance to benthic communities. The response variable is the percent decrease in abundance due to bottom fishing. The response is ranked from lowest (top left) to highest (bottom right). The frequency of natural disturbance corresponds roughly with sediment type, but not directly with particle size. The axes correspond to measurements that should be readily obtainable for most parts of the continental shelf.

Benthic fauna can be ranked according to vulnerability. The most consistent research observation is that vulnerability to mobile gear is predicated on the morphology and behavior of the benthic species. Softbodied, erect, sessile organisms are more vulnerable to mobile gear than are hard-bodied prostrate organisms. Despite limits in the taxonomic resolution of the data, the meta-analysis identified a 68 percent reduction in anemone abundance, as opposed to a 21 percent mean reduction in starfish, after a single trawling event (Collie et al., 2000a). Similarly, chronic exposure (repeated dredging) resulted in a 93 percent reduction for anemones, malacostracan crustaceans, brittle stars, and polychaetes, whereas a single dredge event resulted in a 76 percent reduction. On average, none of these taxa increased in abundance, and the average reductions across taxa amounted to 55 percent (Collie et al., 2000a).

## Modeling Mortality in Relation to Fishing Effort

Based on the general principles outlined above, a model can be derived to predict the effects of bottom fishing. The depletion of a nontarget species can be modeled with the exponential equation:

$$N_E = N_o e^{-mE} \quad [1]$$

$N_0$ is initial abundance, and $N_E$ is abundance after $E$ passes of a particular kind of fishing gear. The mortality coefficient, $m$, is analogous to catchability: it

includes the mortality of individuals not captured but still killed by the trawl. The mortality rate depends on factors such as gear, habitat type, and life history. One obvious but important implication of this exponential model is that repeated trawls at the same location kill diminishing numbers of organisms. Hence, if the distribution of the nontarget species is not positively correlated with that of the target species, a more aggregated fishery will inflict a lower mortality rate.

The depletion equation can be normalized to the proportion of animals killed as a function of the number of tows:

$$\frac{N_0 - N_E}{N_0} = 1 - e^{-mE}$$

[2]

This response variable is bounded between 0 and 1, and larger values correspond to greater hazard or risk. One can envision a family of curves corresponding to different values of each explanatory variable (Figure 3.2). The curves show that species in sandy habitats experience a lower mortality rate than do those in a gravel habitat. In very few cases have the shapes of these mortality curves been systematically measured. Most trawl studies consist of a single disturbance event (1tow) or spatial comparisons of chronically fished and unfished areas (at the asymptote of the curve).

The depletion equation also can be expressed as a linear model of potential explanatory variables:

$$\ln\left[\frac{N_E}{N_0}\right] = -(\overline{m} + aG + bH = cD)E$$

[3]

Mortality, $m$, has been expanded as a linear combination of factors ($G$, gear; $H$, habitat) or continuous variables ($D$, depth). This equation provides the basis for estimating the importance of potential explanatory variables and is similar to the response variable used in the meta-analysis of Collie et al. (2000a).

## Modifications to Habitat Structure

An important consequence of trawling is the reduction in habitat complexity (architecture) that accompanies the removal of sessile epifauna and the alteration of physical structure, such as rocks and cobble. Emergent epifauna, such as sponges, hydroids, and bryozoans, provide habitat for invertebrates and fishes. Disturbance of emergent epifauna can increase the predation risk for juvenile fish. Decreased prey abundance increases the foraging time for juvenile fish, thus exposing them to higher predation risk (Walters and Juanes, 1993). Laboratory studies (Lindholm et al.,

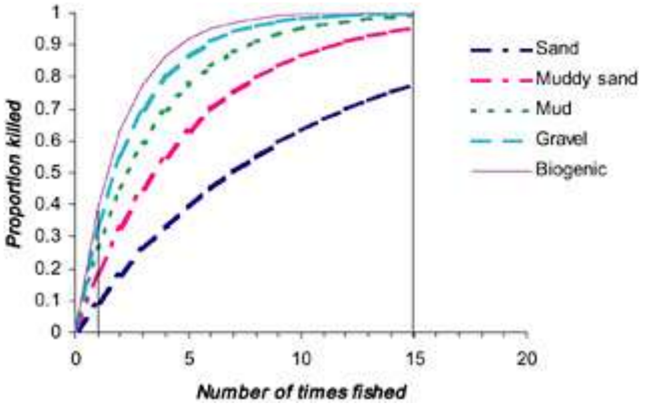

FIGURE 3.2 Hypothetical depletion curves for non-target species in different habitats. The vertical lines indicate that most trawl-impact studies either have been acute (trawled once, vertical line at 1) or compare chronically fished areas (vertical line at 15).

1999) and field studies (Tupper and Boutilier, 1995) have shown that increased epifaunal cover reduces predation risk to juvenile cod.

Information on the linkages between habitat and fish population dynamics is limited; most experimental studies have been conducted in coral reef systems. An extensive literature shows links among larval supply, postsettlement predation, physical attributes of habitat, and adult population size (e.g., Sale, 1991). For example, Sainsbury et al. (1997) provided compelling evidence that loss of structural epibenthos in a tropical system resulted in a shift from a high-value community dominated by *lethrinids* and *lutjanids* (emperors and snappers) to a lower value one dominated by *saurids* and *nemipterids* (lizard fish and bream). By inference, structurally rich habitats in temperate ecosystems also can support a greater diversity of fish species, but the influence of habitat structure on the productivity of economically important species in temperate and boreal ecosystems has not been determined. Where studies have been conducted, and they have been mostly correlative—results are consistent with the assumption that there are linkages between habitat attributes and fish survivorship (e.g., Auster et al., 1995, 1998; Langton et al., 1995; Stein et al., 1992; Tupper and Boutilier, 1995; Yoklavich et al., 2000).

With repeated trawling, the physical relief of the seafloor could be reduced, with a concomitant decrease in the quality of habitat for some species. Juveniles of many demersal fish species are known to aggregate near seabed structure. In trawled areas of the North Sea, the abundance of larger bodied, long-lived benthic species was depleted more than that of smaller, short-lived species, and there was an overall reduction in benthic production (Jennings et al., 2001). Also, removal of physical structure in a habitat can force some species into less optimal environments. For instance, the dredging of oyster reefs in North Carolina has lowered the reefs' vertical height relative to the seafloor. Thus, the only suitable substrate for the oysters is closer to the bottom in deeper areas that are more prone to anoxic events that result from nutrient overloading (Lenihan and Peterson, 1998; Lenihan et al., 2001).

The life histories of demersal fishes exhibit a gradient of linkages to habitat attributes, and the degree of habitat affinity varies by life-history stage. Identifying and quantifying linkages is difficult, especially with data collected during routine population surveys. Figure 3.3 illustrates how the proportion of overall mortality mediated by habitat attributes could change based on life stage and movement rate (as a proxy for

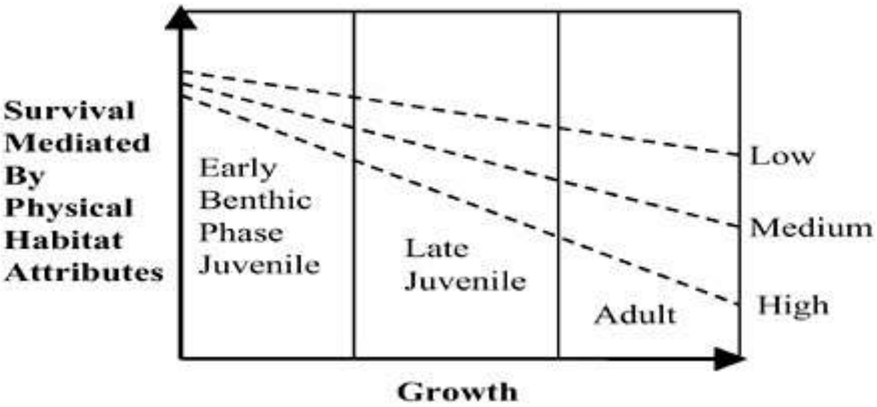

FIGURE 3.3 Conceptual model of the link between habitat attributes and mortality of demersal fishes based on general life history stages. Survival mediated by physical habitat attributes is a direct function of annual movement rates (low, medium, high) that serve as a proxy for habitat affinity. Movement rates are based on movements between habitat patches and are a function of patch size.

habitat affinity). Early benthic-phase juveniles have the highest rates of habitat-mediated mortality. Mortality rates for species that migrate become uncoupled from the physical attributes of habitat because their growth occurs at stages that are earlier than found in species that move less often and have greater affinities for habitat. For example, mortality rates for early benthic-phase Atlantic cod vary in relation to substrate complexity, but adult cod do not seem to exhibit particular small-scale shelter-related behaviors. Mortality of adults can be attributed to disease, senescence, predation from sharks and other large piscivores, and fishing.

## INDIRECT EFFECTS

The relatively few studies of the indirect effects of trawling and dredging on marine ecosystems show results that are consistent with the basic principles of marine ecosystem dynamics and predator–prey interactions. Those potential indirect effects, summarized in Box 3.1, should be considered in evaluating the effects of fishing, and they should be used to inform future research and management decisions.

### Box 3.1 Potential Indirect Effects

- *Nutrient cycling*. Seafloor trawling and dredging could increase or decrease the exchange rate of nutrients between the sediment and water column and introduce pulses of productivity in addition to pulses from the natural seasonal cycle.
- *Community structure*. Decreased abundance of demersal species could alter trophic linkages. For example, disruption of predator–prey relationships could cause a cascade of changes in other parts of the community.
- *Ecosystem processes*. Trawling and dredging remove ecosystem engineers—organisms that are responsible for water purification (oysters), substrate stabilization, and structure formation.
- *Increased susceptibility to other stressors*. Loss of physical structure in a habitat can expose organisms to other stressors, such as predation and hypoxia.

## *Sediment Processes*

Fishing gear that disturbs the sediment surface can change sediment grain size distribution or characteristics, suspended load, and the magnitude of sediment transport processes (Churchill, 1989; Dyekjaer et al., 1995; Pilskaln et al., 1998; Riemann and Hoffmann, 1991). For example, water jets used in hydraulic dredges to harvest razor clams fluidize substrate for extensive periods (Tuck et al., 2000). Because water content and pore water turnover are important determinants of nutrient regeneration in marine sediments (Hopkinson et al., 1999), hydraulic dredging could alter the nutrient flux.

Bottom trawling and dredging can both resuspend and bury biologically recyclable organic material, changing the flow of nutrients through the food web (Mayer et al., 1991). Studies in relatively shallow depths (30–40 m) show a reduction in primary production by benthic microalgae after a disturbance (Cahoon et al., 1990, 1993; Cahoon and Cooke, 1992). Hence, disturbance in shallow water, including resuspension in the wake of trawls and dredges, could affect nutrient recycling and cause shifts in the abundance or type of microalgae.

The effects of gear-induced disturbance on ecosystem processes are difficult to predict for large marine ecosystems. It could be easier to identify systemwide effects at small spatial scales in semi-enclosed systems—such as bays, estuaries, or fjords—where water exchange with openshelf waters is restricted. However, in open coastal and outer continental shelf systems, the effects of gear disturbances can be small relative to the scale and rate of natural processes. Therefore, the spatial and temporal extent of disturbance by trawl and dredge gear should be evaluated to place these indirect effects within the context of the size and complexity of the ecosystem.

## *Species Interactions*

Direct alterations of habitat can cause species shift and a general decline in the abundance of benthic organisms. Even species that are not directly exploited by a fishery are likely to be affected by the removal or disturbance of benthic and demersal biomass. For example, the early life stages of some pelagic species reside in or depend on benthic communities, for food and shelter. It is difficult to separate the indirect effects of trawling and dredging on benthic and pelagic communities from other sources of variation, such as climate change (Jennings et al., 2001).

In some cases, removal of one species can have cascading effects on the rest of the ecosystem. For example, the combination of disease and high harvest rates over the past 150 years has reduced oyster density in the Chesapeake Bay to less than 1 percent. The loss of the filter-feeding oyster’s capacity to consume algae is hypothesized to be partially responsible for the proliferation of algal blooms. This appears to have shifted the composition of the pelagic community from mesozooplankton and fish to a community dominated by predatory jellyfish and comb jellies (Caddy, 1993; Ulanowicz and Tuttle, 1992).

## RATES OF RECOVERY

Recovery is the return of an ecosystem to a state that existed before a disturbance, as measured by ecosystem processes, species composition, and species interactions. Recovery from trawling will depend on the type and extent of the habitat alteration, the frequency of the disturbance compared with natural changes, habitat characteristics, and species and life history characteristics. Recovery times vary according to the intensity and frequency of the disturbance, the spatial scale of the disturbance, and the physical characteristics of the habitat (sediment type, hydrodynamics). Superimposed on these human-related alterations are natural fluctuations, caused by storms or long-term climate changes, for example.

In most circumstances, only a first-order approximation of recovery rate is possible. Experimental evaluations recovery after cessation of trawling are limited and have focused on biotic recovery of small-bodied, short-lived invertebrates. Despite that, we can make some observations about the amount of physical disturbance that is sustainable in some types of habitat. The meta-analysis by Collie et al. (2000a) showed that recovery rate appears to be slowest in the more stable muddy habitats and biogenic (structurally complex) habitats. By comparison, mobile sandy sediment communities could be able to withstand 2–3 trawl passes per year without changing markedly. It is important to bear in mind, however, that although available data allow for prediction of the recovery rate for small-bodied taxa such as polychaetes (which dominate data sets for sandy sediment communities), less abundant, long-lived, and hence more vulnerable species could recover more slowly.

In some biogenic habitats, physical disturbance by dredging and trawling has a long-lasting effect. For example, clam dredging causes severe and persistent changes to seagrass ecosystems (Peterson et al., 1987; Stephan et al., 2000). After a single pass, seagrass biomass fell by about 65 percent below controls, and recovery did not begin for more than two years with seagrass biomass still roughly 35 percent below controls four years later (Peterson et al., 1987). The abundance of fish and shellfish that depend on seagrass for settling locations for protection from predators could be reduced where seagrass is damaged.

Environmental recovery after disturbance depends on the life histories of the organisms that live in or create the habitat. Recovery time is often one to five times the generation time of the organism (Emeis et al., 2001). Therefore recovery times could range from a few months—or less—to several decades (Hutchings, 2000). Many of the larger biogenic structure-forming organisms, such as soft corals and sponges, are slow growing and long-lived (Dayton, 1979; Leys and Lauzon, 1998). Empirical data about recovery times of corals and coral-line algae are sparse, but recovery times of decades to centuries can be inferred from the age of these organisms.

Recovery from trawling also depends on the size of the area disturbed (Thrush et al., 1998), and on the spatial pattern of the disturbance (Auster and Langton, 1999). Each trawl track is a small disturbance, but over a long enough period and with widespread coverage, the small changes can result in a large effect. The consequent habitat loss, and effects on resident species, depends to a large extent on its scale (Deegan and Buchsbaum, 2002). A single small loss might not, by itself, have an observable effect on species that are not directly damaged by trawling. However, the cumulative impact of many small losses may be quite significant at a regional scale (Odum, 1982). In some coastal ecosystems, mosaic-type damage could allow faster recovery than would a large-scale, isolated disturbance (Emeis et al., 2001).

Areas that are trawled with greater frequency could take longer to recover. Almost all studies have examined recovery after a single, acute pass by a trawl rather than after the multiple passes that are typical in frequently trawled, heavily fished areas. There, recovery would be expected to take longer because a larger fraction of the population is removed and immigration rates are lower (Figure 3.2). Results from the meta-analysis (Collie et al., 2000a) indicate that, on average, a single

dredge event results in a 76 percent, whereas repeated dredging results in an average reduction of 93 percent for anemones, malacostracan crustaceans, brittle stars, and polychaetes (Figure 3.3).

Few studies have examined the recovery of ecosystem processes or whole communities. Brylinski et al. (1994) showed that trawling significantly affected benthic diatoms that occurred in the intertidal zone, but that recovery occurred at all stations after about 30 days. The higher light intensity (and spectral composition) in the experimental area than at deeper sites, where trawling normally occurs, might have contributed to the relatively fast recovery.

The limited findings to date concur with theoretical predictions that suggest longer recovery times for more stable and complex habitats (Auster, 1998; Auster and Langton, 1999; Kaiser, 1998). Clearly, habitats with extended recovery periods are strong candidates for protection from disturbance caused by fishing. However, much better data on the geographic distribution and long-term effects of chronic trawling and dredging in these physically more stable habitats are required to estimate recovery rates that will promote strategic, rather than precautionary, management decisions.

## UNCERTAINTY

Underlying the concept of the reversibility of the effects of dredging and trawling is the implicit assumption that eventual recovery to the former state will occur if the activity is halted. This assumption derives from an ecological paradigm in which ecosystems and communities are viewed as part of a successional continuum along a disturbance gradient. An alternative approach recognizes multiple-equilibria, non-linearity, and threshold effects (Holling, 1973; Holling et al., 1995; Patten and Constanza, 1997). In an alternative state, ecosystems have different species compositions, functions, and ability to provide ecological services. They might therefore be valued quite differently by society. Resilience, or the counteractive capacity of the ecosystem, is measured by the ability to maintain structure and function in the presence of stress or disturbance. When resilience is exceeded, the system can flip to an alternative state from which it will not return simply by removing the source of disturbance (Holling, 1973; Holling et al., 1995). These regime shifts can affect valuable ecosystem services, including fisheries yield (Collie and Spencer, 1994; Knowlton, 1992).

Human or natural modification of the marine environment might result in the shift of a community from one stable state that provides economically valuable fish to another stable state dominated by fish of higher or lesser value. Ecosystems respond to perturbation in many ways, including changes in species composition (by loss, inclusion, or replacement) and in the relative abundance of biomass (with an increase or decrease) of some species. Overall production and biomass of an ecosystem can remain the same as species respond to natural or human-induced stress (some species increase while others decrease) (Breitburg, 1998; Fogarty and Murawski, 1998). This change to a new stable state might take place abruptly, right after the disturbance occurs, or it could result from small cumulative shifts in natural forcing variables. Examples of species replacements are the apparent increase in cephalopod species in the Gulf of Thailand, which coincided with the increase in trawl fishing and the reduced abundance of demersal fish, and the increase in pelagic species that seems to have occurred in the North Sea and elsewhere. Its duration may vary. The return time to the initial stage has been predictable in some cases. In other cases, with nonlinear interactions and multiple-equilibrium states, the time the ecosystem will remain in a new state is not predictable. For benthic communities with a long history of fishing disturbance, it is unknown whether the community would return to the undisturbed state if the disturbance were stopped.

Human modifications to marine environments compromise the capacity of marine populations to recover from stresses, such as storms, eutrophication, and climate change, whether natural or anthropogenic. Seagrass ecosystems provide an example in which the synergistic effects of habitat loss due to trawling could compromise the ability of the system to withstand or recover from other disturbance. Seagrass ecosystems are important habitats and locations of fisheries for numerous fish and invertebrate species. The natural distribution of seagrass habitat is controlled by light availability that is a function of water quality, including the presence of phytoplankton and suspended sediments. The physical structure of seagrass, including stem density and the size of beds, increases water clarity by filtering water column particulates and depositing them on the bottom (Thayer et al., 1984). This creates a zone of clear water around seagrass beds that allows them to persist and expand. Trawling can fragment the seagrass bed into small pieces that do not effectively trap suspended particles, resulting in light

imitation. Eutrophication also enhances the proliferation of faster growing phytoplankton, epiphytic algae, and macroalgae that compete with seagrass for light and space (Kemp et al., 1983; Phillips et al., 1978; Short et al., 1995; Twilley et al., 1985). Light limitation of seagrasses leads to diminished growth and stature, increased shoot mortality and declines in shoot density (Duarte, 1995; Moore et al., 1996; Short et al., 1995), resulting in declines in seagrass habitat area. Initial habitat fragmentation by trawling and dredging can make seagrass habitats more susceptible to the negative effects of eutrophication.

The maintenance of the ecosystem in an alternative state will depend on interactions with adjacent ecosystems and the intensity of the new biologic links. Additional disturbance generated by natural events or by new trawling and dredging can help maintain the assemblage in this state of equilibrium or transfer it to a new state. In the benthos, disturbances can be physical (hurricanes, suspension of sediment by surf, lateral transport by bottom currents, seasonal hypoxia generated by the input of nutrients, limited export of biogenic carbon) or biological (predation, flux and export of biogenic carbon, deposition of debris, bioturbation, competitive exclusion). Their common action is to remove organisms and to open spaces for colonization by other organisms. If disturbances are frequent, gaps will constantly reset to one of the multiple stable stages. If disturbances are rare, most of the community will remain in a stable state for most of the time. The loss of complexity and biodiversity can threaten important ecologic functions (the cycling of important elements or the control of populations of particular species) or the resilience of ecosystems to change or disturbance.

## SUMMARY

For the most part, existing information about the direct responses of benthic communities to trawling and dredging is consistent with the general principles that govern how ecologists expect communities and ecosystems to respond to acute and chronic physical disturbance. Trawling and dredging change the physical habitat and biologic structure of ecosystems and therefore can have potentially wide-ranging consequences. Mobile gear reduces benthic habitat complexity by removing or damaging the actual physical structure of the seafloor, and it causes changes in species composition. The reduction of physical structure in repeatedly trawled areas results in lower overall biodiversity. Of direct concern to commercial and recreational fisheries is the possibility that losses of benthic structural complexity and shifts in community composition will compromise the survival of economically important demersal fishes. Mobile gear also can change surficial sediments and sediment organic matter, thereby affecting the availability of organic matter for microbial food webs.

## RESEARCH NEEDS

It is clear that the links between habitat alteration and loss of fisheries production can be subtle and diverse and that they operate on many spatial scales, from site-specific to regional. Most studies have been done in shallow water in small areas. Researchers have examined acute disturbances, rather than chronic, and they have studied short-term response focused in animal communities, as opposed to ecosystem processes such as nutrient regeneration. Although there have been many acute studies, few have examined the effects of short-term multiple passes, and future research should address this type of disturbance.

Perhaps the biggest research gap is on chronic effects and recovery dynamics. More studies on chronic disturbance by fishing gear are needed to determine the dose–response relationship as a function of gear, return time, and habitat type. Research also should address recovery dynamics, with consideration given to estimating the large-scale effects at current fishing intensities (e.g., Collie et al., 1997). This research should include quantitative studies undertaken in deeper water (>100 m) and studies in stable and structurally complex habitats, for which the recovery trajectory will be measured in years to decades. The statistical power to detect fishing effects will be greatest when biologic sampling can be combined with high-resolution spatial data on fishing effort.

# Findings and Recommendations

The most challenging aspect of evaluating the effects of trawling and dredging on seafloor habitats is translating observed effects from experimental studies to the scale of actual fishing effort in the various fisheries around the United States. Studies that examine changes in seafloor structure and biological communities after disturbance by various types of mobile fishing gear have yielded consistent patterns of acute effects that can be categorized by gear type, habitat characteristics, composition of the benthic community, and frequency of disturbance. To convert those results into an assessment of ecosystem-level effects on seafloor habitats requires analysis of the frequency of bottom trawling and dredging and fine-scale mapping of this effort relative to the geography of seafloor habitats in the fishing grounds. Further research will be necessary to fully understand the effects of chronic disturbance by mobile bottom gear and to more accurately assess the effects of habitat disturbance on the productivity of commercial and recreational fisheries.

The acute, gear-specific effects of trawling and dredging on various types of habitat are well documented (Chapter 3). Many studies indicate that stable communities of low mobility, long-lived species are more vulnerable to acute and chronic physical disturbance than are communities of short-lived species in changeable environments. Habitat complexity is reduced by towed bottom gear that removes or damages biological and physical structures. The extent of the initial effects and the rate of recovery depend on the stability of the habitat. The more stable biogenic, gravel, and mud habitats experience the greatest changes and have the slowest recovery rates. In contrast, less consolidated coarse sediments in areas of high natural disturbance show fewer initial effects. Because these habitats tend to be populated by opportunistic species that recolonize more rapidly, recovery also is faster.

Data on the geographic distribution and frequency of trawling and dredging are limited in spatial resolution, and there is considerable regional variation in reporting methods and in records for recent years (Chapter 4). However, data collected in the early 1990s indicate that the most intensive effort (Table 4.1) was in the fishing grounds of the Gulf of Mexico and New England regions. Bottom trawling in the mid-Atlantic, Pacific, and North Pacific regions was relatively light, with less than 1 tow per year in many reporting areas. Even in heavily trawled regions, effort was not evenly distributed; thus, some areas were trawled several times per year while others were trawled infrequently if at all. Throughout the 1990s and into 2001 there were significant reductions in the intensity and spatial extent of bottom trawling (Figure B.38). These decreases resulted from reductions in fishing effort, area closures, and gear restrictions instituted by managers in response to problems with declining fish stocks, bycatch, or interactions with endangered species.

The largest information gap is in the spatial distribution of different habitat types in trawled or dredged areas. For most areas only coarse maps are available on habitat distribution. This mismatch in the spatial scales of experimental results, habitat maps, and trawl effort reporting data makes it difficult to accurately assess effects of trawling and dredging on marine ecosystems. Nonetheless, there is enough information currently available to support efforts to improve the management of the effects of fishing gear on seafloor habitats. Specific recommendations for making the best use of current information and suggestions for research are provided below.

## RECOMMENDATIONS

The following recommendations fall into three categories: 1) interpretation and use of existing data; 2)integration of management options; and 3) policy issues raised by existing legislation. Recommendations for research appear at the end of this section.

## *Interpretation and Use of Existing Data*

**Recommendation**

**Fishery managers should evaluate the effects of trawling based on the known responses of specific habitat types and species to disturbance by different fishing gears and intensity of fishing effort, even when region-specific studies are unavailable.** The direct responses of benthic communities to trawling and dredging (Chapter 3) are consistent with ecological models of how biological communities and ecosystems respond to acute and chronic physical disturbance. Although area-specific studies on the effect of trawling and dredging gear will allow more targeted management approaches, adequate information is available to address fishing effects on seafloor habitat. Predictions developed from common trends observed in comparable habitats will provide reasonable estimates of fishing effects to serve as the basis for management. Estimates should be revised as more site-specific information becomes available. An adaptive management strategy could be used both to reduce the effects in the short-term and to provide additional information for improving management in the long-term.

**Recommendation**

**The National Marine Fisheries Service and its partner agencies should integrate existing data on seabed characteristics, fishing effort, and catch statistics to provide geographic databases for major fishing grounds.** The potential consequences of fishing can be most efficiently assessed by the simultaneous and consistent presentation of all available data on the characteristics of the seabed and fishing effort. Although some data exist on habitat characteristics and on the location and intensity of fishing (Chapter 4), the available data have been prepared by different agencies, in different formats, at variable levels of resolution, and are collected in separate archives. Integration of these databases into a single, geographic information system will assist managers in evaluating regional needs for habitat conservation.

## *Integration of Management Options*

**Recommendation**

**Management of the effects of trawling and dredging should be tailored to the specific requirements of the habitat and the fishery through a balanced combination of the following management tools.**

- *Fishing effort reductions.* Effort reduction is the cornerstone of managing the ecological effects of fishing, including, but not limited to, effects on habitat. Other management tools (gear restrictions or modifications and closed areas) may also require effort reduction to achieve maximum benefit. However, effort reduction alone might not be sufficient to reduce effects in highly structured habitats where there is low potential for recovery.
- *Modifications of gear design or restrictions in gear type.* Disturbance depends on the extent of contact of the gear with the seafloor; gear designs that minimize bottom contact can reduce habitat disturbance. In addition, shifts to a different gear type or operational mode can be considered, but the social, economic, and ecological consequences of gear reallocation should be recognized and addressed.
- *Establishment of areas closed to fishing.* Closed areas effectively protect biogenic habitats (e.g., corals, bryozoans, hydroids, sponges, seagrass beds) that are damaged by even minimal fishing.

The appropriate combination of management approaches will depend on the characteristics of the ecosystem and the fishery—habitat type, resident seafloor species, frequency and distribution of fishing, gear type and usage, and the socioeconomics of the fishery. Each characteristic should be evaluated during development of a mitigation strategy.

**Recommendation**

**The regional fishery management councils should use comparative risk assessment to identify and evaluate risks to seafloor habitats and to rank**

**management actions within the context of current statutes and regulations.** Risk assessment provides a scientifically informed approach to clarifying environmental policy issues by elucidating the environmental consequences of particular policy choices (Chapter 5). Comparative risk assessment can be used when there is incomplete scientific information because it relies on a combination of available data, scientific inference, and public values. Mobile bottom gear is only one of many factors contributing to the degradation of benthic habitats; the comparative approach provides a method for simultaneous consideration of a wide range of risks, including pollution, drilling, and natural disturbance. Comparative risk assessment enables stakeholder involvement in the decision-making process and improves the sharing of information among different groups to aid in the development of solutions that have broad societal support.

## *Policy Issues Raised by Existing Legislation*

**Recommendation**

**Guidelines for designating essential fish habitat (EFH) and habitat areas of particular concern (HAPC) should be established based on standardized, ecological criteria.** The EFH concept recognizes that management of exploited fish populations requires addressing effects on other parts of the ecosystem upon which fish depend. Its effective use rests upon a clear understanding of the population biology and the spatial distribution of each managed species. The current designation of EFH does not require the use of consistent criteria with respect to the assignment of habitat to each life stage of species covered by fishery management plans. Instead, the regional councils develop the criteria, often based on data availability. Typically, EFH designations are too extensive to form a practical basis for managing fisheries (Chapter 1). Although this approach could assist in mitigating some habitat threats, it provides little guidance for evaluating the effects of trawling and dredging. For example, in some management plans habitat is identified based on the frequency with which fish are found in a particular area. Although this method is based on sound ecological principles, it is important to refine the use of frequency distributions to identify the habitats that support the main fraction of the population rather than to simply document where the fish are found.

The term HAPC should be clearly and narrowly defined with establishment of specific guidelines for regulating fishing activities. The effectiveness of the designations should be reviewed periodically. HAPC forms a subset of EFH based on the ecological value of the area, its susceptibility to perturbation, and whether it is rare or currently stressed (National Marine Fisheries Service, 1997). However, current policy does not require additional protection for HAPC. Because of the demonstrated importance of HAPC in the life cycles of exploited fish populations, HAPC sites should receive priority in fishery management plans.

**Recommendation**

**A national habitat classification system should be developed to support EFH and HAPC designations.** A classification system with common habitat designations will improve efforts to protect, inventory, and construct regional or national maps of habitats of importance or concern. Standardizing classifications would facilitate tracking changes over time and provide the basis for developing functional links between the underlying mechanisms that structure the ecosystem and the biological systems that support fisheries production. A habitat classification system would assist in ranking the relative importance of different habitats for fisheries and for biodiversity, estimating the vulnerability of the habitat to disturbance, and facilitating the application of research conducted in one region to the management of habitats in other regions.

## FUTURE RESEARCH

In the course of this study, many gaps were identified in the current understanding of the effects of fishing on the seafloor. The following recommendations are intended to direct research towards filling these gaps. They have been organized into three primary areas of research—gear impacts and modification, habitat evaluation, and management—with some overlap between categories.

## *Gear Impacts and Modification*

Further research on gear effects will be required to develop a predictive capability to link gear type and effort to bottom disturbance, fish production, and recovery times in particular habitats. Active engagement of resource users in the research will help ensure that mitigation strategies are practical, enforceable, and acceptable to the fishing community. This could be accomplished through cooperative research programs involving fishermen and scientists. Topics for future research include the following:

- identification of the forces produced by fishing gear on the seafloor and the threshold forces that injure and dislodge a range of benthic organisms;

- use of various empirical approaches, such as sidescan sonar, to assess the spatial extent and overlap of trawl and dredge effects in conjunction with higher resolution effort reporting data;
- development of fishing gear to reduce damage to habitat and to meet other conservation goals such as bycatch reduction and maintenance of biological communities; and
- investigation of why some areas appear to continue to produce fish despite chronic disturbance by fishing gear.

## Habitat Evaluation

Habitat disturbance has been studied mainly at small spatial scales with short-term observations of acute disturbance. Development of a landscape-scale perspective of the effects of trawling and dredging on the seabed will require a long-term commitment to higher resolution mapping of the continental shelf and slopes. Because most studies have focused on animal communities, more studies are needed on ecosystem processes (e.g., productivity, nutrient regeneration). Topics for future research include the following:

- the rates and magnitude of sediment resuspension, nutrient regeneration, and responses of the plankton community in relation to gear-induced disturbance;
- the dose-response relationship as a function of gear, recovery time, and habitat type to evaluate effects of repeated disturbance by fishing gear;
- recovery dynamics, with consideration given to estimating large-scale effects at current fishing intensities;
- acute and chronic effects of trawling in deeper water (>100 m);
- recovery rates in stable and structurally complex habitats;
- relative magnitude of different sources of bottom habitat disturbance;
- long-term trend data for benthic production versus fisheries production; and
- the effects of habitat fragmentation on total production.

## Management

Constructive interactions among stakeholders and policymakers can be facilitated through user group funding of research and through collaborative research that involves scientists and fishermen. Increased participation also will support cooperative development of alternative gears and practices. Comparative risk assessment can be used to identify priorities for acquiring quantitative data to improve risk analysis. Monitoring and evaluation of the consequences of existing management measures (e.g., gear restrictions, area closures, effort reductions) should be used to support the development of new management plans, especially in understudied regions. Aggregation and analysis of existing information on habitats, fishing effort, and efficacy of various management measures will help the regional fishery management councils meet their mandate to protect EFH. Topics for future research include the following:

- develop testable hypotheses of how biological communities in different habitat types respond to fishing;
- establish baselines for characteristic habitats and regions to document the effects of various fishery practices;
- design quantitative models to predict fishing effects in areas that have not been studied;
- validate the use of frequency-dependent distribution approaches for designating EFH and HAPC through analysis of community structure and life history parameters; and
- collect and analyze data on the social and economic characteristics of trawl, dredge, and nonmobile gear fisheries to assess the tradeoffs among various management alternatives.

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