12 The Global Destruction of Bottom Habitats by Mobile Fishing Gear

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Throughout virtually all of the world's continental shelves, and increasingly on continental slopes, ridges, and seamounts, there occurs an activity that is generally unobserved, lightly studied, and certainly underappreciated for its ability to alter the sea floor habitats and reduce species diversity. That activity is fishing with mobile gear such as trawls and dredges. In the last half-century there has been a persistent push on the part of governments, international agencies such as the Asian Development Bank, and other organizations, to encourage fishing nations to develop their trawler fleets. As this chapter will show, where the trawler fleets fish, habitat complexity is inexorably reduced and benthic communities are nearly completely changed.

Structure of the Sea Floor

Most people think of the sea bottom as a "featureless" plain surrounding islands of high biodiversity, as is seen in coral reef areas. However, the sea bottom is inhabited by a very large number of small to large animals, including invertebrates and fishes. Outside of the larger undersea features (e.g., coral reefs, seamounts, and hydrothermal vents), most of the important structures in the sea bottom are not readily visible with standard undersea cameras or other imaging technologies. Thus the bottom is not featureless if viewed at the appropriate scale. Rather, the upper few centimeters of the bottom muds harbor everything from bacteria to large tube-dwelling sea anemones, often in startlingly high numbers. Most shallow marine sediments contain about 5×10^9 bacteria per gram of sediment, about 1 to 2×10^4 small-sized animals, and 5×10^3 larger animals per 0.1 m^2 of sediment (Giere 1993; Reise 1985). Of course, in deeper water these numbers decrease, especially for the larger-sized creatures. Nevertheless, even in the deep sea there is likely to be about 5×10^7 bacteria per gram of sediment.

A typical view of the modern sea floor appears in Figure 12.1. What catches one's eye is the preponderance of larger fishes and invertebrates living above—and to a certain extent in—the sea floor. Yet this view does not reflect the kinds of numbers outlined above. In fact, more than 70 percent of the benthic fauna can be found within 5 to 8 cm of the sediment surface (Giere 1993). As organic matter settles to the sea floor, it is largely used by the organisms living in this layer, and as much as 75 percent might be returned to the overlying water in the form of dissolved nutrients (Graf 1992; Rowe et al. 1975). If the sediment were transparent, one would see in its upper layers a veritable bustle of activity, with worms, small crustaceans, tiny clams and snails, all wriggling about in search of food or mates. Below about 1 cm from the sediment surface, all oxygen has been used, primarily by sediment-dwelling bacteria, so animals living deeper in the sediment generally have to construct burrows or tubes to maintain

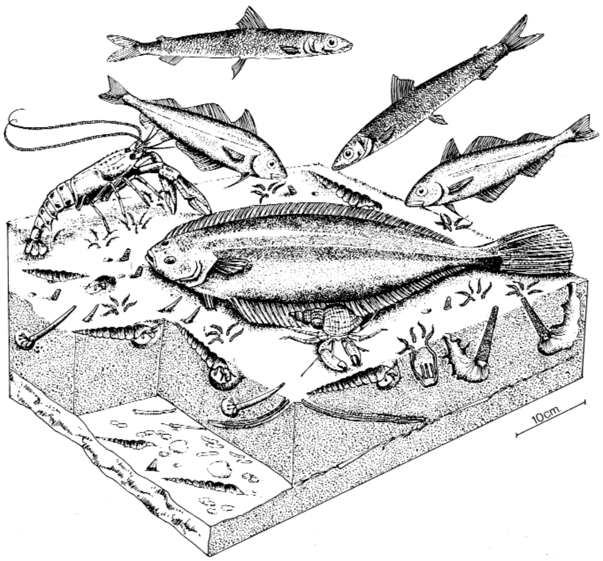


FIGURE 12.1. Three-dimensional view of the shallow seafloor in the North Atlantic Ocean. Noticeable are the large invertebrates (lobsters) and vertebrates (fishes). This illustration was made to show what portion of the marine biota would fossilize, but it also reflects what most people know about marine biodiversity—missing are the myriad smaller life forms that account for most of the life in the sea (from McKerrow 1978).

some contact with the overlying oxygenated water (e.g., Kristensen 2000; Reise 1985). Even so, by 5 centimeters' depth into the sediment the only animals to be found have much larger bodies and construct larger burrows. It is the entrances to these larger subterranean structures that are often seen in bottom photographs, yet these bigger species represent only a small fraction of the living beings inhabiting the seafloor.

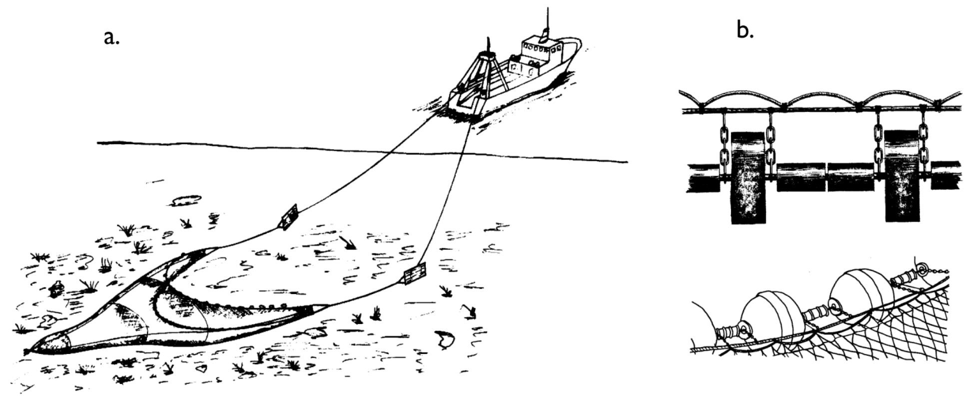
Of course, there are dazzling exceptions to this picture of the flat bottom. Throughout the world there are reefs built by corals, rocky chimneys made of minerals deposited by hydrothermal vents, ancient volcanic seamounts, and, at higher latitudes, large boulder and gravel deposits left by glaciers. All of these areas harbor large organisms that are easily photographed and quite photogenic. Many of the large animals present in these biotopes are long-lived (for example, Druffel et al. 1995 found a colonial anemone living at 600 m in the Florida Straits to be 1,800 years old, and other cold water corals are usually more than 200 years old) and their bodies or the skeletal material they leave behind provide habitat for a vast number of smaller species. Off Norway and the Faroes, for example, more than 700 smaller species have been found living in the interstices of *Lophelia pertusa* (a cold water coral) reefs (Jensen and Fredericksen 1992).

Mobile Fishing Gear

Two major classes of mobile fishing gear are commonly used today, trawls and dredges (Figure 12.2, from Sainsbury 1996). Trawls are large nets that are pulled over the bottom, whereas dredges are usually constructed of a heavy iron frame to which is fixed a chain-link bag.

There are several major trawl designs but the two most commonly used are the otter trawl and the beam trawl. The mouth of the otter trawl net consists of a footrope, which drags along the bottom, and a headrope bearing floats to keep it as high as possible in the water. The mouth is pulled open by large steel plates, called doors, which are designed to push laterally as they are hauled through the water, thus pulling the net mouth open. These doors can be many meters away from the actual mouth of the net, they are usually very heavy, and they almost always gouge large plow marks in the seafloor. The ropes that connect the doors to the net act as fences that help herd fish into the net. Otter trawls are generally used to catch fishes that feed on the bottom but swim some short distance up into the water, although they can also be used for strictly pelagic species. As the fisheries of smooth bottom areas of the continental shelves have been depleted, otter trawls have been modified, chiefly by adding larger rollers or discs to the footrope, so that the net can safely be pulled over areas with boulders as large as 1 m in diameter (see Figure 12.2).

Beam trawls are used primarily in flatfish fisheries. This type of trawl consists of a large, often very heavy, iron frame to which is attached a series of heavy chains and a long net for retaining the fish. The iron frame can be up to 18 m wide; it consists of two



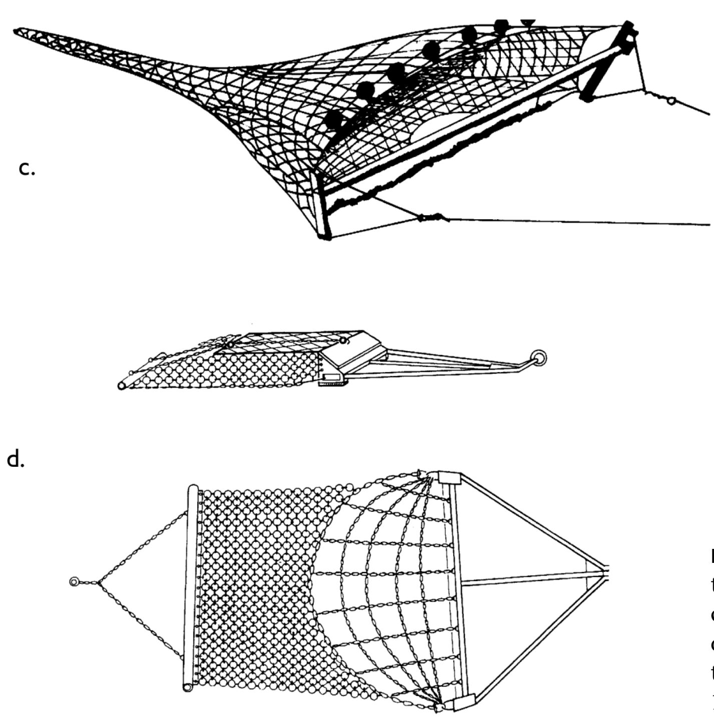


FIGURE 12.2. Typical mobile fishing gear in use today. 12.2a: Otter trawl. 12.2b: Roller gear that can be fixed to the bottom (= foot) rope of an otter trawl allowing the gear to be used on bottoms with boulders or corals. 12.2c: Beam trawl. 12.2d: Scallop dredge. (All from Sainsbury 1996)

D-shaped end pieces joined across the top by a large bar that keeps the end pieces a fixed distance apart. To stir up the sediment-dwelling flatfishes, a large series of chains, sometimes in the form of a chain mat, is attached between the bottom of the end pieces and the beginning of the net. These chains can dig into the sediment as much as 8 cm during a single pass of the trawl (Lindeboom and de Groot 1998).

Scallop dredges are the heaviest type of gear used in any commercial fishery, at least in terms of weight per unit size. They consist of an iron frame with a large chain bag attached. In some areas the bottom front bar might also be equipped with several long, very heavy teeth. These dredges, sometimes called "drags," are built so ruggedly that they can be towed over almost any kind of bottom where scallops are likely to be found.

Modern Fishing Practices

Those who drag gear across the bottom in their search for fish or shrimp usually do not target the bottom

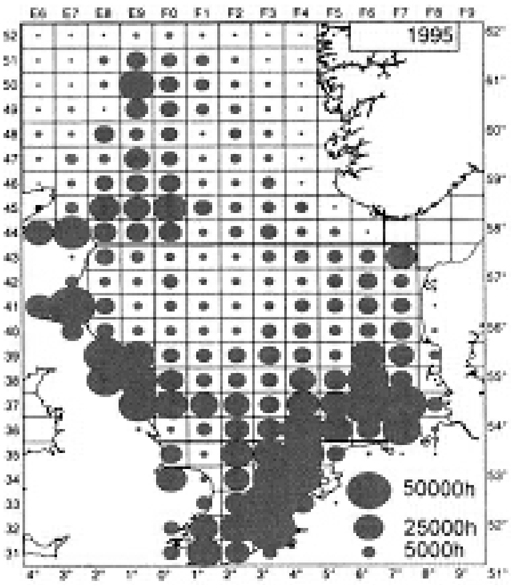


FIGURE 12.3. Map of North Sea showing spatial distribution of international otter and beam trawl fishing in the North Sea in 1995 (from Jennings et al. 1999). Each box is 0.5 degree latitude by 1 degree longitude and the gray level represents the total hours of fishing effort in each rectangle each year.

randomly. They generally bring years or generations of experience to bear on selecting areas to fish, unless, as in the case of the northwest shelf of Australia, the area is far from long-term habitation and has not been fished before. In most areas of the world that have been fished for a long time, there are preferred areas of bottom that are repeatedly fished. Thus some areas might be dragged over many times during the course of a fishing season and other areas can be disturbed only once or twice. Consequently, some areas of the sea floor will see very frequent disturbance whereas other, perhaps even adjacent, areas will be disturbed infrequently (Figure 12.3). The time between disturbance events is undoubtedly critical to the ability of the benthic organisms to repopulate or recolonize disturbed areas.

On a global basis there are few areas of the world's continental shelves that are not disturbed by mobile fishing gear (Figure 12.4, based on information published in United Nations Food and Agricultural Organization 1997). In the North Atlantic and North Pacific, the target species are primarily bottom-dwelling fishes, although there is usually a winter fishery for pandalid shrimps. Most of the warm temperate to tropical continental shelves of the world are heavily fished for penaeid shrimps. In the Southern Hemisphere, especially where waters are deep and cold, there is a newly developed fishery for deep-sea species living on and around seamounts (Koslow 1997; Koslow et al. 2001). Most recently, some governments, notably those of Britain, France, and Spain, have been subsidizing attempts to develop a fishery on the continental slopes down to depths as great as 1,800 m (Gordon 2001; Merritt and Haedrich 1997).

Impacts of Fishing Gear

When mobile fishing gear is hauled over the sea floor, multiple impacts can occur depending on the composition of the substratum and gear used. If the bottom is dominated by boulders (up to 1 m in diameter) and gravel, then either rock-hopper gear or a scallop dredge is likely to be used. As rock-hopper gear is pulled over the bottom, it rolls and scrapes over the surface, sometimes riding up and over large boulders, but often catching on a boulder that is then pushed along the bottom until it in turn hits something and rolls. In all cases, the gear is very effective at removing larger organisms living in gravel and boulder bottoms, especially sponges and other erect forms. A recent study showed that even the smaller fauna of the boulders is lost in areas that are heavily trawled, with as much as 50 percent of the species missing (Pugh 1999). One group of organisms that seems to tolerate this level of disturbance reasonably well is the sea anemones, and indeed, one can see one or two sea anemones on the top of otherwise bare boulders in areas of heavy trawl use.

Scallop dredges are generally used in areas where the substratum is gravel, cobble, or sand, with only occasional large boulders present. Because of its weight, the dredge tends to plow a wide furrow in gravel or

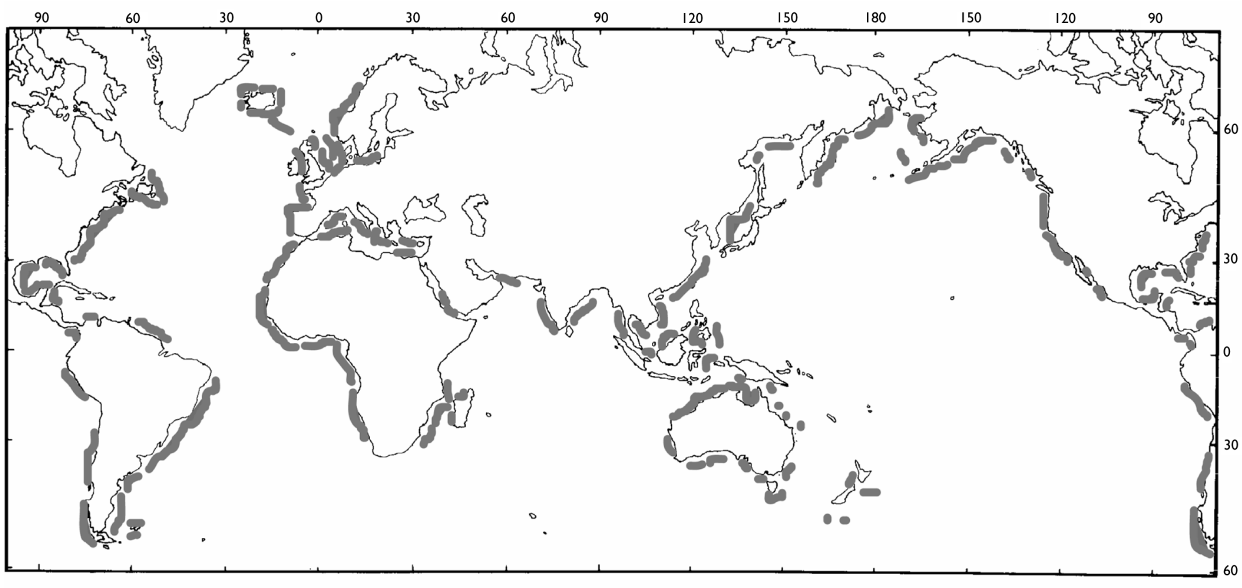


FIGURE 12.4. Trawling grounds of the world. Areas in gray are regions of the continental shelf subject to trawling for either fish or shrimp. Data from Food and Agricultural Organization (1997).

sandy substrates, or roughly scrapes over the surface in areas of smaller rocks. Larger organisms are always removed, and some smaller animals might be launched into the water and are either eaten by fish or carried away on the tide (e.g., Collie et al. 1997; Thrush et al., 1995). In a muddy sand area, Watling et al. (2001) noted that repeated passage of a scallop drag in one afternoon lowered the sediment surface by 4 cm and reduced its food quality. As a result, some marine invertebrates that were dependent upon this sediment for food avoided the dragged area for several months.

Otter trawls are the most common gear type used on muddy bottoms. The doors, which can weigh from one to several tons, tend to dig large furrows in the sea floor that are usually deep and wide enough to be visible in side-scan sonar images. The groundrope and the net create a zone of turbulence that resuspends great clouds of mud into the water (Churchill 1989). As has been noted already, in muddy bottoms most of the biodiversity exists within the upper 5 to 8 cm of the sediment. Consequently, as the bottom muds are thrown up into the water, so are many of the bottom-dwelling creatures. In fact, Pilskaln et al. (1998) found several species of bottom-dwelling worms in sediment traps located 25 m off the bottom. The disturbance of the sediment surface causes the loss of tubes and burrows made by deeper-dwelling bottom animals and a general reorganization of the bottom community (Tuck et al. 1998). As yet, we do not know the long-term consequences of those losses, although some predictions, especially involving decreases of sedentary annelids and subsurface-dwelling echinoids, have recently been tested (Frid et al. 1999).

Burrows and tubes are critical structural elements in muddy bottoms. Burrows made by animals living under the mud surface are used as conduits for pulling oxygenated water into the sediments to satisfy the respiratory needs of the burrow dweller. Tubes are usually constructed to help bottom-living animals reach into the overlying water for food particle collection. Because oxygenated water penetrates into burrows and tubes, "halos" of oxygenated sediment commonly exist in the surrounding sediment. This oxygen delivery deep into the sediments enhances nutrient recycling from the sediment to the overlying water. For example, Mayer et al. (1995) showed that there is an order of magnitude increase in oxidation of ammonia in the walls of a burrow inhabited by an animal that pumps water at 25 milliliters per hour or greater. Similarly, a 10-fold increase in oxygen flux across the sediment–water interface occurred in the model of Furukawa et al. (2000) as burrow numbers increased from 700 to 10,000 burrows per m^2. Clearly, the geochemical character of marine sediments is related strongly to the presence of invertebrate burrows and tubes. These structures have to be viewed as important three-dimensional features of what is usually termed "featureless" habitat. In fact, Codispoti et al. (2001) noted that some of the deficit in their oceanic fixed nitrogen budget could be due to ecosystem changes caused by human activities, such as bottom trawling.

Sandy bottoms are generally considered to be the safest for trawling. Yet, in the North Sea, where sandy substrates have been trawled for many decades by beam trawls, the majority of species now found in those areas are ones that produce large numbers of young each year (summarized in Lindeboom and de Groot 1998). Brown et al (in press) found that the turbulence created by the net as it was pulled over the bottom was approximately equal to the turbulence resulting from storm waves in the Bering Sea, and was sufficient to resuspend sand particles. They also noted that the turbulence caused by the trawl gear occurred during the summer, when the sand bottom habitat would normally not be disturbed by storm waves. In other areas, such as the northwest Atlantic Ocean, the use of otter trawls on sandy bottoms has resulted in a general flattening of large sand waves that might be used for shelter by very young fish (Auster et al. 1995). Still, sandy bottom areas in northern cold waters continue to produce fishable quantities of flatfish. Other sandy areas that seem to be impacted to a greater degree are the shrimp grounds in tropical waters. These areas support large numbers of epifaunal species, such as sponges, sea whips, and sea fans, most of which are only loosely anchored into the sand. As the trawl passes over these animals, they are either uprooted or damaged from the impact. In general, significant decreases in these species are seen in heavily trawled shrimping grounds (Poiner et al. 1998).

In a few cases, we also know the long-term consequences of using mobile fishing gear in continental shelf environments (Hall 1999). In most instances the ecosystem changes seen are documented only for fishes in the community, but the lessons are clear. In areas as far apart as the Gulf of Thailand, the northwest shelf of Australia, and Georges Bank off the east coast of the United States, the picture has been the same. An area with a diverse fish community is fished heavily with bottom trawl gear. After some years, the original target fish species show sharp declines in abundance and are eventually replaced by some other, previously not-so-common, group of fishes. If the bottom habitat is examined, as it was in Australia, there are clearly visible changes in habitat structure. Of course, such changes can be assumed to be occurring when, during the course of the fishery, bycatch levels are very high to begin with and then suddenly decline. Such was the case for the northwest Australian shelf community (Sainsbury 1987, 1991). Here, the bycatch was initially recorded in the thousands of tons. When the bottom was examined with a camera, untrawled areas were seen to support a virtual forest of epifaunal species, while trawled areas looked like a submerged sand beach. The species of initial interest, emperors (*Lethrinus* spp.) and snappers (*Lutjanus* spp), were feeding on the invertebrates living on the large epifaunal species. As the epifauna was removed, only the less desirable sand-bottom-feeding sea breams (*Nemipterus* spp.) and grinners (*Saurida* spp.) were caught.

Long-term changes have been seen in the infauna as well, although the records are incomplete (e.g., Philippart 1998). In the North Sea, where bottom trawling has been occurring for nearly a century, significant changes have been documented for the mollusks, particularly the bivalves and gastropods (Rumohr and Kujawski 2000). Of the 39 bivalve species examined, 9 (mostly formerly less common, deeper-water species) increased in abundance, 19 decreased in abundance but were still present, and 11 had completely disappeared. Among the 13 gastropods only 3 had decreased in abundance, 1 had disappeared, and the remaining 9 were as abundant or had greatly increased in numbers. As it turns out, the latter species are all scavengers. In fact, an increase in scavenger abundance is one of the most consistent results of all trawling impact studies conducted in the North Sea region (e.g., Ramsay et al. 1996, 1998). What is unknown, unfortunately, is the long-term fate of the hundreds of smaller, less conspicuous species in areas impacted by trawling. Certainly, decreases in abundance of larger epifaunal species must result in the loss of the smaller species dependent on the larger ones for substratum or food. Unfortunately those kinds of data do not exist, so we must make inferences about species losses from short-term studies, such as that done recently by our group on boulder bottoms in the Gulf of Maine (Pugh 1999).

Comparison with Natural Disturbances

In shallow water, especially, any aspect of physical disturbance that might be attributable to mobile fishing gear has to be studied in relation to potential natural disturbance events (Watling and Norse 1998). For example, storm waves, strong currents, scouring by icebergs, feeding of large mammals (especially whales) or fishes, and mixing of sediment by burrowers can all shape the structure of benthic habitats. Coral reefs that have existed undisturbed for a century or more can be altered by the passage of a hurricane. At high latitudes, the marine benthos at depths as great as 500 m can be scoured by grounding icebergs (Barnes 1999; Conlan et al. 1998). The most severe and large-scale natural disturbances, such as hurricanes or iceberg groundings, recur over very long time intervals while the less severe and smaller-scale disturbances, such as animal burrowing, are frequent and predictable. As a consequence, most species living in the impacted areas have evolved population characteristics that allow them to grow in, or repopulate, disturbed sites. Fishing with mobile fishing gear is both very severe and large scale, but the return interval between disturbance events is often short relative to the life span of most species. Further, mobile fishing gear is often used in areas that have never been subject to such severe physical forces, such as below the storm wave base, in depositional basins where sediments are settling and would otherwise never be resuspended, or on the continental slopes and upper parts of the deep sea (Bett 2001; Friedlander et al. 1999; Gage 2001; Merrett and Haedrich 1997). This kind of disturbance is a very recent event in the evolutionary history of marine benthic species, and there has been no time for any adaptation to it.

Comparison with Disturbances on Land

The largest equivalent physical disturbance in the terrestrial realm is that of forest clear-cutting. To gain an appreciation of the extent to which the marine benthos is disturbed by trawling, Watling and Norse (1998) compared the impact of mobile fishing gear with forest cutting practices (summarized in Table 12.1). Some key similarities can be seen: both activities

1. remove large amounts of biomass from the ecosystem,
2. alter the substratum,
3. eliminate late-successional species, and
4. release large pulses of carbon to the overlying air or water.

There are, however, some key differences:

1. Much more area of the sea bottom is impacted by trawling than land is influenced by forest clear-cutting (1.5 million km^2 vs. 0.1 million km^2).
2. The return time of the disturbance is much shorter in the sea than on land (days to years vs. tens to hundreds of years).
3. Ownership of the land is both private and public whereas the sea floor has always been considered to be publicly owned.
4. There are many scientific studies dealing with forest clear-cutting but relatively few with impacts of mobile fishing gear.
5. A legal framework has been developed to deal with logging and forest preservation whereas the concept of limiting activities in the sea is still in its infancy.

TABLE 12.1. A Comparison of Forest Clear-Cutting with Bottom Trawling

	Clear-Cutting	*Bottom Trawling*
Striking Similarities		
Effects on substratum	Exposes soils to erosion and compresses them	Overturns, moves, and buries boulders and cobbles, homogenizes sediments, eliminates existing microtopography, leaves long-lasting grooves
Effects on roots or infauna	Stimulates, then eliminates saprotrophs that decay roots	Crushes and buries some infauna; exposes others, thus stimulating scavenger populations
Effects on emergent biogenic structures and structure-formers	Removes or burns snags, down logs, and most structure-forming species aboveground	Removes, damages, or displaces most structure-forming species above sediment–water interface
Effects on associated species	Eliminates most late-successional species and encourages pioneer species in early years–decades	Eliminates most late-successional species and encourages pioneer species in early years–decades
Effects on biogeochemistry	Releases large pulse of carbon to atmosphere by removing and oxidizing accumulated organic material, eliminates nitrogen fixation by arboreal lichens	Releases large pulse of carbon to water column (and atmosphere) by removing and oxidizing accumulated organic material, increases oxygen demand
Latitudinal range	Subpolar to tropical	Subpolar to tropical
Key Differences		
Recovery to original structure	Decades to centuries	Years to centuries
Typical return time of disturbance	40–200 years	40 days–10 years
Area covered/yr. globally	~0.1 million km^2 (net forest and woodland loss)	~14.8 million km^2
Ownership of areas where it occurs	Private and public	Public
Published scientific studies	Many	Few (but increasing)
Public consciousness	Substantial	Very little
Legal status	Activity increasingly modified to lessen impacts or not allowed in favor of alternative logging methods and preservation	Activity not allowed in a few areas

The Watling and Norse paper was widely criticized in the fishing industry media by supporters of the use of mobile fishing gear (e.g., Commercial Fisheries News, January 1999, p. 6B). The primary objection was the comparison with clear-cutting; the term itself was said to be inflammatory. These critics have since argued that a better analogy would be the plowing of land and harvesting of crops. Their argument is based on the idea that many areas of the world's ocean have been trawled for decades, if not centuries, and yet fish are still being produced. While this analogy works on one level, it has at least two major problems. First, the species of fishes being produced from some areas of the sea bottom are not the same ones being caught initially. And second, in the course of trawling these bottoms, the habitat has been completely altered, usually by removal of large epibenthos or flattening of the sediment surface, and noncommercial species—a sizeable portion of the sea's biodiversity—has been lost. The analogy of plowing is applicable only if one first considers that most plowed land was long ago altered to produce crops, either by removal of trees or by destruction of natural prairie. Because the sea bottom is not owned by individuals, but by all of us, we should ask public policy makers whether our publicly owned marine areas should be subjected to the same wholesale disturbance and change in species composition, structure, and function that is allowed on privately owned farmlands or whether we should manage marine habitats to maintain the sea's biodiversity.

Comparison with Oil Exploration and Production

Marine conservationists and members of environmental organizations in North America and Europe, especially, can be counted on to raise their voices when governments indicate that additional drilling for oil is needed on their continental shelves. To put the extent of ecosystem alteration due to fishing activities into perspective, it is useful to compare that activity with oil exploration and production (Table 12.2) because the latter is widely recognized as an issue requiring vigilance. Some facts to consider include:

1. Both fishing and oil drilling activities occur mainly on the continental shelves, although both are gradually moving into waters more than 1,000 m deep.
2. While bottom fishing with mobile gear occurs today on nearly all continental shelves, there are vast areas of the shelf that have no potential to produce oil.
3. Numerous studies have shown that the impact of oil drilling, in the absence of a blowout (which is exceedingly rare), is restricted to an area about 1 km in diameter around the drilling rig. In contrast, an equivalent area will be disturbed at least as severely by a fishing vessel towing gear at an average speed of 4 knots in less than 20 minutes. Watling and Norse (1998) estimated that an area equivalent to about half of the continental shelf area of the world is trawled over every year.
4. Oil drilling and production activities at one site can last, at most, for several decades, whereas some fishing areas have been trawled repeatedly for a century.
5. An oil spill impacts a large area of the sea bottom for about one decade (Dauvin 1998; Dauvin and Gentile 1990); however, because fishing grounds are repeatedly disturbed, there may never be a recovery.
6. Public awareness of the issues surrounding oil drilling is very high, public reaction to additional exploration is often highly charged emotionally, and as a result, government regulation is extensive. In contrast, the public generally does not understand how fish are caught, there is little news coverage of gear impact issues outside of coastal fishing communities, and there is only minimal regulation of fishing gear and how it can be used.

Without attempting in any way to minimize the potential impacts of oil exploration and production on coastal and oceanic ecosystems, it needs to be realized that very similar—but larger in scope and

TABLE 12.2. A Comparison of Habitat Impact due to Bottom Trawling versus Oil Exploration

	Bottom Trawling	*Oil Exploration*
Depth Range	Inshore to 2000 m	Inshore to ~1000 m
Regions covered	Nearly all continental shelves and some slopes	Concentrated in several specific regions
Area of impact	Broad, nearly entire bottom where fishing occurs	Narrow, impact restricted to zones approx 1 km around drilling rig
Impact duration	Occurs repeatedly over multiple decades	Occurs continuously over decades
Collateral impacts	Alteration of habitat can impact ecosystem function for unknown (100s of years?) lengths of time	Spills can impact some components of ecosystem for one or two decades
Public awareness	Low	Very high
Public reaction to news about	Virtually none	Very strong, emotional
Government regulation	Almost none	Much

longer lasting—impacts on the sea bottom are happening daily all over the globe. Sadly, the concerns voiced readily about oil drilling have not been raised with the same vigor and volume in relation to bottom fishing. So, while we fret about habitat destruction and loss due to oil exploration, habitat is, in fact, being lost due to mobile fishing gear.

Conclusions

Fishery management plans rarely, if ever, include any details about preservation of habitat or biodiversity; indeed, "for many years, fisheries scientists were in denial that ecosystems could be adversely affected by fishing" (T.J. Pitcher in Hall 1999). Notwithstanding the emphasis on fisheries habitat in the revised (1996) Magnuson-Stevens Fishery Conservation and Management Act in the United States, or references to protecting marine biodiversity in the United Nations' Code of Conduct for Responsible Fisheries (Food and Agricultural Organization 1996), marine conservation biologists will need to become advocates for biodiversity and habitat, either through normal management channels, by promoting consumer action (Caddy 1999), or by civil actions, if necessary. Some management steps that could be taken immediately, for example, would include taking a precautionary approach to ecosystem effects of fishing (Botsford and Parma, Chapter 22). In this framework, structurally complex habitats would be off-limits to mobile fishing gear unless the use of that gear could be shown to have no significant impact. Understanding the relationship between fishing gear and the benthos could be used to zone the sea bottom for different gear usage (Norse, Chapter 25). Especially valuable areas of biodiversity would be set aside as Marine Wilderness Areas (Brailovskaya 1998) and fished only in the most benign manner possible, if at all.

However, one important consideration is that the sea bottom is truly out of sight to most people, and therefore, not only out of mind but also outside experiential reality. One of the major initiatives of marine conservation biologists should be the development of marine education programs geared toward stimulating interest in marine biodiversity with particular emphasis on the smaller marine creatures. Of course, conservation biologists everywhere need to develop the awareness that they are also "stakeholders" when it comes to marine issues. After all, most marine biologists are avid and often vocal supporters of terrestrial conservation issues. It is time that they turn their hearts, their minds, and their sights, to the sea.

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Literature Cited

Auster, P.J., R.J. Malatesta, and S.C. LaRosa (1995). Patterns of microhabitat utilization by mobile megafauna on the southern New England (USA) continental shelf and slope. *Marine Ecology Progress Series* 127: 77–85

Barnes, D.K.A. (1999). The influence of ice on polar nearshore benthos. *Journal of the Marine Biological Association of the United Kingdom* 79: 401–407

Bett, B.J. (2001). UK Atlantic Margin Environmental Survey: Introduction and overview of bathyal benthic ecology. *Continental Shelf Research* 21: 917–956

Brailovskaya, T. (1998). Obstacles to protecting marine biodiversity through marine wilderness preservation: Examples from the New England region. *Conservation Biology* 12: 1236–1240

Brown, E.J., B. Finney, M. Dommisse, and S. Hills (in press). Effects of commercial otter trawling on the physical environment of the southeastern Bering Sea. *Continental Shelf Research*

Caddy, J.F. (1999). Fisheries management in the twenty-first century: Will new paradigms apply? *Fish Biology and Fisheries* 9: 1–43

Churchill, J.H. (1989). The effect of commercial trawling on sediment resuspension and transport over the Middle Atlantic Bight continental shelf. *Continental Shelf Research* 9: 841–864

Codispoti, L.A., J.A. Brandes, J.P. Christensen, A.H. Devol, S.W.A. Naqvi, H.W. Paerl, and T. Yoshinari (2001). The oceanic fixed nitrogen and nitrous oxide budgets: Moving targets as we enter the anthropocene. *Scientia Marina* 65 (Supplement 2): 85–105

Collie, J.S., G.A. Escanero, and P.C. Valentine (1997). Effects of fishing on the benthic megafauna of Georges Bank. *Marine Ecology Progress Series* 155: 159–172

Commercial Fisheries News (1999). January, p. 6B

Conlan, K.E., H.S. Lenihan, R.G. Kvitek, and J.S. Oliver (1998). Ice scour disturbance to benthic communities in the Canadian High Arctic. *Marine Ecology Progress Series* 166: 1–16

Dauvin, J.C. (1998). The fine sand *Abra alba* community of the Bay of Morlaix twenty years after the *Amoco Cadiz* oil spill. *Marine Pollution Bulletin* 36(9): 669–676

Dauvin, J.C. and F. Gentile. (1990). Conditions of the peracarid populations of subtidal communities in northern Brittany France ten years after the *Amoco Cadiz* oil spill. *Marine Pollution Bulletin* 21(3): 123–130

Druffel, E.R.M., S. Griffin, A. Witter, E. Nelson, J. Southon, M. Kashgarian, and J. Vogel (1995). *Gerardia:* Bristlecone pine of the deep sea? *Geochimica et Cosmochimica Acta* 59: 5031–5036

Food and Agricultural Organization (1996). *Precautionary Approach to Fisheries, Part 1: Guidelines on the Precautionary Approach to Capture Fisheries and Species Introductions.* FAO Fisheries Technical Paper 350/1. UN Food and Agriculture Organization, Rome (Italy)

Food and Agricultural Organization (1997). Review of the state of world fishery resources: Marine fisheries. FAO Fisheries Circular No. 920, Rome (Italy)

Frid, C.L.J., R.A. Clark, and J.A. Hall (1999). Long-term changes in the benthos of a heavily fished ground off the northeast coast of England. *Marine Ecology Progress Series* 188: 13–20

Friedlander, A.M., G.W. Boehlert, M.E. Field, J.E. Mason, J.V. Gardner, and P. Dartnell (1999). Sidescan-sonar mapping of benthic trawl marks on the shelf and slope off Eureka, California. *Fishery Bulletin* 97: 786–801

Furukawa, Y., S.J. Bentley, A.M. Shiller, D.L. Lavoie, and P. Van Cappellen (2000). The role of biologically enhanced pore water transport in early diagenesis: An example from carbonate sediments in the vicinity of North Key Harbor, Dry Tortugas National Park, Florida. *Journal of Marine Research* 58: 493–522

Gage, J.D. (2001). Deep sea benthic community and environmental impact assessment at the Atlantic Frontier. *Continental Shelf Research* 21: 957–986

Giere, O. (1993). *Meiobenthology, the Microscopic Fauna in Aquatic Sediments*. Springer-Verlag, Berlin (Germany)

Gordon, J.D.M. (2001). Deep water fisheries at the Atlantic Frontier. *Continental Shelf Research* 21: 987–1003

Graf, G. (1992). Benthic–pelagic coupling: A benthic view. *Oceanography and Marine Biology, an Annual Review* 30: 149–190

Hall, S.J. (1999). *The Effects of Fishing on Marine Ecosystems and Communities*. Blackwell Science, Oxford (UK)

Jennings, S., J. Alvsvag, A.J.R. Cotter, S. Ehrlich, S.P.R. Greenstreet, A. Jarre-Teichmann, N. Mergardt, A.D. Rijnsdorp, and O. Smedstad (1999). Fishing effects in northeast Atlantic shelf seas: Patterns in fishing effort, diversity and community structure, III: International trawling effort in the North Sea: An analysis of spatial and temporal trends. *Fisheries Research* 40: 125–134

Jensen, A. and R. Frederiksen (1992). The fauna associated with the bank-forming deepwater coral *Lophelia pertusa* (Scleratinaria) on the Faroe shelf. *Sarsia* 77: 53–69

Koslow J.A. (1997). Seamounts and the ecology of deep-sea fisheries. *American Scientist* 85: 168–176

Koslow, J.A., K. Gowlett-Holmes, J.K. Lowry, T. O'Hara, G.C.B. Poore, and A. Williams (2001). Seamount benthic macrofauna off southern Tasmania: Community structure and impacts of trawling. *Marine Ecology Progress Series* 213: 111–125

Kristensen, E. (2000). Organic matter diagenesis at the oxic/anoxic interface in coastal marine sediments, with emphasis on the role of burrowing animals. *Hydrobiologia* 426: 1–24

Lindeboom, H.J. and S.J. de Groot, eds. (1998). *IMPACT-II: The Effects of Different Types of Fisheries on North Sea and Irish Sea Benthic Ecosystems*. Netherlands Institute for Sea Research (NIOZ), Texel (the Netherlands)

Mayer, M.S., L. Schaffner, and W.M. Kemp (1995). Nitrification potentials of benthic macrofaunal tubes and burrow walls: Effects of sediment NH_4^+ and animal irrigation behavior. *Marine Ecology Progress Series* 121: 157–169

McKerrow, W.S., ed. (1978) *The Ecology of Fossils, An Illustrated Guide*. MIT Press, Cambridge, Massachusetts (USA)

Merrett, N.R. and R.L. Haedrich (1997). *Deep-Sea Demersal Fish and Fisheries*. Chapman and Hall, London (UK)

Philippart, C.J.M. (1998). Long-term impacts of bottom fisheries on several by-catch species of demersal fish and benthic invertebrates. *ICES Journal of Marine Science* 55: 342–352

Pilskaln, C.H., J.H. Churchill, and L.M. Mayer (1998). Resuspension of sediment by bottom trawling in the Gulf of Maine and potential geochemical consequences. *Conservation Biology* 12: 1223–1229

Poiner, I., J. Glaister, R. Pitcher, C. Burridge, T. Wassenberg, N. Gribble, B. Hill, S. Blaber, D. Milton, D.B., and N. Ellis (1998). *Final Report on Effects of Trawling in the Far Northern Section of the Great Barrier Reef: 1991–1996*. CSIRO Division of Marine Research, Cleveland (Australia)

Pugh, A.E. (1999). *A Comparison of Boulder Bottom Community Biodiversity in the Gulf of Maine: Implications for Trawling Impact*. M.S. thesis, University of Maine, Orono, Maine (USA)

Ramsay, K., M.J. Kaiser, and R.N. Hughes (1996). Changes in hermit crab feeding patterns in response to trawling disturbance. *Marine Ecology Progress Series* 144: 63–72

Ramsay, K., M.J. Kaiser, and R.N. Hughes (1998). The response of benthic scavengers to fishing disturbance in different habitats. *Journal of Experimental Marine Biology and Ecology* 224: 73–89

Reise, K. (1985). *Tidal Flat Ecology: An Experimental Approach to Species Interactions*. Ecological Studies, no. 54. Springer-Verlag, Berlin (Germany)

Rowe, G.T., P. Poloni, and R. Haedrich (1975). Benthic nutrient regeneration and its coupling to primary productivity in coastal waters. *Nature* 255: 215–217

Rumohr, H. and T. Kujawski (2000). The impact of trawl fishery on the epifauna of the southern North Sea. *ICES Journal of Marine Science* 57: 1389–1394

Sainsbury, K.J. (1987). Assessment and management of the demersal fishery on the continental shelf of Northwestern Australia. Pp. 465–503 in J.J. Polovina and S. Ralston, eds. *Tropical Snappers and Groupers: Biology and Fisheries Management*. Westview Press, Boulder, Colorado (USA)

Sainsbury, K.J. (1991). Application of an experimental approach to management of a tropical multispecies fishery with highly uncertain dynamics. *ICES Marine Science Symposium* 193: 301–320

Sainsbury, J.C. (1996). *Commercial Fishing Methods: An Introduction to Vessels and Gears*. 3rd ed. Fishing News Books, Oxford (UK)

Thrush, S.F., J.E. Hewitt, V.J. Cummings, and P.K. Dayton (1995). The impact of habitat disturbance by scallop dredging on marine benthic communities: What can be predicted from the results of experiments. *Marine Ecology Progress Series* 129: 141–150

Tuck, I.D., S.J. Hall, M.R. Robertson, E. Armstrong, and D.J. Basford (1998). Effects of physical trawling disturbance in a previously unfished sheltered Scottish sea loch. *Marine Ecology Progress Series* 162: 227–242

Watling, L. and E.A. Norse (1998). Disturbance of the seabed by mobile fishing gear: A comparison to forest clearcutting. *Conservation Biology* 12: 1180–1197

Watling, L., R.H. Findlay, L.M. Mayer, and D.F. Schick (2001). Impact of a scallop drag on the sediment chemistry, microbiota, and faunal assemblages of a shallow subtidal marine benthic community. *Journal of Sea Research* 46(3–4): 309–324