Disturbance of the Seabed by Mobile Fishing Gear: A Comparison with Forest Clear-Cutting

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Abstract: *Bottom trawling and use of other mobile fishing gear have effects on the seabed that resemble forest clear-cutting, a terrestrial disturbance recognized as a major threat to biological diversity and economic sustainability. Structures in marine benthic communities are generally much smaller than those in forests, but structural complexity is no less important to their biodiversity. Use of mobile fishing gear crushes, buries, and exposes marine animals and structures on and in the substratum, sharply reducing structural diversity. Its severity is roughly comparable to other natural and anthropogenic marine disturbances. It also alters biogeochemical cycles, perhaps even globally. Recovery after disturbance is often slow because recruitment is patchy and growth to maturity takes years, decades or more for some structure-forming species. Trawling and dredging are especially problematic where the return interval is shorter than succession to the ecosystem's original structure; extensive areas can be trawled 100-700% per year or more. Their effects on biodiversity are most severe where natural disturbance is least prevalent, particularly on the outer continental shelf and slope, where storm-wave damage is negligible and biological processes (including growth) tend to be slower. Recent advances in fishing technology (e.g., rockhopper gear, global positioning systems, fish finders) have all but eliminated what were* de facto *refuges from trawling. The frequency of trawling (in percent of the continental shelf trawled per year) is orders of magnitude higher than other severe seabed disturbances, annually covering an area equivalent to perhaps half of the world's continental shelf, or 150 times the land area that is clear-cut yearly. Mobile fishing gear can have large and long-lasting effects on benthic communities, including young stages of commercially important fishes, although some species benefit when structural complexity is reduced. These findings are crucial for implementation of "Essential Fish Habitat" provisions of the US Magnuson-Stevens Fishery Conservation and Management Act that aim to protect nursery and feeding habitat for commercial fishes. Using the precautionary approach to management, modifying fishing methods, and creating refuges free of mobile fishing gear are ways to reduce effects on biological diversity and commercial fish habitat.*

"New opinions are always suspected, and usually opposed, without any other reason but because they are not already common."

--**John Locke**, English philosopher. Dedicatory Epistle to *An Enquiry Concerning Human Understanding* (1690).

Introduction

Disturbances influence patterns of ecosystem diversity by affecting species composition, spatial structure and biogeochemistry (Grassle & Sanders 1973; Pickett & White 1985; Huston 1994). Disturbance processes span a wide range of spatial and temporal scales, from the burrowing of individual annelid worms to single treefalls to stand-replacement forest fires to plate tectonics; in general, larger-scale disturbances are rarer. Organisms also vary markedly in their ability to withstand disturbance (resistance) and recover from it (resilience). As a result, natural ecosystems are mosaics that reflect their disturbance history and organisms' responses (Huston 1994). Disturbances that humans superimpose on natural disturbance regimes alter community mosaics and form the core of conflicts such as the one over clear-cut logging of Pacific Northwest (USA) ancient coniferous forests (Norse 1990). From tropical rainforests to the taiga, clear-cutting has become a major issue for conservation biologists, advocates, and policy makers, but there is another comparably severe anthropogenic ecosystem disturbance that is far more prevalent worldwide, yet has received little scrutiny. It is the use of mobile fishing gear (trawls and dredges) to catch bottom-dwelling marine animals (Hutchings 1990, Jones 1992, Dayton et al. 1995). This paper details how mobile gear can alter benthic ecosystems and compares this disturbance to other marine disturbances and forest clear-cutting.

Trawling is a widespread method of catching marine fishes and invertebrates. Individual trawling vessels from 10–130 m long (or, sometimes, pairs of trawlers) fish by pulling large nets through the sea. Midwater or pelagic trawls are used to catch fishes in the water column (e.g., walleye pollock, *Theragra chalcogramma*, in the North Pacific Ocean, and hoki, *Macronuronus novazelandiae*, off New Zealand). Midwater trawling affects biological diversity by removing portions of target populations and others that are caught incidentally (bycatch), but causes no long-lasting habitat disturbance so long as the trawl does not touch the bottom. However, most trawling (and all dredging, when heavy chain-rigged or hydraulic suction devices are used) occurs on the seabed, targeting species such as demersal groundfish (e.g., Atlantic cod, *Gadus morhua*, and plaice, *Pleuronectes platessa*) on the continental shelves of the North Atlantic, green sea urchins (*Strongylocentrotus droebachiensis*) in nearshore waters of the New England, shrimps in the genus *Penaeus* on Gulf of Mexico and northern Australian shelves, and scallops (family Pectinidae) in both northern and southern hemispheres.

In its first decades, conservation biology has focused mainly on the terrestrial realm (Irish & Norse 1996). Because human activities in the sea are likely to be less familiar to conservation biologists and trawling has been likened to clear-cutting (McAllister 1995; Levy 1998), we compare these two sources of ecosystem disturbance.

Mobile Fishing Gear

The most widely used towed bottom fishing gear is the otter trawl (Fig. 1), whose forward motion spreads a pair of otter boards, each weighing tens to thousands of kilograms, that hold the trawl mouth open. The bottom of an otter trawl mouth is a footrope or groundrope that can bear many heavy (tens to hundreds of kilograms) steel weights (bobbins) that keep the trawl on the seabed. A growing fraction of bottom trawls, called roller trawls or rockhoppers, are armed with large (to 40 cm diameter) rubber discs or steel bobbins that ride over obstructions such as boulders and coral heads that might otherwise snag the net. Some trawls are armed with tickler chains that disturb the seabed to flush shrimp or fishes into the water column to be caught by the net. The constricted posterior netting of a trawl is called the cod end. When filled with tens to thousands of kilograms of marine organisms, rocks, and mud, and dragged for kilometers across the bottom, the cod end, like the otter boards, bobbins, rollers, and tickler chains, can disturb the seabed.

Another type of mobile fishing gear, the beam trawl (Fig. 2), is held open by a steel beam (total aperture 4-12 m) instead of otter boards, and is typically fitted with chains, with an empty weight up to 13 tons; beam trawls can be towed at speeds of up to 14.8 km/hour (Polet et al. 1998). Other towed gear, including scallop, oyster, and crab dredges, consist of steel frames and fiber or metal chain mesh bags that plow over and through the surface layers of the seabed to sift out target species. These dredges can be so effective at collecting objects in sediments that they were used in 1996 to gather buried debris at the crash site of TWA Flight 800 off Long Island, New York, after divers could no longer locate any wreckage at the sediment-water interface. Bivalve mollusks such as ocean quahogs (*Arctica islandica*) and surf clams (*Spisula solidissima*) are caught by hydraulic dredges that liquefy and suck up large amounts of seabed (Messieh et al. 1991). Continental shelf-, slope- and seamount-dwelling anthozoans used for jewelry, such as precious corals (*Corallium* sp.) and black corals (*Antipathes* sp.), are dragged with mobile gear called Italian bars (Risk et al. 1998), tangle nets, and St. Andrews crosses.

Trawling has a long history, mainly in estuaries, bays, and continental shelf waters at depths from a few to hundreds of meters, but it accelerated sharply with the introduction of diesel engines starting in the 1920s (Lindeboom & de Groot 1998). But as more continental shelf fish stocks are overfished, the search for new fisheries has extended bottom trawling onto the continental slope to depths of 1,400 m, even to 1,829 m (Gordon & Hunter 1994; Merrett & Haedrich 1997). In the last several decades, bottom trawling has also extended from traditional fishing grounds near the margins of industrialized nations such as the North Sea and Georges Bank, to waters off developing nations and even the remotest oceanic seamounts of the Southern Ocean (Watling, personal observation). Until the 1980s or early 1990s, many areas were *de facto* refuges because their numerous obstacles or steep slopes made trawling risky. Recent deployment of rockhopper trawls, global positioning systems and fish finders has allowed trawlers to work in previously unfished waters. As a result, trawls or related fishing gear are now used on every kind of bottom type from subpolar to tropical waters.

Unlike clear-cutting, most trawling is concealed from view and happens far from traditional study sites, which helps to explain why its effects have been overlooked. This is not a trivial oversight. As on land, biodiversity in the sea is profoundly threatened (Norse 1993; Butman &

Carlton 1995). The estuaries, bays, and continental shelves where most trawling occurs, together constituting ~7.4% of the sea's area (Sharp 1988), are among the most biologically productive (Koblentz-Mishke et al. 1970; Walsh 1988) and heavily altered (Norse 1993) marine ecosystems. Moreover, trawling might have serious economic consequences: many of the world's fisheries have declined sharply, and trawling has been thought to contribute to diminished fish catches (Messieh et al. 1991), including the commercial extinction of once-bounteous fisheries for haddock (*Melanogrammus aeglefinus*) and cod on the Grand Banks (Canada) in the North Atlantic. There have been protests in Europe against trawling gear since the 14th century because of its presumed effects on benthic organisms (de Groot 1984; Berrill 1997). Most studies of trawling effects have focused on the North Sea (e.g., Kaiser 1998, this issue; Lindeboom & de Groot 1998) and tropical Australia (e.g., Sainsbury et al. 1993; ICES 1996). It is difficult to explain why there is virtually no scientific literature on effects of trawling for shrimp in the Gulf of Mexico, one of the world's more heavily trawled areas, nor in US Pacific, Latin American, African, or Asian waters.

Benthic Structures: Distribution and Ecological Significance

Gauging the impact of mobile fishing gear requires understanding of how natural disturbance affects benthic communities (Hall 1994). The sea's geological substratum ranges from massive rocky reefs through boulders, cobbles, pebbles, sands, and muds (silts and clays), reflecting depositional and erosional processes past and ongoing. In general, reefs and coarser clastic substrata are far less common than muds. Reefs and coarse sediments are most prevalent on shallower parts of continental shelves where storm-generated waves can resuspend and remove finer sediments. Below a few tens of meters depth on the continental shelf and slope, muds are almost universal except for sand chutes and exposed rocky outcrops in steep-sided submarine canyons, or in high-latitude areas where large boulders, cobbles or pebbles were deposited by icebergs or retreating glaciers and may now occur in deep water. In general, sandy bottoms are the least stable substrata, and their surface is often rippled with waves having periods of centimeters to one meter, reflecting ongoing or episodic resuspension. Pebbles, cobbles, and boulders are more resistant to resuspension by waves or currents and often remain fixed in ecosystems where sands are repeatedly shifted. At the smaller end of the size spectrum, silt and clay particles in muds are so vulnerable to resuspension and removal that they accumulate mainly in areas with a low frequency of resuspension (e.g., the deep sea) or high supply (estuaries).

On both hard and soft substrates, structural complexity of benthic ecosystems is further increased by living organisms. A wide variety, including foraminiferans, coralline algae, corals, brachiopods, bryozoans, worms, and mollusks, form structures of shelly calcium carbonate on rocks down to the size of cobbles or even pebbles. Many other organisms, including algae, seagrasses, mangrove trees, sponges, cerianthid anemones, gorgonians, sea pens, phoronids, polychaete worms, amphipod crustaceans, sea urchins, and crinoids, create solid or tubular structures on the seabed.

Although the largest brown algae, giant kelp (*Macrocystis* spp.), can exceed 30 m from holdfasts on the seabed to the sea surface, biogenic structures in marine ecosystems are generally orders of magnitude smaller than in terrestrial forests. Some marine structure-formers can reach similar ages, however (Risk et al. 1998), and are no less important because their scarcity is often limiting to the abundance of many benthic species. Far more than on land, structures that reach even a few centimeters into the water column are heavily used by a diversity of taxa, including post-settlement young of commercially important fish species, for at least three reasons. First, because seawater is far denser than air, gravity is less a deterrent to marine than to terrestrial organisms. Many organisms hover close to seabed structures, a behavior that is scarce in terrestrial species. Second, in contrast to land, where there are few suspension-feeders, a large portion of marine species capture small particles from the passing water. The speed of currents increases dramatically in the first few centimeters above the sediment-water interface (Snelgrove & Butman 1994); therefore, organisms in or on benthic structures have access to faster-moving waters, which can carry larger food particles. Third, dissolved oxygen in the millimeters-thick bottom boundary layer results from diffusion of oxygen from overlying waters and respiration in the sediment below. Oxygen in this thin layer can be eliminated by biological activity (Jørgensen & Revsbech 1985). Thus, a sizable number of benthic organisms must either extend some part of their body into the overlying well-oxygenated waters or climb even small seabed structures to avoid sediment-related anoxia.

As on land, there is also abundant biogenic structure *within* the substratum (Rhoads 1974). Thick mats of seagrass rhizomes maintain sediment stability in some areas (Orth 1977), and annelid and echiuran worms, bivalve mollusks, amphipod crustaceans, shrimps, crabs and fishes (together comprising the infauna) construct long-lived (weeks to years) burrows and tubes in soft sediments that pump oxygen into what would otherwise be an anaerobic environment (Aller 1988; Meyers et al. 1988). The perception that the seabed is a featureless biological desert occurs because people's most common experience of the seabed--on sandy intertidal beaches–is an anomalous situation where nearly incessant wave pressure largely eliminates long-lived structures. In contrast, the vast majority of the seabed is interrupted and honeycombed with biogenic structures, and this heterogeneity is crucial to benthic ecosystems (e.g., Taylor 1978). MacArthur and MacArthur's (1961) observation–that bird species diversity is positively correlated with forest structural diversity–is even more true of species in marine benthic ecosystems.

Because most of the sea bottom is essentially level, the major sites of increased surface area for habitation by small invertebrates and post-settlement fishes are structures created by larger organisms. In general, areas of the continental shelf seabed with biogenic structures have increased levels of species diversity compared to those areas lacking such structures. Coral reefs, among the most rugose marine ecosystems, offer a large surface area and myriad interstices for their exceptional diversity of infauna, epibiota and associated suprabenthic species (Roberts & Ormond 1987; Reaka-Kudla 1997). In the deep sea, where diversity is generally high, mudballs created by polychaete worms provide habitat for a greater diversity of harpacticoid copepods (Thistle & Eckman 1988); mounds made by sea cucumbers attract suspension-feeding bivalves, amphipods, and polychaetes (Levinton 1995).

Habitat structure provides surfaces for feeding and hiding places from predators, and are therefore important in regulating population dynamics and species interactions of fish communities, as has been demonstrated for coral reefs, rock reefs, seagrass beds, and kelp beds (e.g., Heck & Orth 1980; Ebeling & Hixon 1991). Much less work has been done in deeper outer continental shelf waters. Juveniles of many fish species and other mobile fauna associate with small-scale habitat features (e.g., Grimes et al. 1986; Lough et al. 1989; Auster et al. 1994, 1995; Langton et al. 1995; Tupper & Boutilier 1995) such as cobbles, sand ripple crests, biogenic mounds and pits, clam shells, burrows, macroalgae, sponges, and amphipod tubes. The use of these features can be obligatory or facultative to particular life history stages of a species, but habitat complexity increases survivorship of individuals by providing cover from predators in species such as Atlantic cod (Gotceitas & Brown 1993; Walters & Juanes 1993) and American lobster, *Homarus americanus* (Wahle 1992a, 1992b; Wahle & Steneck 1992). Lough et al. (1989) found that the pelagic juvenile stage of Atlantic cod occurs over large areas of Georges Bank, but the subsequent benthic phase juveniles were found only on the gravel habitat of the Northeast Peak. Assuming that cod settle over the whole bank, predation pressure might be responsible for this pattern of differential survival. Off Nova Scotia, Tupper & Boutilier (1995) demonstrated that juvenile cod settle in all habitats (i.e., seagrass, sand, cobble, and rock reef), but survivorship and growth are higher in structurally more complex habitats where the cod can avoid predators. Gregory & Anderson (1997) showed that the youngest cod were cryptically colored and hovered above gravel substrates with low relief while older juveniles seemed to spend more time around individual large boulders.

Life Histories of Structure-formers

The effects of disturbance on benthic ecosystems are determined, in part, by species' life histories. As in forest ecosystems, structural dominants in many marine ecosystems are slow-growing and long-lived (years, decades, even centuries). Some sponges, for example, are believed to live 50 years or more (Dayton 1979). NE Pacific geoduck (*Panope generosa*) and Atlantic ocean quahog clams are estimated to reach up to 146 and 221 years, respectively (Goodwin & Pease 1989; Kraus et al. 1989). A small colony of the gorgonian *Primnoa reseda* from waters between Georges and Browns Banks, Nova Scotia, Canada was recently estimated to be about 500 years old; larger ones could reach 1,500 years (Risk et al. 1998), more than the maximum longevity for Douglas-fir (*Pseudotsuga menziesii*) trees (Norse 1990). In the sea, no less than in forests, frequency of disturbance relative to recruitment and growth of structure-formers determines the severity of human impact, and slow growth rates of key species make recovery from disturbance a long-term process.

Again, as in forests, where widely varying proportions of species can recover from fire or logging by resprouting, some epifaunal and infaunal species can rebuild their structures after disturbance, but others, such as the tube-dwelling polychaete worm *Amphitrite johnstoni*, cannot (Watling, personal observation). Disturbances that destroy the integrity of burrows or tubes can expose infauna to high risk from predation (Kaiser & Spencer 1994), so recruitment is the only means by which these species can recover after disturbance exposes them. But like many long-lived terrestrial species, such as Douglas-fir trees–which generally produce substantial seed crops once every 5-7 years and recruit successfully perhaps once in decades (Norse 1990)–many long-lived marine species do not recruit successfully every year (e.g., Beukema & Essink 1986; Dörjes et al. 1986; Lundälv 1986). The rate of ecosystem recovery after a disturbance that kills structure-forming species can be delayed by slow recruitment, spatial patchiness of recruitment, and slow post-recruitment growth. As Runkle (1985) noted, a disturbance that is both very severe and occurs over a large area can result in very long recovery times.

Recolonization and Spatial Scale

Ecosystem resilience in the sea, as on land, is affected by the spatial scale of a disturbance (Sousa 1985). Because so many marine organisms have dispersal stages that live in the plankton for hours to months (usually days or weeks), one might assume that the rate of recolonization after a disturbance would be similar for all patch sizes less than kilometers in diameter. An experiment by Thrush et al. (1996), however, suggests that even much smaller disturbed areas may show size-dependent recolonization. They defaunated intertidal sand patches of 0.203 m^2, 0.81 m^2, and 3.24 m^2 and sampled for nine months to assess recovery. They found surprisingly slow recovery after defaunation, particularly in the larger patches. Because the sandflat in the experiment was prone to disturbance by wind-driven waves, sediments were unstable after defaunation removed a dense mat of polychaete tubes, hampering recolonization. This suggests that larger disturbances that destroy organisms that maintain habitat stability are likely to recover very slowly, particularly in wave-disturbed, soft bottoms.

Several mechanisms can be invoked to explain slow recolonization of even small patches. First, colonization of patches is affected by patch type: Type I patches (those surrounded by undisturbed communities) are colonized from both the perimeter and by dispersed propagules (Connell & Keough 1985; Sousa 1985) whereas Type II patches (undisturbed spots surrounded by vast disturbed areas) are the source of colonizers, especially over short distances. Key components of benthic ecosystems, including amphipods, isopods, and other small crustaceans do not have planktonic larvae, but have direct development and characteristically short-distance dispersal across the seabed. In addition, in temperate waters, at least, production of propagules is very seasonal so disturbed patches may sit for some time before recolonization can occur. Second, disturbance alters the seabed physically and chemically. Watling et al. (in ms) have shown that scallop dredging in Maine muddy sand sediments removed the top 4 cm of sediments. They found that this upper sediment layer contains the highest quality food, but is easily resuspended and carried away by mobile fishing gear, so sediment food quality decreases. Several groups of invertebrates did not recolonize the disturbed patch until the food quality had recovered. And third, there are likely to be nonlinear changes in recolonization depending on the aggregation of individual disturbances and the resulting fragmentation of the landscape (Hall et al. 1994).

Adaptation to Disturbance Frequency

The severity of a disturbance can range from damaging only the most sensitive organisms to destruction of all multicellular life. The prevailing disturbance regime and the degree to which it is ameliorated by biotic structures (e.g., tube mats of polychaetes that bind sand grains together) are key factors determining the impact of anthropogenic disturbances (Brylinsky et al. 1994; Kaiser & Spencer 1996). In communities visited by severe disturbances at frequent intervals, only the most resistant or resilient species are likely to be present as adults when the next disturbance occurs. Thus, an event that resuspends the upper 10 cm of sediment in a sandy beach is likely to have minimal effects because organisms living there must have adaptations that confer resistance (such as rapid burrowing), or else recolonize disturbed areas very quickly; organisms lacking these abilities were eliminated by previous disturbances. Conversely, communities that rarely experience severe disturbances are likely to lose many species because their selection regimes have not filtered out organisms with low resistance or resilience. In general, frequency of severe disturbances decreases sharply with increasing depth; continental slopes (except in high relief areas such as submarine canyons, where turbidity currents can occur) have few or no natural agents of severe, large-scale physical disturbance.

Agents of Benthic Disturbance: Severity and Frequency

Agents of benthic disturbance include abiotic processes such as lava flows and volcanic ashfalls, mass-slumping on steep slopes in submarine canyons, wave-generated turbulence, currents generated by tides, winds or waves, and iceberg scour. Biological disturbance processes include bioturbation (sediment movement by animal burrowing and tunneling) and digging for food by whales, walruses, fishes, and crabs. Anthropogenic disturbances include harbor dredging and dredge disposal, gravel extraction, anchoring and ship grounding, fishing techniques using explosives, muro ami (in which weighted bags smash reef corals to scare fishes from their hiding places so they can be netted by divers), and towed gear such as bottom trawling and dredging.

Although size, shape and types (I or II) of disturbed patches (Sousa 1985) affect recolonization and succession after disturbance, a useful first-order estimate of the *global* impact of a disturbance is the product of severity and frequency. If either is low, then impact overall is low; for example, the global impact of a severe local disturbance is not high if its frequency is low when averaged over the vast area of the world's continental shelves. Severity can be measured as the proportion of individuals damaged, removed or killed, or by the energetic cost and time required for rebuilding burrows, tubes, or shells, etc. Frequency (analogous to fire frequency in Agee 1993) is the percent of area disturbed per year. The inverse is what fire ecologists call return interval, the time between successive events at a given place. We can begin to quantify effects of disturbances on continental shelves worldwide by examining these factors for natural and anthropogenic disturbances.

<u>Natural Disturbances:</u>

Very large storm waves can affect the seabed at maximum depths of about 30-40 m, with increased current velocities at 60-70 m (Hall 1994), perhaps even deeper. Wave impacts are most important in the narrow intertidal and shallow subtidal zones, especially near exposed outer coast headlands. For example, Witman (1987) noted that Northwest Atlantic horse mussels (*Modiolus modiolus*) are excluded from depths <9 m at many wave-exposed sites and that storm-related dislodgment is the most significant source of mortality. Although wave intensity is high during major storms, severity is low because most species living in storm-affected areas are adapted to resisting these events or recovering quickly. Hurricane-force storms can increase wave pressure in bands hundreds of kilometers wide, but the seabed is physically disturbed mainly in the shallows. Frequency of major storms can vary from several per month along exceptionally stormy coasts to one per century or longer. Averaged over the world's continental shelves, storm frequency is fairly low and we rate the impact of wave disturbance as low.

Nearshore tidal currents can resuspend and remove all but the largest sediment particles, leaving bottoms of boulders, cobbles, or pebbles. In deeper waters offshore, currents are rarely strong enough to remove even fine, silt-sized particles (Nowell et al. 1981). Where high currents are nearly constant, severity is generally low because organisms are adapted to deal with (and benefit from) currents, and are seldom lost. As with waves, because of low severity, we rate the impact of current disturbance on benthic communities as low.

Icebergs can plow deep gouges in the seabed as winds and currents move them. They are important agents of disturbance along the coasts of Antarctica, in the Arctic Ocean and even (occasionally) on the Grand Banks of Newfoundland. Iceberg scour is severe; few (if any) organisms can withstand the tremendous forces that icebergs generate. In nearshore Antarctic and Arctic waters, iceberg scour is frequent enough that communities are structurally more complex and more diverse below the depth of scour. However, the frequency of iceberg scour averaged over the world's continental shelves is very low, so impact is low.

Animals moving through marine sediments shift sediment particles (bioturbation), thereby disrupting the lives of smaller sediment-dwellers. Digging by large, deep-dwelling polychaetes, bivalve mollusks, and thalassinid crustaceans can slow or stop recruitment by covering newly settled larvae repeatedly with layers of sediment. But most sediment movement from bioturbation is extremely local, occurring over a scale of millimeters to a few centimeters (Wheatcroft et al. 1990) except, perhaps, for the large mounds produced by thalassinid crustaceans (Suchanek 1983). Therefore, while sediment movement rates may be remarkably high (to thousands of litres of sediment annually shifted per m^2), sediment particles (and the binding organic matrix) are generally not removed and most animals are not affected by movements of the individual mineral grains. Severity is low because sediment-dwellers have time to repair burrows or tubes as other animals are shifting sediment particles. Although frequency can be very high, severity is low and, therefore, impact is low.

In some regions, foraging by animals such as California gray whales (*Eschrichtius robustus*) can remove up to 6 m^2 of the sediment surface in one bite (Oliver & Slattery 1985), whereas fishes and birds can disturb patches on the order of tens of cm^2 (Hall et al. 1994). This type of foraging can be successful only where there the bottom supports dense aggregations of prey (amphipod crustaceans of the genus *Ampelisca* in the case of the gray whales). Blue crabs (*Callinectes sapidus*) seeking bivalves and polychaetes dig pits that can be an important source of disturbance where their populations are high (Virnstein 1977). Severity from foraging is high but very local (e.g., near hauling-out sites used by walrus, *Odobenus rosmarus*), and frequency is low when averaged over the continental shelf. The impact of foraging predators, therefore, is low.

Anthropogenic Disturbances

Dredging of the seabed in harbors and navigation channels completely removes upper sediment layers and resident biota and often redeposits them onto an area of seabed that can differ geologically and biologically. Recolonization of dredged and disposal sites can be rapid, but new colonizers are unlikely to be the same species as the original inhabitants, and it can take years for the dredged site to return to a community composition approximating the pre-dredge conditions (Rhoads et al. 1978). Further, because harbor sediments are often heavily polluted, this issue is as much one of contaminant dispersal as it is one of physical disturbance. Although severity is high and individual disturbances may be large–tens to hundreds of meters wide along a channel that can be kilometers in length–dredging occurs only in shallow waters and the vast majority of the shelf is never dredged, so frequency is low and impact, overall, is low.

Marine gravel deposits are mined for building, but gravel beds can have high species diversity because the individual sediment particles are quite large and pack loosely, leaving interstitial spaces large enough to be inhabited by infauna. Gravels also offer hard substrate for epibiota. When gravel is mined, severity is great: The entire fauna is removed. Moreover, the pits left by gravel mining operations are large (tens to hundreds of meters), but gravel mining is so localized that the average frequency for the continental shelf is low. Overall impact of this activity is, therefore, low.

Trawling and Dredging Severity

Two types of studies have examined effects of mobile fishing gear: 1) experimental studies where an area of the sea bottom is disturbed by fishing gear and the post-disturbance biota is compared with an undisturbed nearby area; and 2) observational studies where a fished area is compared with an area that is either off-limits to fishing or where such fishing has not yet commenced. Results from the two types of studies are summarized in Tables 1 and 2. Table 1 contains only those studies where there was evidence of a reasonably undisturbed control site which could be compared to the experimentally trawled site, thereby omitting much published research done in areas where fishing was still occurring.

Note that all experimental studies were done in shallow waters on substrates that are generally hard or clean, that is, with very little silt or clay, or in areas that were not fished because on most bottoms that can be fished control sites are unavailable. Since the bottoms studied are primarily sands, most of these sites either have strong currents or are swept by storm waves. Because these situations have infaunal communities dominated by species adapted to frequent physical disturbances, it is hardly surprising that impacts of trawling and dredging seen in these studies were limited. Even so, each community studied showed loss of some species, usually the larger-bodied species living buried in the sand. Notably different is the study of Watling et al. (in ms.) of a muddy sand community subjected to scallop dredging, where exclusion of species from the dredged site due to the loss of low-density, high-quality food particles from the sediment persisted until the food value of the surface layer improved.

Missing from these experimental studies are those that might be conducted at depths below the storm wave base or in areas of significant epifaunal growth. A number of the observational studies, on the other hand, were conducted in just those areas where experimental studies would be difficult. In the heavily trawled North Sea, Riesen & Reise (1982) and Reise (1982) note that the epifauna, especially the large *Sabellaria* reefs, have already been removed. In areas where there has been substantial fishing pressure on bottoms with large epifaunal, colonial invertebrates–especially sponges and cnidarians–there is clear evidence that epifauna were removed by the fishing gear (e.g., Bradstock & Gordon 1983 in New Zealand; Sainsbury 1991 in Western Australia). On Jeffreys Bank in the Gulf of Maine, large sponges disappeared from bottom communities at 100 m depth (Auster et al. 1996) between July 1987 and August 1993. The presence of overturned boulders in 1993 suggests the cause was mobile fishing gear. In a comparison before and after the start of a large trawl fishery in Northwestern Australia, Sainsbury (1987, 1988) found the proportion of commercial fishes in the high-value genera *Lethrinus* (emperors), *Lutjanus* (snappers or seaperch) and *Epinephelus* (groupers or rockcod) dropped from 45-77% of the catch before trawling to 15% afterward. Fishes that are much less prized commercially, including the genera *Nemipterus* (threadfin-bream) and *Saurida* (lizardfishes or grinners), became far more important. Sainsbury concluded that trawling effects on habitat were most likely responsible because catch rates of structure-forming sponges and gorgonians had also decreased dramatically. Photographs showed emperors and snappers often associated with sponges, while threadfin-bream and lizardfishes were associated with open sandy bottoms. In all the cases in Table 2, evidence for biodiversity loss is seen either as a drop in structure-formers in bycatch, decrease in catch of target species using structurally complex bottoms, or loss of large, structure-formers observed from submersibles or remotely operated vehicles.

In areas inhabited by species adapted to being excavated or resuspended, such as sandy beaches or current-swept channels between islands, trawling and similar fishing methods might approximate natural physical disturbances. But the extent of these ecosystems is very limited. Elsewhere, trawling kills seabed organisms by crushing them, by burying them under sediment, and by exposing infauna and under-rock cryptofauna to predators. Bergman et al. (1998) found marked differences in resistance among species in the path of beam and otter trawls in different substrates. For example, a 12 m beam trawl towed on silty sediment killed none of the jackknife clams (*Ensis* spp.) but 82% of sanguin clams (*Gari fervensis*); a Norway lobster (*Nephrops norvegicus*) otter trawl on silty sand killed 34 to 100% of individuals among various groups of smaller benthic crustaceans.

Effects of mobile fishing gear where severe disturbances are naturally rare or absent depend on substrate type. First, in “hard bottom” areas, where the seabed consists of various combinations of rocky reefs, boulders, cobbles, and pebbles, and there is an abundance of emergent epibiota, mobile fishing gear removes large epifaunal invertebrates (such as sponges, cnidarians, and bryozoans) and moves boulders along the bottom. This reduces habitat for myriad small species and food for others. Second, on pebbles, sands, and muds, homogenization of the bottom eliminates habitat features important to recruits to the exploited fish populations and to many other species, including ones that commercial fishes eat. Loss of nursery habitat can mean progressive decline in economically important fisheries. And third, on muddy bottoms, mobile gear passing over and through the upper ten or so centimeters of the seabed collapses burrows and breaks the tubes that house small invertebrates. Many of the resident species cannot excavate new burrows or construct new tubes in later life history stages.

Thus, mobile fishing gear reduces structural complexity of bottom communities. Hydraulic clam dredging is as severely disturbing as harbor dredging or iceberg scour. Depending on the substratum, community type and the way trawls are rigged, trawling is not always as severe because it kills only a portion of the megafauna in its path. Use of other mobile gear, such as scallop dredging, falls between hydraulic clam dredging and trawling in severity. Overall, we rate mobile fishing gear severity as high.

Trawling and Dredging Frequency

Estimates of trawling and dredging frequency have appeared in a few sources (Table 3). Because the data are of varying quality and several sources are old, these values should be considered rough indicators of disturbance from mobile fishing gear. Estimating the frequency of bottom trawling (the most extensively used mobile gear) as a percentage of the world's continental shelves (which constitute 7.4% of the ocean's area, or 28 million km^2) is more difficult because data are few and assumptions can be off the mark. Nonetheless, we can give two estimates. McAllister (1995) assumed there were 12,000 active trawlers (of 23,000 over 100 tons) towing nets 25 m wide at 5 km/hour for 6 hours a day for 175 days per year, thus covering 1.575 million km^2 per year. This figure, equivalent to 5.6% of the total area of continental shelf, is too low, in part because it omits the large majority of trawlers, those under 100 tons.

Other data and assumptions can produce a very different estimate. Slavin (1981) noted that in 1978, Mexico's 3,000 shrimp trawlers caught 67,000 tons. If shrimp trawlers from other nations caught an equivalent tonnage per boat, then the 1978 world shrimp catch of 1.324 million tons was caught by 59,292 boats. Assuming that shrimpers constituted two thirds of the world's trawlers, the number of trawlers of all kinds was 88,939 worldwide. Assuming two thirds of those were active and that they towed nets 25 m wide at 5 kilometers/hr for 10 hours a day for 200 days/year, then the area they swept annually was 14.8 million km^2, or 53% of the world's continental shelf area, an order of magnitude higher than McAllister's (1995) estimate. Moreover, this estimate might be too low, for three reasons. First, Pilskaln et al. 1998 (this issue) used "realistic estimates" of 40 m trawl track widths and 5.5 km/hr trawl speeds; use of these figures would raise our estimate another 76%. Second, we omitted other towed gear; their inclusion would further raise estimates. Third, because fishing effort and fishing power have increased considerably since 1978, our estimate likely errs on the low side. Until more reliable data are available, it is reasonable to assume that an area equivalent to the world's continental shelf is swept by trawlers every two years. Even if our estimate is high by a factor of two, trawling an area equivalent to the entire world's continental shelf every four years is nonetheless a disturbance to the biosphere on a scale that had not previously been imagined. Of course, trawl frequency is unevenly distributed; in an area that is trawled an average of 100% annually, a substantial fraction might not get trawled in a given year, whereas some spots can be trawled an astounding 40,000% annually (Rijnsdorp et al. 1991). Figure 1 in Pilskaln et al. 1998 (this issue) hints at the variability in trawling effort in the Gulf of Maine.

Not all trawling occurs on the shelf. As the most accessible fisheries continue to decline, trawlers are focusing increasingly on "underutilized species" of the deeper continental slope and remote oceanic seamounts, such as orange roughy (*Hoplostethus atlanticus*) and grenadiers or rattails (family Macrouridae) (reviewed in Merrett and Haedrich 1997). Deep-water trawling must profoundly alter ecosystems whose species generally are not adapted to resisting or recovering from severe physical disturbances.

In unaltered benthic ecosystems, severe disturbances tend to be low in frequency (they are either large and rare or common but restricted spatially, Connell & Keough 1985). This is also true in forest ecosystems: "Where fires burn frequently, they are seldom highly destructive;

infrequent burns, on the other hand, tend to be catastrophic" (Perry 1994). But use of mobile fishing gear is exceptional among agents of disturbance: its effects are severe, yet it occurs at a frequency orders of magnitude higher than other severe disturbances.

Other Effects of Mobile Fishing Gear on Sediments

Mud bottoms comprise sediments with very small mineral grains bound loosely with organic material and associated microorganisms, on and in which live epifaunal and infaunal macroorganisms. Anoxic conditions commonly occur within a few millimeters of the sediment-water interface, except where pumping by burrow-dwellers oxygenates the surrounding sediment. Although impacts of mobile fishing gear on structural complexity are clear, their effects on sedimentary microenvironments are less certain. Using knowledge of fundamental biological oceanographic processes, we can hypothesize that repeated use of mobile fishing gear has several consequences. First, the homogenization of muddier sediments decreases the sediment-water interface area by collapsing burrows and destroying tubes made by species dwelling within the sediment. This could have consequences to carbon and nitrogen cycling that are presently unknown (Pilskaln et al. 1998, this issue). Second, trawling on the continental shelf south of Georges Bank (Churchill 1989) and in Wilkinson Basin (Pilskaln, personal communication) results in a much thickened bottom nepheloid layer of resuspended sediment. When resuspended, organic material with high quality as food is oxidized to some extent in the water column and settles to the bottom much lower in food value. Diminished availability of high quality food on the seabed might reduce species diversity of these muddy bottom areas. Third, the removal of organic material by mobile fishing gear is biogeochemically analogous to the common post-clear-cutting practice of broadcast burn or pile-and-burn site preparation, which oxidizes large amounts of slash (remains of logged trees) and forest floor (organic detritus), exporting the ecosystem's nutrients as ash into the atmosphere. Given the high frequency of trawling, the increased resuspension and subsequent oxidation of carbon that would otherwise be buried in sediments could be a significant source of carbon to the water column and atmosphere.

Trawling and dredging for shellfish resuspend large amounts of sediments (Pilskaln et al. 1998, this issue). Riemann and Hoffmann (1991) found short-term increased suspended sediment loads of 960-1,361%. The sediment plume and organisms (e.g., polychaetes, amphipods) entrained within it affect water clarity, oxygen content, and energy relations of organisms living or feeding where the plume interacts with the bottom. High suspended sediment loads in shallow waters affect photosynthesizers in the water column and on the seabed. High suspended sediment loads are associated with shifts in fish communities from domination by visual predators to those that find food by touch and chemosensation, as well as alteration of the benthic community from one dominated by suspension-feeders to one having a preponderance of deposit-feeders. Once deposit-feeders become dominant, they can prevent recovery of suspension-feeders by feeding on and smothering settling larvae (Dayton et al. 1995).

Resuspension of buried organic material by trawlers increases oxygen demand in the water column; in areas where dissolved oxygen is already limiting, this increase could significantly affect plankton and nekton species composition, even contributing to the growth of anoxic areas such as “the Dead Zone” in the Gulf of Mexico. Indeed, it could be a substantial unaccounted source of atmospheric CO_2. In polluted areas resuspension can also increase exposure of water column and benthic species to toxic materials adsorbed on sediment grains which were previously sequestered in the sediment. Resuspended sediment and pore water can also add to the nutrient loading of the water, perhaps triggering phytoplankton blooms.

Trawling and Clear-cutting

Trawling disturbs the seabed in ways that can be compared to terrestrial disturbances. Like surface mining, it displaces large amounts of surface organic material, but it doesn’t necessarily kill all macroscopic life. Like plowing it disturbs the upper several centimeters of substrate at return intervals of years or months; however, it is not conducted on private lands where harvested species are reseeded but in areas that are under public ownership and considered "natural." It is more similar to clear-cutting (Table 4), but there is one great difference -- whereas forest loss is estimated at 100,000 km^2/year worldwide (Food and Agriculture Organization of the United Nations 1995), the area trawled annually is about 150 times as great. Indeed, FAO’s estimate of annual worldwide forest loss, however alarming, is smaller than the combined area of Georges Bank and the Gulf of Maine (Auster et. al. 1996) that is trawled each year.

Mobile Fishing Gear As A Conservation Issue

Since the dimensions of the biological diversity crisis became clear (Myers 1979; Lovejoy 1980; Norse & McManus 1980), biologists have told decision makers and the public that physical disturbance (particularly habitat loss from forest clear-cutting) is the leading cause of biological diversity loss. Until this decade, however, biodiversity loss in the sea was largely overlooked, with the scant attention focused mainly on the important threats of overexploitation of fisheries and pollution. Now, with growing understanding that marine biodiversity is imperiled, we have shown that the sea is experiencing physical alteration from bottom trawling and other towed fishing gear on a scale that was not previously appreciated. The use of mobile fishing gear, whose effects resemble those of clear-cutting, occurs at a rate two orders of magnitude higher than forest loss worldwide. With the possible exception of agriculture, we doubt that any other human activity physically disturbs the biosphere to this degree. The lack of scrutiny of bottom trawling until now is indicative of the mismatch between humankind's environmental impacts and priorities.

An activity that severely disturbs an area of seabed as large as Brazil, the Congo, and India combined each year must affect structure, species composition, and biogeochemistry of benthic ecosystems on both local and global scales. It is disheartening that scientists have not yet done the research necessary to determine whether trawling has caused large numbers of extinctions or none, and that sequential overfishing, improved technologies, and the lack of marine protected areas makes it difficult or impossible to find suitable control areas.

Modern society's marine conservation ethic is far less advanced than our land ethic. For example, recent decades have seen a dramatic change in attitude in many countries about killing apex predators such as tigers, wolves, and eagles, whereas there has been much less concern about killing sharks, tunas, and marlin. In the USA (SeaWeb 1996), and many other countries, public concern about maintaining marine biodiversity seems to be increasing but has not yet become deep or pervasive. But even in the face of compelling evidence for concern about effects of trawling on benthic biodiversity, the pivotal question for many people will be economic: how does trawling affect fisheries? In Australia, on the other hand, perhaps because there is the widespread acceptance that their biodiversity is truly unique, there is a more balanced view. Recently, for example, the President of the South East Trawl Fishing Industry Association proposed a voluntary interim closure of a 370 km^2 region of seamounts south of Tasmania until a biodiversity assessment could be made (story from The Australian, Sydney, 9 June 1998, pg. 8).

Like clear-cutting, use of mobile fishing gear does not eliminate biological activity. Rather, it converts ecosystems dominated by disturbance-intolerant equilibrial species to ones dominated by disturbance-tolerant opportunistic species. In general, trawling undermines fisheries for species that benefit from complex benthic structure. For fishes that do not need benthic structure, however, some trawling is likely to increase their populations by encouraging opportunistic prey species or reducing disturbance-intolerant competitors. Thus, increasingly trawled seabeds might have fewer sabellariid polychaete reefs but more cirratulid and capitellid polychaetes, fewer sponges and gorgonians but more penaeid shrimps and brittle stars, fewer groupers and snappers, but more threadfin-bream and lizardfishes, fewer cod but more plaice. In general, where structure-forming species have life spans of years or more but the chronic disturbance of trawling occurs at shorter return intervals, benthic succession will not proceed to climax and fish communities that need a structurally complex seabed will disappear. A terrestrial analogue is the change in animal species when virgin forest is converted to cattle pasture. Thus, trawling could prevent recovery of diminished fish stocks, such as Georges Bank and Grand Banks Atlantic cod, whose juvenile stages have higher survivorship in structurally complex habitats, but it can benefit fisheries for some other species. This kind of anthropogenic change–which foresters call “type conversion”–has occurred in an intensively trawled offshore area in the Irish Sea (Lindeboom & de Groot 1998), who say “[t]he present species-poor and low biomass fauna may represent an artificial man-made community adapted to the regular fishing disturbance experienced at this site.” They conclude, “if trawling intensity remains high, these communities may never recover.”

At present, people trawl almost anywhere they want, and the sea’s equivalents of ancient forests are becoming cattle pastures by default, not by design. Merrett and Haedrich (1997) put the issue this way: "there still seems to be a general frontier mentality that operates in high-seas fisheries" (p. 180). Governments generally do not apply the precautionary principle to the sea; individuals and corporations do what they wish unless some governing authority can demonstrate conclusively that they should not, decides to prohibit the activity, and enforces its prohibition. As highly structured benthic ecosystems and fisheries continue to decline, fishery managers must make more conscious choices about the mix of disturbance-intolerant communities (including fishes) and disturbance-tolerant ones under their jurisdiction.

In general, fisheries managers regulate the use of varying kinds of fishing gear by trying to determine the influence of the gear on the population parameters of target species. When disputes arise, the common response has been to look at the issue as a "gear conflict." This is especially true for mobile fishing gear, which were not used on hard bottoms in northern waters such as the Gulf of Maine, the Grand Banks and the Bering Sea until the mid-1980s. Rather, those ecosystems were typically fished with hook and line gear, which has far less physical impact on the bottom community. As the fishing industry developed rockhopper trawls, topographically rough bottoms were no longer unfishable and longline fishermen saw their fishing grounds produce progressively fewer fish. The response from the New England Fishery Management Council, as an example, has been to consider the complaints of the long-liners under the rubric of gear conflict, thus escaping the need to look at the more fundamental question of whether trawling is reducing the economic value of the fisheries overall as a result of reduced habitat complexity, or the even broader question of what trawling is doing to biological diversity.

Typically, people who catch and process fish have been considered the primary stakeholders in this conflict and decisions have often been driven by short-term economic factors. Because of the long-term–even irreversible–changes that mobile fishing gear can bring to benthic communities, anyone with an interest in the sea's biological diversity and integrity should consider themselves a stakeholder in this debate. In the US Pacific Northwest, the political decisions that governed logging of ancient forests on federal lands began to change in the late 1980s, when citizens beyond Northwest timber towns became aware and involved. Examining use of mobile fishing gear from the viewpoint of a broader group of stakeholders might produce very different solutions. To serve the public interest, meaningful input on managing the seabed has to involve people with interests broader than fisheries alone.

Recent developments suggest that concern about fishing effects is increasing in the USA. The recently reauthorized Magnuson-Stevens Fishery Conservation and Management Act (National Marine Fisheries Service 1997) contains provisions for the first time that require regional Fishery Management Councils to identify Essential Fish Habitat (EFH), which is "those waters and substrate necessary to fish for spawning, breeding, feeding, or growth to maturity." This law requires the National Marine Fisheries Service and the Fishery Management Councils to identify "activities with known or potential adverse effects on EFH," and allows them to impose fishing gear restrictions or to close areas to fishing.

Still, management of living resources of the U.S. seabed is effectively controlled by the Department of Commerce’s National Marine Fisheries Service, which now is responsible for determining which aspects of the habitat are important for fish production. We have already seen, however, that some benthic communities can have productive fisheries in the face of continual physical disturbance by mobile fishing gear. The question, therefore, is: who is responsible for maintaining the overall biodiversity of the seabed? To date, maintenance of biodiversity has hardly been a priority of fisheries managers.

Some management options could stem the loss of biodiversity and fisheries dependent on benthic structure, benefit all fishers and consumers in the longer term and minimize economic short-term harm to trawlers and dredgers:

1. Use a precautionary approach to management; the burden of proof should rest with those who would alter the sea's biodiversity and integrity. This might lead to lessened use of mobile fishing gear in structurally complex benthic ecosystems.

2. Match fishing gear types to the disturbance-vulnerability of the seabed, thus minimizing long term impacts of all types of gear. This most likely would give preference of some gear types over others in each bottom type, but would maintain species diversity and fisheries production in each.

3. Establish "no trawling zones" in a portion of all continental shelf and slope ecosystems, allowing the recovery of benthic communities to their pre-trawling state. Such reserves would offset, to some extent, the loss of *de facto* reserves in areas that could not previously be fished with mobile gear and where commercially important fishes were more abundant. This would provide crucial information on effects of mobile gear and requirements for sustainable fisheries over the long term.

4. Educate the public about the nature of the seabed and its importance for biodiversity, including its role in supporting fisheries.

5. Ensure opportunities for more sectors of society (beyond fishing interests) to influence the policy-making process and to hold positions of authority, in recognition that all of us are "stakeholders" when it comes to publicly owned marine resources.

Conclusions

Mobile fishing gear exceed other natural and anthropogenic disturbances in the marine continental shelf and slope. By crushing, burying, and exposing benthic organisms to predation and by altering sediment and water column biogeochemistry, trawling and dredging disrupts the structure of benthic communities from high latitudes to the tropics in ever-deeper waters. Many marine species, including the young of commercially caught fishes, use lithic and biogenic structures to avoid predation, so loss of these structures due to use of mobile fishing gear could be a major factor–in addition to overfishing–underlying diminishing demersal fish stocks worldwide. Indeed, trawling and other mobile fishing gear have effects resembling a disturbance–forest clear-cutting–that has generated far more comment yet occurs on a scale two orders of magnitude smaller than use of mobile fishing gear. Thanks to improvements in fishing technologies and inadequate regulation, there are few places in the world's continental shelves with commercially valuable fishery resources that have not been trawled or dredged. Given the rapid, progressive collapse of commercial fish stocks and the less-noticed but even more worrisome loss of biodiversity worldwide, it seems prudent to devote more resources to understanding effects of mobile fishing gear and to act decisively to ameliorate their impacts on commercial fishery resources and other species comprising the world's marine biodiversity.

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Table 1. Some experimental studies on trawling and dredging impacts on benthic communities.

Gear	Substrate type, depth	Region	Study conditions	Results	Author
beam trawl, 2 m	sand, 20 m	southern North Sea	site hauled once; number of tickler chains altered	sessile organisms such as hydroids, tube making polychaetes, light-shelled bivalves and echinoids were badly damaged. Mobile macrofauna not affected	de Groot & Apeldoorn 1971
beam trawl, 12 m	sand, well packed, 30 m	southern North Sea	area trawled 3 times; sampling by box core pre- and immediately post-drag	decreased abundance of small heart urchins, and various polychaetes; increased abundance of small tellinids and magelonids, possibly due to redistribution in sediment	Bergman & Hup 1992
beam trawl, 4 m	gravel, cobble, 32 m	Irish Sea	10 hauls with 4 m and 3 with 2 m beam trawl; catches compared	density of sessile epifauna reduced 50%	Kaiser & Spencer 1994
beam trawl, 4m	sand, 30 m	Irish Sea	experimental lines trawled 10-20 times	benthos of less mobile sediments showed a 58% reduction in abundance and 50% reduction in species. Least abundant species suffered most severe losses	Kaiser & Spencer 1996
otter trawl, 20 m footrope and 90 kg doors	very fine mud, 20 m	Maine, USA	site hauled once; sampled 1 d post-drag.	surface sediment lost	Mayer et al. 1991
otter trawl	sand, 10 m	New South Wales, Australia	area trawled repeatedly for one week; samples pre- and post-trawl by grab	most infauna were rare making comparisons difficult; however, there appeared to be no difference in the faunal composition pre- and post-trawling	Gibbs, et al. 1980
roller-rigged otter trawl	gravel, cobble, 20 m	Georgia, USA	area trawled once; area surveyed by divers	heavy damage only to barrel sponges; slight damage to octocorals; all recovered after twelve months	Van Dolah et al. 1987

scallop dredge	muddy sand, 4 m	Maine, USA	site hauled many times; sampled 3 times over 5 mo. pre-drag and 3 times over 9 mo. post-drag	upper 4 cm of sediment lost; sediment coarsened. Recovery took 9 months for amino acids, total microbial biomass, and total abundances of cumaceans, and phoxocephalid and photid amphipods	Watling et al. unpublished
scallop dredge	sand, 5 m	Scotland	several tows over the same track over 9 d; samples at 1-5 & 9 d.	infauna numbers tended to increase with increasing dredge activity, but biomass decreased. Sessile polychaetes, heart urchins, and sand eels suffered greatest decreases	Eleftheriou & Robertson 1992
scallop dredge	poorly sorted mud with shell hash, 8 m	Maine, USA	site hauled once; sampled 1 d post-drag	surface labile organic matter (especially chlorophyll and protein) lost from upper 2 cm, some due to resuspension and some to burial. Surface layers also became enriched in anaerobic microbiota	Mayer et al. 1991
scallop dredge	sand, 24 m	New Zealand	5 parallel tows in experimental site	immediately after dredging 50% of the macrofauna showed significant abundance reductions; community composition also differed between control and experimental plots; some plots remained different for 3 months	Thrush et al. 1995
scallop dredge	sand, 15 m	Victoria, Australia	each site towed twice	most species showed reductions of 20-30% in abundance after area dredged; recovery strong with seasonal recruitment, although some species had not returned 14 months after impact	Currie & Parry 1996
hydraulic dredge	silt and clay to silty sand, 2 m	Italy	site dredged nearly completely once	fine sediments were resuspended and removed resulting in change in grain size; furrows 10 cm deep persisted up to two months; all larger macrobenthos removed by dredging; after 2 months site recolonized by small individuals	Pranovi & Giovanardi 1994

Table 2. Some observational studies on trawled or dredged sites, with inferences being drawn about disturbance mechanism. All sites chosen have high probability of having been disturbed by fishing activities.

Gear	Substrate type	Region	Observations	Author
otter trawl with chains and rollers	sand & cobble, with extensive bryozoan beds; 10-35 m depth	New Zealand	no trawling in the grounds until synthetic fibres were available. Extensive trawling from 1960s to 1970 then destroyed almost all the bryozoan beds, considered to be a nursery area for snapper. Trawling prohibited in 1980	Bradstock & Gordon 1983
otter trawls	sand with extensive epibenthic organisms; 50-200 m depth	Australia, NW shelf	area not trawled until 1959. Extensive trawling by Japanese and Taiwanese produced tons of by-catch and resulted in shift of major fish species being caught. Preferred species were associated with epibenthic colonial invertebrates. Half of shelf closed to trawling by 1987; recovery is being monitored	Sainsbury,1991; Sainsbury et al. 1993
otter trawls	gravel bank with mud overlay; 100 m depth	Gulf of Maine, Jeffreys Bank	extensive sponge community observed in 1987; repeat observations in 1993 showed overturned boulders and reduced cover of sponges. Area may be a refuge for juvenile gadoids	Watling, unpublished; Auster et al. 1996
scallop dredge and otter trawl	sand, cobble, and shell; 30-40 m depth	Gulf of Maine, Swans Island	reference and fished sites surveyed by ROV video. Epifaunal organisms dominant in reference areas; cover of these species decreased in fished areas	Auster et al. 1996
scallop dredge and otter trawl	gravel and cobble, 40-90 m	Georges Bank	areas closed to fishing were compared with fished sites. Compared with the disturbed sites, undisturbed areas had higher numbers of organisms, biomass, species richness and species diversity. Undisturbed sites had higher numbers of bushy organisms making the benthic	Collie et al.1997

			environment structurally more complex	
scallop dredge	sand, boulders; 80 m depth	Gulf of Maine, Fippennies Ledge	area fished for scallops showed reduced densities of scallops, polychaetes (*Myxicola*) and tube-dwelling anemones (*Cerianthus*) as observed by submersible photos	Langton & Robinson 1990
scallop dredge	sand	Gulf of Maine, Stellwagen Bank	dredge path and adjacent areas examined with ROV video. Dredge path identified as linear strips devoid of benthic microalgae. Hydroids were dense in undisturbed area but eliminated from dredge path. Shrimp density increased with increased hydroid density outside of dredge path but were absent in dredge path	Auster et al. 1996
prawn trawl	sand	Gulf of Carpenteria, Australia	areas fished for 20 years were surveyed before and after opening for prawn trawl fishery. The numerical abundance of 52 of 82 fish species remained unchanged. 30 taxa changed in abundance, some decreased (benthic) and others (bentho-pelagic) increased. Impacts on invertebrates were not reported	Harris & Poiner 1991
prawn and scallop trawls	sand	SW Australia	areas open and closed to trawling were surveyed for bycatch (primarily fish). Trawled and untrawled areas were not significantly different in their catch. One area, with seagrass and not trawled had very high biodiversity. Impact of trawling is considered to be low because the target species live primarily on open sand bottoms	Laurenson et al. 1993

Table 3. Frequency of trawling in several areas.

Location (Area)	Percent trawled annually	Source
Limfjord, Denmark	200	Riemann & Hoffmann 1991
Irish Sea (3 ICES rectangles)	4, 12, and 50	Kaiser et al. 1996
Southern North Sea	150-200	Lindeboom & de Groot 1998
Georges Bank (37,000 km^2)	21 (1970)	Caddy 1973
Georges Bank (40,806 km^2)	200 to nearly 400 (1976-91)	Auster et al. 1996
Gulf of Maine (65,013 km^2)	100 (1976-91)	Auster et al. 1996
Gulf of Maine and Georges Bank, US vessels only	0-450 (1993)	Pilskaln et al. 1998 (this issue)
Shelf south of Nantucket and Nantucket Shoals, Massachusetts 30' x 30' rectangles	up to 413 (1985)	Churchill 1989

Table 4. A comparison of the impacts of forest clear-cutting and trawling of the seabed Sources include Norse (1990), FAO (1995), and discussions at the 1996 MCBI trawling workshop.

Impact	Clear-cutting	Bottom trawling
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
Recovery to original structure	decades to centuries	years to centuries
Typical return time	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
Latitudinal range	subpolar to tropical	subpolar to tropical
Ownership of areas where it occurs	private and public	public
Published scientific studies	many	few
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

Figure Legends.

Fig. 1. Top, a modern bottom trawl shown in operation on the seabed; bottom, two types of roller gear applied to the groundrope of the net to aid in trawling over very rough bottom conditions (from Sainsbury 1996).

Fig. 2. Modern beam trawl designs, showing two ways in which chains are arranged in front of the groundrope. The chains are used to disturb the sand, thus helping to increase the catch of species, such as flatfishes, that live in contact with the bottom (from Sainsbury 1996).