Physical disturbance and biological implications of sediment resuspension from commercial fishing gear in the Gulf of Maine

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Senior Integrative Exercise
March 11, 2003

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Abstract:

The Gulf of Maine is a semi-enclosed continental shelf sea characterized by irregular bathymetry and heterogeneous sedimentary characteristics. Many benthic fish species are commercially harvested in and around the Gulf of Maine using bottom trawls and scallop dredges. This fishing gear may act as a physical disturbance to the seafloor, and as a sediment resuspension mechanism.

The prevailing counterclockwise gyre in the Gulf of Maine is modified by a system of localized tidal, wind, wave, and current activity exhibiting complex variability with season and local bathymetry. Seabed sediment in topographically shallow areas such as Georges Bank in the eastern Gulf of Maine is reworked year-round, while the benthos of deep basins are unaffected by even the largest storm-induced wave orbitals or bottom currents. Bottom fishing gear may introduce a greater disturbance to these deep basins.

Bottom trawls and dredges may penetrate from two to ten centimeters into bottom sediment, generate turbid plumes with residence times on a scale of days, and increase nutrient and trace metal concentrations in the water column. Following disturbance by fishing gear, total microbial biomass may decrease in the top centimeter of sediment, with increases in the relative proportion of anaerobic prokaryotes, perhaps due to redox oscillation. Nutrient pulses released by turbid plumes may augment primary productivity in the photic zone, while suppressing autotrophic activity through attenuation of light at depth.

Keywords: Gulf of Maine, hydrodynamics, suspension, sediment transport, sediment-water interface, productivity

Introduction

The Gulf of Maine is a semi-enclosed, glacially carved continental shelf sea (Fig.1) (Kelly, 1999). Its borders to the south are defined by deposits which accumulated during and after the retreat of the Late Wisconsinan Laurentide ice sheet (Valentine et al., 1993), forming Cape Cod, as well as parts of Nantucket Shoals and Georges Bank (Dorsey, 1998; Poppe and al., 1989). The Maine coast and Nova Scotia enclose the Gulf of Maine to the northwest and northeast respectively. The Northeast Channel - located between Browns and Georges Bank - and the Great South Channel - located between Georges Bank and Nantucket Shoals - connect the Gulf of Maine to the north Atlantic.

Many species of fish are commercially harvested using bottom trawls or scallop dredges in and around the Gulf of Maine, including benthic species such as Atlantic cod, haddock, flounder, and the Atlantic sea scallop (Overholtz and Tyler, 1985). In the Gulf of Maine, the total area swept by trawl and dredge gear per month is approximately equal to the area of the Gulf itself, while fishing grounds just outside the Gulf such as Georges Bank may be swept a total of three times their area per month (Collie, 1998) (Fig. 2). In addition to the removal of benthic epifaunal communities, bottom fishing may act as a disturbance to the seabed itself by resuspending sediment, releasing nutrients and trace metals into the water column, and altering benthic microbial communities. However, it is essential to examine the sedimentary characteristics and natural resuspension processes for the Gulf of Maine and its surrounding New England waters in order to determine when and where bottom fishing “disturbs” the seabed.

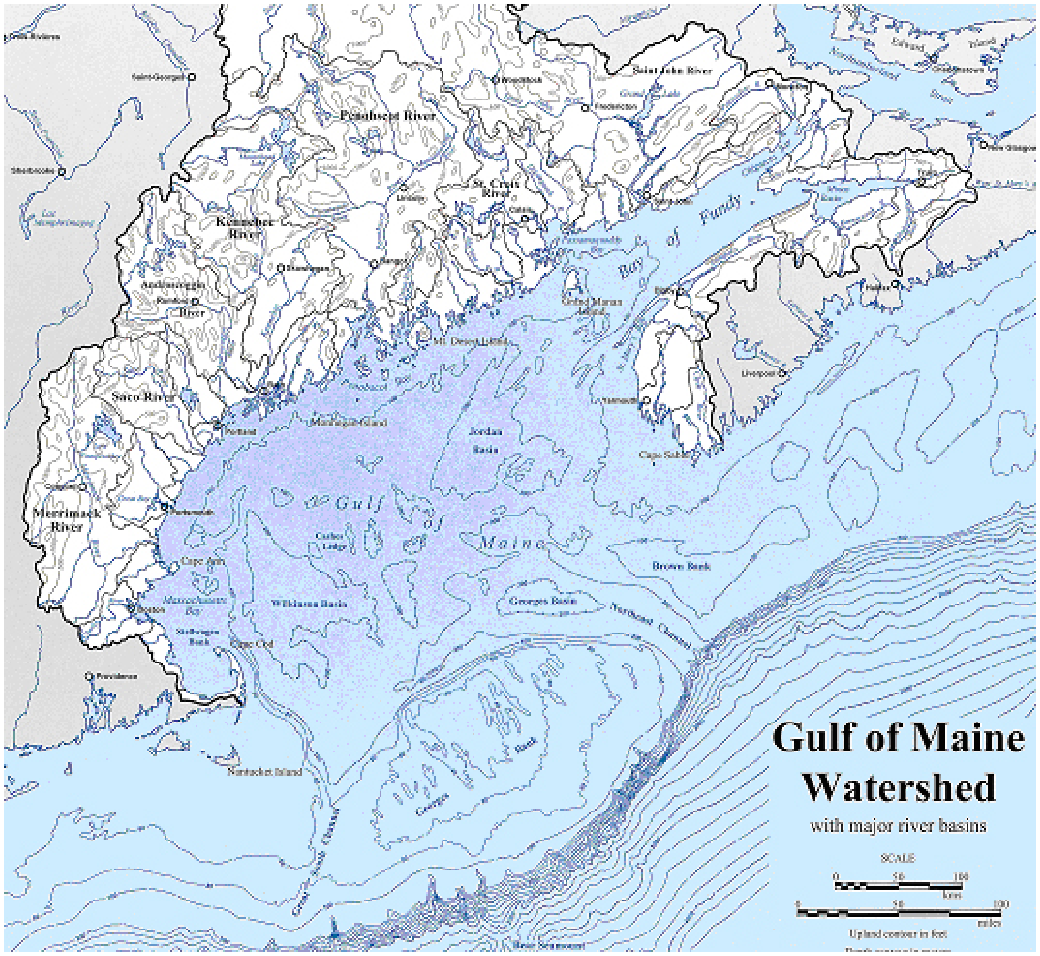


Figure 1. Map of the Gulf of Maine watershed (from Kelly 1999).

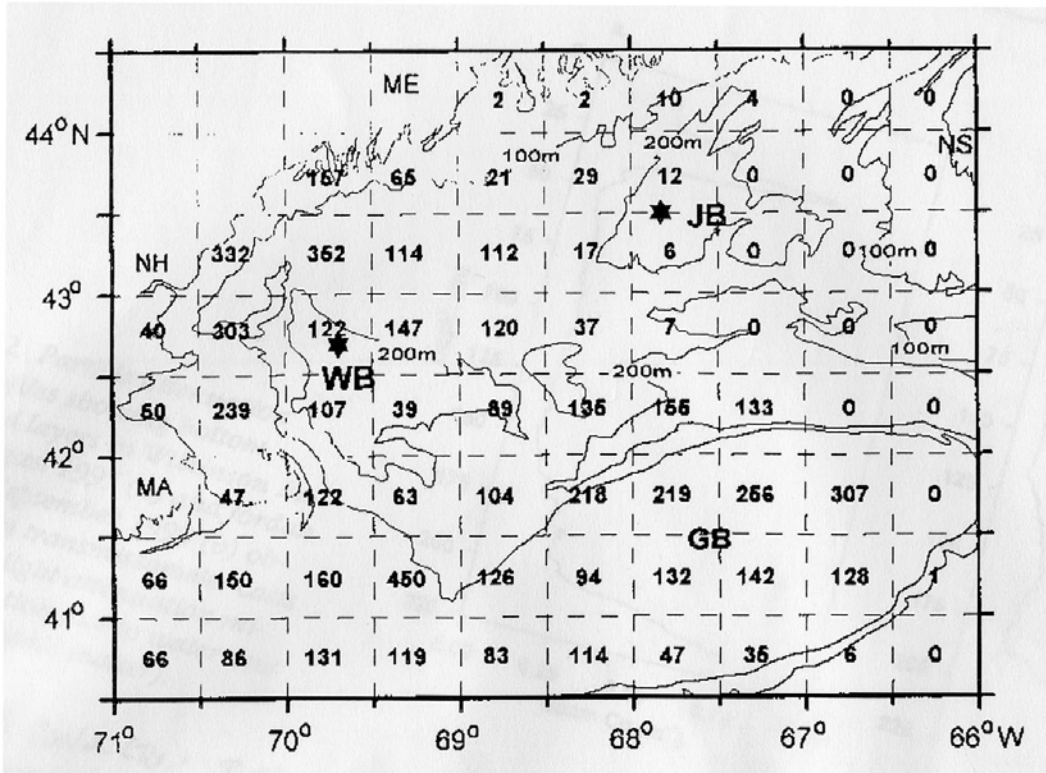


Figure 2. Monthly bottom trawling activity in the Gulf of Maine and Georges Bank for 1993 given as percent area trawled, with each square representing 810 nm^2. Zeros indicate Canadian regions for which no National Marine Fisheries Service bottom trawling data were available, and areas closed to trawling on the eastern edge of Georges Bank. Labels are Jordan Basin (JB), Wilkinson Basin (WB), and Georges Bank (GB) (from Pilskaln et al. 1998).

Sedimentary characteristics

The Gulf of Maine seafloor is dominated by glaciomarine and post-glacial sedimentary deposits. Although sediment types are highly heterogeneous, three primary regions can be generalized: sand, mud (silt and clay), and heterogeneous but bedrock dominated (Fig. 3 and 4). Sand is the dominant sediment type at the southern glacial extent and southward, including Georges Bank, the continental shelf to the west, and the Cape Cod seafloor. These areas, however, are broken up by glacially deposited gravel on the northern edge of Georges Bank and accumulations of the “Mud Patch”, a low-energy region of deposited silt and clay (Dorsey, 1998). Silt and clay comprise most areas of the

Gulf of Maine below 60 meters depth. Rises between basins are composed of unsorted glacial till. Modified till - sand mixed with silt, clay, and gravel - exists at the eastern edge of the Gulf as it climbs to the sand and gravel shoals of Browns Bank and the Scotian Shelf. Bedrock exposures exist on the western edge of the Gulf north of Cape Cod in waters less than 60 meters deep, the lowest depth that sea level fell during the last ice age, passing over the seafloor and removing surficial sediments (Kelley and Belknap, 1991). Bedrock also surrounds islands and peninsulas, extending underwater as rocky ridges (Dorsey, 1998; Poppe and al., 1989).

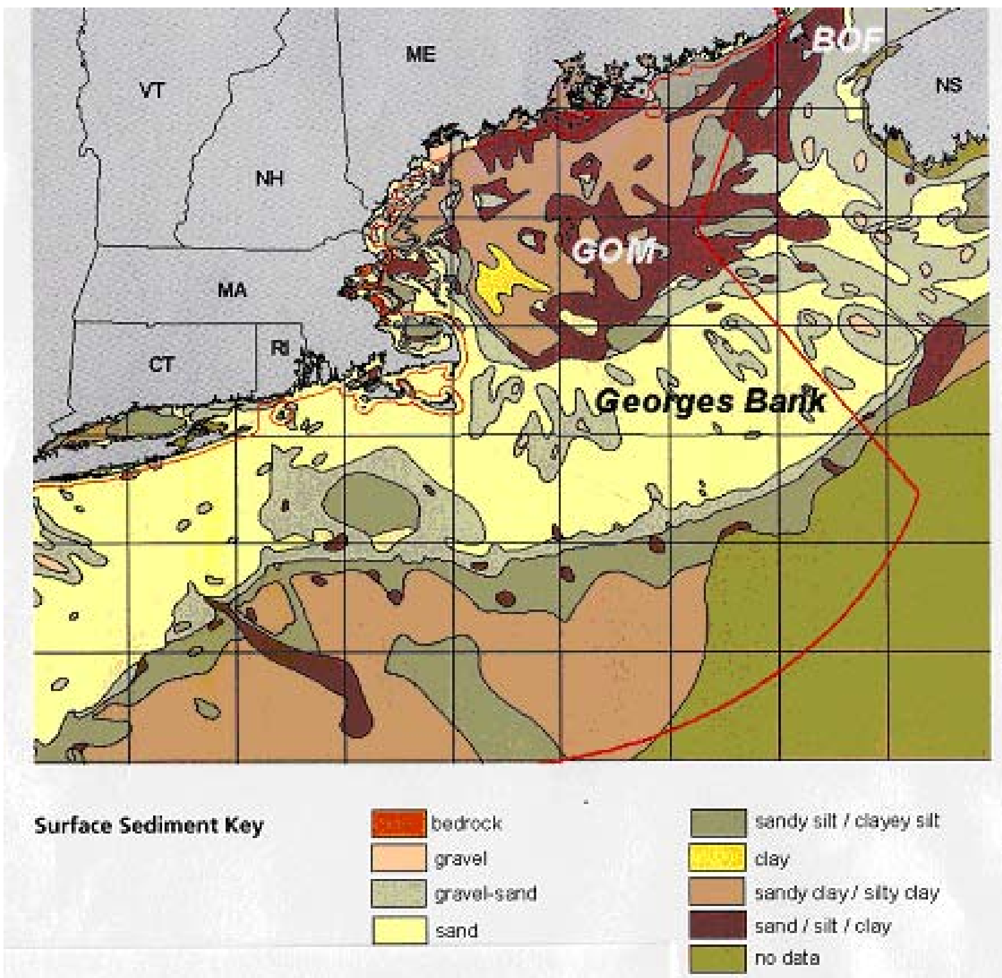


Figure 3. Sedimentary characteristics of the Gulf of Maine (GOM) and Georges Bank (from Poppe et al. 1989).

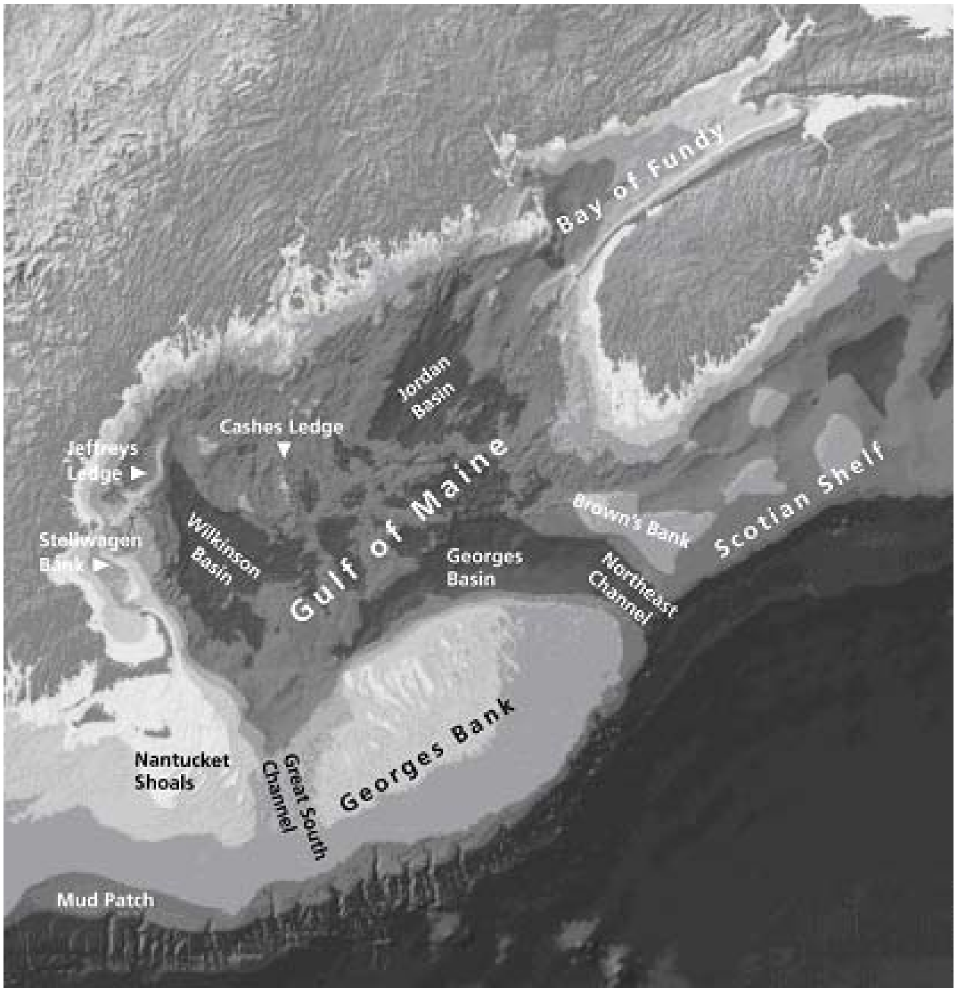


Figure 4. Shaded relief map of New England Seafloor bathymetry. The shallow areas are pale gray, and deeper areas are progressively darker gray. Generated by Rich Signell and Ed Roworth, U.S. Geological Survey (from Dorsey 1998).

Natural sediment suspension mechanisms

The prevailing counterclockwise gyre in the Gulf of Maine is governed by the intrusion of dense continental slope water through the Northeast Channel, freshwater flows from more than sixty rivers, and tidal amplification from the shoreline configuration and underwater features (Richert, 2003). Localized water movement, however, is a largely unexplored system of tidal, wave, wind, and current activity exhibiting complex variability with season and local bathymetry (Lynch et al., 1995).

Although natural sediment resuspension within and surrounding the Gulf of Maine varies with these localized hydrodynamic systems and sediment characteristics, resuspension is generally frequent year-round in coastal and topographically shallow areas, but rare in deeper basins of the Gulf.

Inshore of the 100 meter isobath

Inshore of the 100 meter isobath (Fig. 1), marine dynamics are primarily due to local influences, including locally-variable wind driven waves, tidal currents, and buoyancy inputs from freshwater runoff at the coast (Lynch et al., 1995).

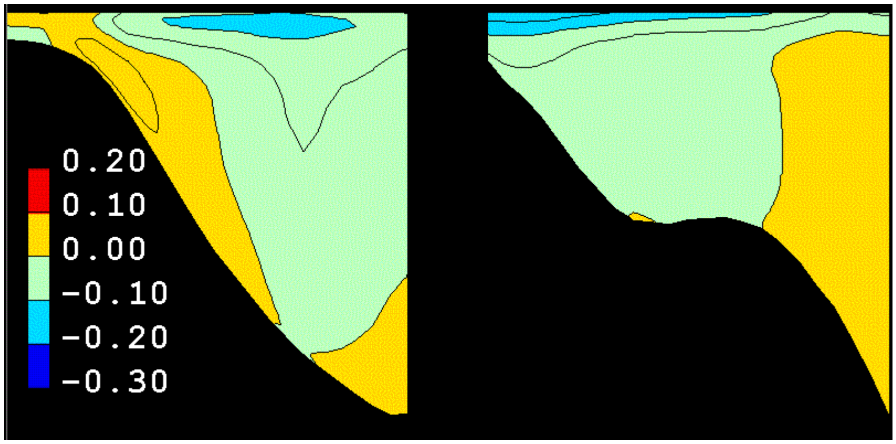
In the Gulf of Maine, the strongest winds are from the northeast during storms, while non-storm westerly winds have a northerly component in the winter and a southerly component in the summer. Wind/wave-induced shear stresses and subsequent sediment resuspension are generated by the retardation of currents and wave orbital velocities at the sea bed, and are important mechanisms in water depths less than 30 meters since wave orbital velocities decrease exponentially with depth (Hall, 1994; Morris and Howarth, 1998; Watling and Norse, 1998). The rate of wave-induced sediment resuspension is determined by sediment type, the shape of the seabed, and the difference between the bed stress and a critical shear stress below which sediment cannot be eroded (Floderus and Pihl, 1990; Morris and Howarth, 1998).

Tides in the Gulf of Maine are semidiurnal, and range from 2.7 meters south of Portland to 5.7 meters in far eastern Maine near Eastport, with 0.3-0.6 meter increases in water level during neap tides. Although a mechanism for sediment resuspension, tides are unlikely to be a "disturbance" adversely affecting marine systems due to their regularity. Although tides are generally not strong enough to resuspend the bulk of seabed sediment, erosion will occur when tides combine with wind and wave action, enhancing the bed shear stress (Jones et al., 1998), and mixing coastal waters in the Gulf of Maine year-round (Bothner et al., 1980). Tides therefore should be addressed in this assessment of natural resuspenders of sediment.

In addition to these local influences, the Maine Coastal Current (MCC) may also have an effect on the benthic nearshore environment. The MCC is the shoreward component of the Gulf of Maine's overall counterclockwise cyclonic circulation. It is initiated in the eastern Gulf of Maine, travels westward along the northern and western Gulf margins, and exits along the eastern tip of Cape Cod toward the Great South Channel. In addition to the transportation of phytoplankton blooms, nutrients, and pollutants (Franks and Anderson, 1992; Townsend, 1991), the coastal current's strength coupled with wind events may affect bottom sediment.

Nearshore transects cut vertically through the coastal current at the outflow of the Kennebec and Androscoggin Rivers into Casco Bay indicate increases in near-bed current velocity during a large-scale wind event (Fig. 5). The wind stress, measured over two days, is twenty times the climatalogical mean, and consists of a strong southwestward wind which reverses halfway through the period, becoming a northeastward wind (Holboke and Lynch, 1995). A wind stress of this magnitude can be compared with a seasonal storm event, potentially resuspending nearshore sediment.

a.



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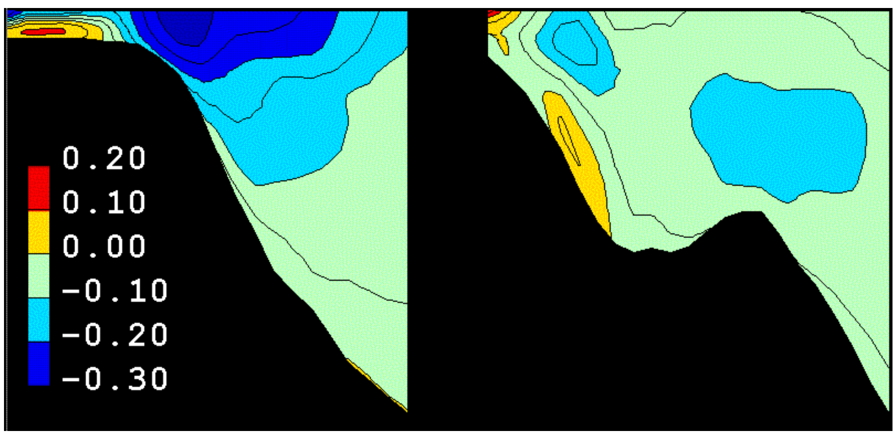

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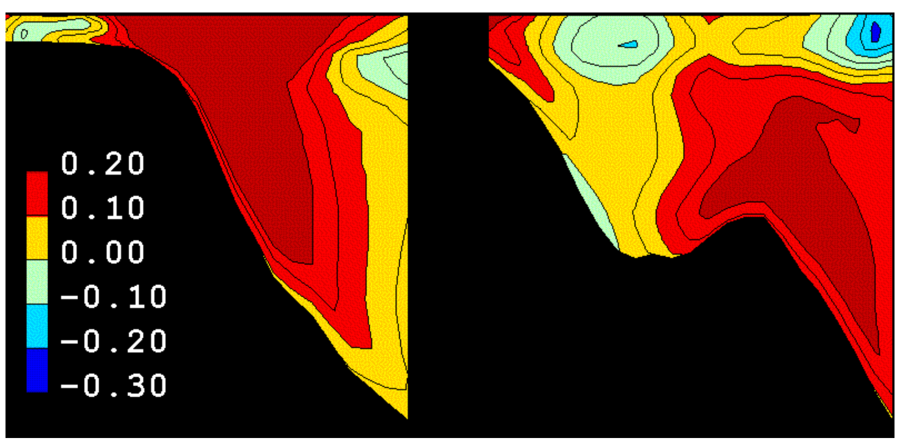


Figure 5. Nearshore transects of the Maine Coastal Current (60 meters in length and 150 meters deep) for a) average current velocity (m/s) from data by Naimie et al.1994, b) velocity during the southwestern wind event, and c) velocity during the northeastward wind event. Positive values indicate flow into the page with the coast on the left (from Holboke and Lynch 1995).

Shallow offshore locations

Localized influences resuspending sediment in coastal locations may also affect bottom sediment in topographically shallow areas including Browns Bank, Georges Bank, and Nantucket Shoals.

Hydrodynamics on Georges Bank are characterized by complex circulation (Ashjian et al., 2001; Butman and Beardsley, 1987; Hopkins and Garfield III, 1981), however strong northwest and southeast semidiurnal tidal currents dominate, ranging from a fraction of a knot on the outer banks to greater than two knots at the crest of the banks. Water on this crest is separated from Gulf of Maine water to the north and shelf water to the south by northern and southern tidal mixing fronts. These tidal currents may account for more than 80% of the total current variance on Georges Bank (Sherman et al., 1996). There is extensive year-round reworking of medium to coarse sands in Georges Bank crest waters less than 50 meters deep produced by the combination of tidal currents, winds, waves (Bothner et al., 1980; Dorsey, 1998), and the anticyclonic flow around the margins of the crest outside the tidal mixing fronts (Ashjian et al., 2001; Limeburner and Beardsley, 1996).

Aperiodic storms are a large contributor of suspended sediment load, particularly from January to April over Nantucket Shoals and Georges Bank (Churchill, 1989). A study by Bothner et al. (1981) indicates that storms on Georges Bank can generate enough bottom turbulence to suspend sediments, and maintain seston concentrations in suspension for seven days. Two storms were observed on Georges Bank: the summer storm increased seston concentrations by stimulating biological productivity, while the winter storm increased turbidity by maintaining sediment in suspension. Although the effects of wave-induced resuspension are greater at 30-40 meters depth, winter storm-induced long-period waves can transport material across the continental shelf even at 100 meters depth (Drake and Cacchione, 1985).

Deep Basins

The Gulf of Maine is characterized by twelve deep basins which were once river valleys draining the surrounding pre-glacial land. These basins include Jordan and Wilkinson Basins reaching 300 meters depth, and Georges Basin, the deepest point in the Gulf of Maine at 350 meters (Fig.4) (Dorsey, 1998).

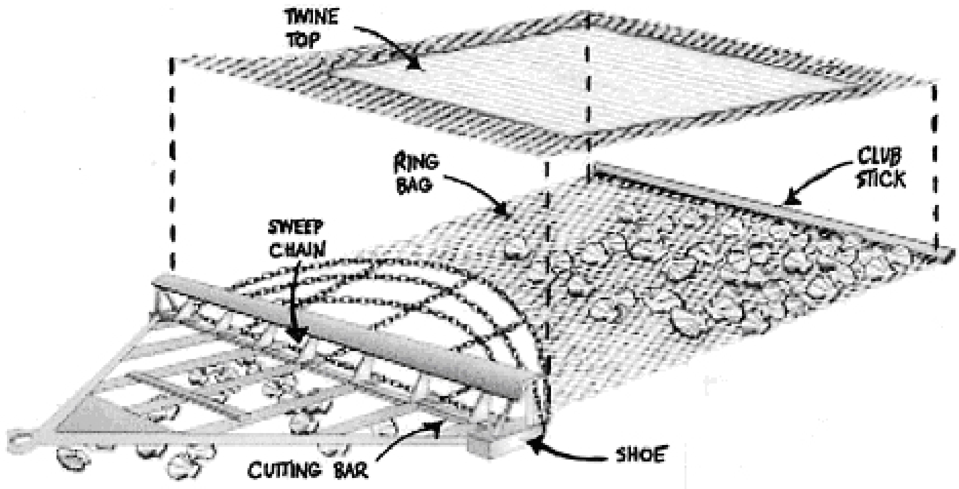
Nutrient-rich slope water enters the Gulf of Maine through the Northeast channel, accumulates in Georges Basin, crosses a sill, and enters Jordan Basin, enhancing a counterclockwise gyre partially driven by nearshore buoyancy forces and the wind (Christensen et al., 1996) (Richert, 2003). Nutrients in Jordan Basin are upwelled and entrained in the strong southwest flow of the Maine Coastal Current operating seaward of the 100 meter isobath, and winter convection creates vertically homogenous waters to 130 meters depth. However, gyre, current, and convection activity are too weak to erode the seafloor of these basins, creating bottom water with residence times of approximately one year (Kelley and Belknap, 1991).

Bottom fishing gear

Any assessment of the effects of fishing gear on the seafloor must detail the specifics of gear type. Although there exist numerous types of gear with various specifications based on the species targeted, the New Bedford style scallop dredge (Fig.

6a) and bottom trawling gear, particularly the otter trawl (Fig. 6b), are the primary gear types used in and around the Gulf of Maine.

a.



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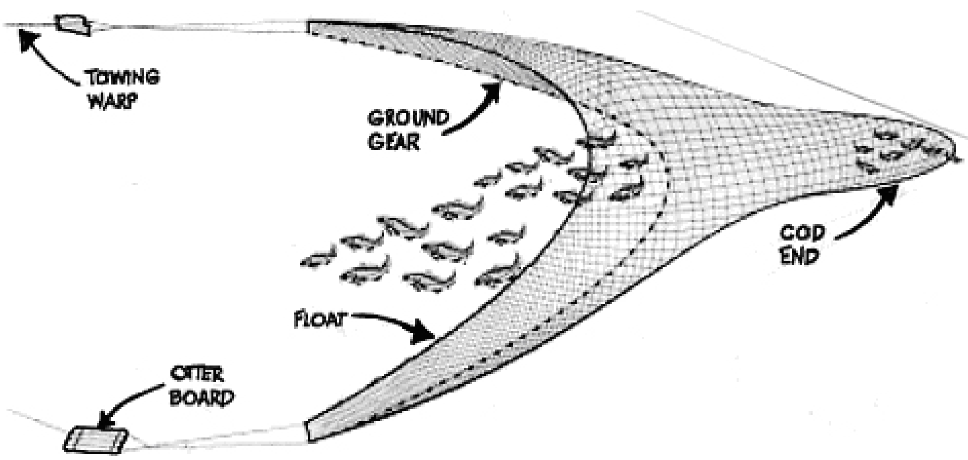

Figure 6. The a) New Bedford style scallop dredge, with top removed for illustration, and b) otter trawl (from Smolowitz 1998).

Scallop dredge

The primary catch objective for the New Bedford style scallop dredge is the Georges Bank and north Atlantic sea scallop. Scallop dredges are used in both high and low energy sand environments, as well as shallow, high-energy gravel environments. Those used on the Maine coast tend to be smaller (5.5 to 8.5 feet) than their New England counterparts (Smolowitz, 1998).

Scallop dredges are defined by the width of their two towed frames, generally 13-15 feet. The front of this steel frame is called the bale, and generally rides off the sea floor. The bottom aft part of the frame, the cutting bar, rides about four inches off the bottom, creating turbulence and stirring up the bottom sediment. Each end of the dredge frame has a bottom pad called the shoe, which attaches the sweep chain from end to end. At a typical towing speed of five knots, this chain does not dig into the bottom substrate. The chain moves back in an arc from the frame and attaches to a bag composed of metal rings with chafing gear on the bottom and twine mesh on the top. This bag drags along the bottom. A club stick maintains the bag's shape (Smolowitz, 1998).

Bottom trawl

Another primary gear type in New England is the bottom trawl which primarily targets haddock. The bottom trawl net is kept laterally open by two doors which tend to leave grooves in the seafloor as deep as 10-15 centimeters depending on the bottom substrate. The doors are intended to create turbid clouds, herding fish into the path of a trawl. Many different types of ground gear can be used on the sweep of bottom trawls, and impacts to bottom substrate vary by gear type (Smolowitz, 1998).

One type of bottom trawl frequently used in outer continental shelf regions and deep water basins of the Gulf of Maine is the Otter Trawl (Fig.6b). Generally, the otter board, ground rigging behind the board, and the net contact the seafloor (Hall, 1994; Smith et al., 2000). However, there exist a diversity of otter trawl gear types depending on the bottom substrate and target species. Otter trawls are designed to target specific species rather than act as sieves to collect all species in their path. When whiting and squid are targeted, for example, a light chain sweep is used, but flatfish are targeted with more ground rigging designed to sweep the fish off the bottom. The ratio of weight in water to weight on land varies with different otter trawl configurations. However, in order to maintain its shape, trawl gear must be relatively light (Smolowitz, 1998).

Bottom fishing induced sediment resuspension

The physical resuspension and disturbance of marine sediments is a combination of both natural suspension mechanisms and bottom fishing gear. The relative contribution of each mechanism is determined by the depth of disturbance, size of the turbid plume generated, settling behavior of suspended particles, local sediment characteristics, physical regime of the system, and season.

For example, trawling appears to be the dominant resuspension mechanism over the Mud Patch from January to March at depths greater than 100 meters where currents are too weak to erode sediments, while currents are the primary suspension mechanism at depths less than 100 meters during this time (Churchill, 1989) (Fig. 7).

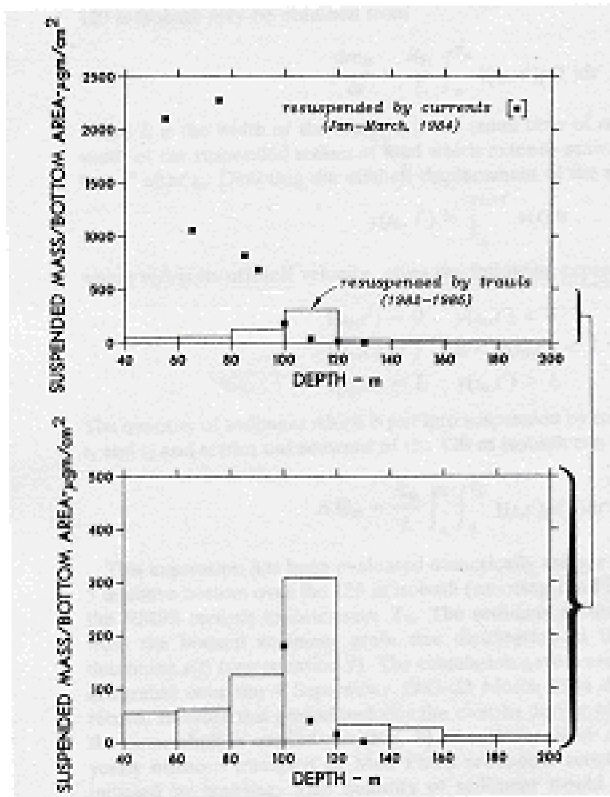

Figure 7. Histogram of time-averaged suspended load mass per unit bottom area at the Mud Patch from trawling (1982-1985) and currents (1985). The vertical scale is expanded in the lower plot to show trawl-induced suspended mass loads in water between 100-140 meters depth (from Churchill 1989).

The suspended load on Nantucket Shoals, for example, is largely a function of season. Trawling contributes anywhere from 20-99% of the suspended load between May and December, while storm activity is the largest contributor of suspended sediment load from January to April (Churchill, 1989). Sands on Georges Bank and Stellwagen Bank are periodically resuspended by severe storms, and are therefore less vulnerable to the impacts of fishing gear (Collie, 1998).

Slight variation in these site-specific characteristics will significantly alter the overall effects of sediment resuspension. Until studies focus specifically on the Gulf of Maine, it is worthwhile to examine previous studies documenting the depth of trawl disturbance, residence times for turbid plumes, and the composition of post-trawl surficial sediments in areas sharing characteristics with the Gulf of Maine, as valuable analogs for commercial fishing-induced resuspension.

Depth of trawl disturbance

The depth of trawl disturbance tends to be greater in fine, soft sediments. A study of a muddy, previously unfished continental shelf region in the northwestern Mediterranean measured erosion of sediment following an otter trawl. The net between the gears removed two to three centimeters of sediment on average, and the overall erosion from both gears and water velocity was greater than three centimeters (Palanques et al., 2001). Demersal trawling gear in the Kattegat Sea, western Sweden, is used in muddy sediment below the halocline, and it is estimated that the otter board, the sweep, and the bottom rope of the trawl penetrate five to ten centimeters into the sediment at 2.5 to 3.5 knots (Floderus and Pihl, 1990). Another study in Port Phillip Bay, a large semi-enclosed tidal embayment in southeastern Australia, found the depth of disturbance from a scallop dredge to range from four centimeters in coarse sediments to six centimeters in soft sediments (Black and Parry, 1994). A study on the Damariscotta River, Maine estimated that three to four centimeters of surficial sediment was lost following a scallop drag on a silty sand bottom (Watling et al., 2001).

Turbid plume

Trawling increases the natural levels of sediment in suspension, but the magnitude of suspension and residence time for a turbid plume varies widely depending on an environment's energy. When the dominant natural circulation and suspension mechanisms are a combination of tidal currents and wave orbital currents disrupted by storms, suspended sediment concentrations following a scallop dredge can reach two to three orders of magnitude higher than natural levels. These turbid plumes can persist for 17 seconds after disturbance, reduce to storm levels in nine minutes (Black and Parry, 1994), and possibly reduce to two percent of the original plume size after 30 minutes (Black and Parry, 1999). However, in areas of muddy sediment, water turbidity can increase during the first 100 hours following an otter trawl and remain at three orders of magnitude higher than natural levels for four to five days following the trawl in a stratified water column where waves and currents are not strong enough to rework the seabed (Fig. 8) (Palanques et al., 2001).

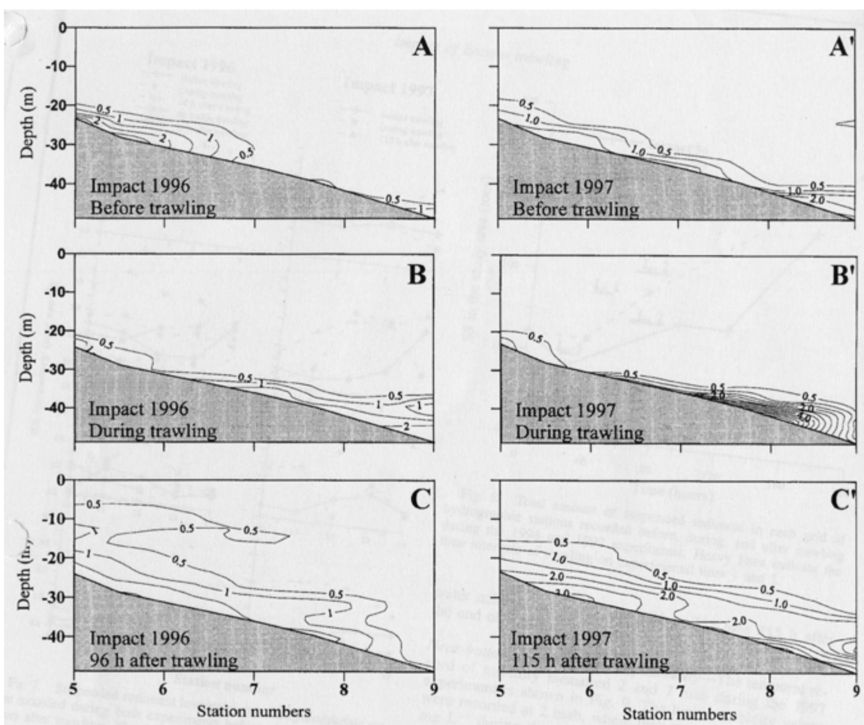

Figure 8. Profiles of suspended sediment concentration (mg L^{-1}) across trawling lines recorded (A and A′) before trawling, (B and B′) during trawling, and (C and C′) about 100 hours after trawling during 1996 and 1997 experiments in the northwestern Mediterranean (from Palanques et al. 2001).

The suspension and residence time of a trawling-induced plume is governed by the energy of an environment and its sedimentary characteristics. A study comparing average conditions of the Mud Patch and Nantucket Shoals, with fine and coarse sediments respectively, estimated similar average shoreward concentrations of suspended sediment. These similar concentrations exist despite heavier trawling activity on Nantucket Shoals, suggesting that coarse sediments are resuspended at a lower rate and settle out more quickly from the water column (Churchill, 1989; Morris and Howarth, 1998).

Surficial sediment composition

Sediment resuspension and subsequent deposition may alter the composition of surficial sediment, and the likelihood of resuspension. Trawling may result in the loss of fine material in local sediments since fine particles travel much further following entrainment than sands and coarse sediments (Black and Parry, 1999; Mayer et al., 1991; Watling et al., 2001). These coarse sediments that remain locally will require more stress to be resuspended. However, dredging may break natural cohesive and biological sediment bonds, increasing their likelihood of renewed suspension during storms (Black and Parry, 1999).

Resuspension and subsequent deposition during a phytoplankton lifecycle may actually increase the critical entrainment velocity for particles through sediment binding by diatoms (Dyer, 1986; Hall, 1994). Aggregation of phytoplankton modifies particle settling behavior and dynamics of suspended particulate matter. Certain species of diatoms including *Nitszchia pseudoseriata* produce extracellular polysaccharides, particularly when nutrient-stressed, which cause colliding individuals to attach.

Moreover, these organisms scavenge fine inorganic particles in suspension as they settle out, thereby allowing both phytoplankton and particle settlement beneath the thermocline and into the bottom mixed layer (Jones et al., 1998). Experiments showed that the entrainment velocity of particles rose by up to 60% with the presence of carbohydrate-rich mucus between the grains (Rhoads et al., 1978).

Bottom fishing gear may alter the sedimentary organic carbon distribution from surface marine sediments. Coastal environments produce more organic carbon than they respire (Smith and Hollibaugh, 1993; Wollast, 1991), and some portion of this non-respired dissolved organic carbon may be suspended and exported from continental margins to abyssal environments (Hartwig, 1976; Wollast, 1991). The likelihood of lateral distribution of this carbon is higher in shallow, well-mixed environments where residence times of suspended organic matter in the water column are long (Hopkinson, 1985; Martin et al., 1987). Heavy chain dredges could also mix surface organic material into subsurface layer (Jones, 1992), increasing total organic carbon at five to eight centimeters depth (Mayer et al., 1991).

Increased nutrient concentrations

Resuspension of sediment recycles nutrients between the seabed and water column (Fanning et al., 1982). The components of resuspended material typically include an inorganic component from the original weathering of rocks and coastal erosion, nutrients derived from organic matter decay and nutrient remineralization within sediments, as well as an organic component of local detritus from plankton cycling forming a carbon-rich layer across the seabed following a bloom (Morris and Howarth, 1998). Much of the organic carbon, nutrients, and trace metals deposited in marine sediments are decomposed through benthic respiration, or returned to the water column via the flushing and dissolution of accumulated porewater nutrients from sediments (Hopkinson et al., 2001; Marinelli et al., 1998), and through upward physical transport driven by molecular diffusion. Balzer (1984) examined benthic degradation of organic matter and the cycling of carbon, nitrogen, and phosphorus at a station in the western Baltic at 20 meters depth. From the organic matter deposited via sedimentation, only 22% of the organic carbon accumulated below ten centimeters depth as sedimentary carbon. Seventy-five percent of carbon, 66% of organic phosphorus, and 50% of nitrogen input were returned to the water column (Fanning et al., 1982). Although natural rates of recycling these elements are high, increasing the frequency and intensity of nutrient recycling could hold implications for marine productivity.

In a study by Fanning et al. (1982), nutrient profiles taken from the continental shelf of the Northeastern Gulf of Mexico at water depths of 70 meters or less indicated the near-bottom enrichment of silica and nitrate above coarse sediments (Fig.9). The enrichment was attributed to storm-induced sediment load suspension, mixing pore water with bottom water during and after suspension, putting silicate into solution, and increasing interstitial ammonia concentrations in the overlying water column. The oxidation of increased ammonia in the water column could produce N-nitrite. Another study suggests similarly that pulses of sediment resuspension hold important implications for the input of sedimentary nitrogen and silica into the water column in the Gulf of Maine (Mayer et al., 1998).

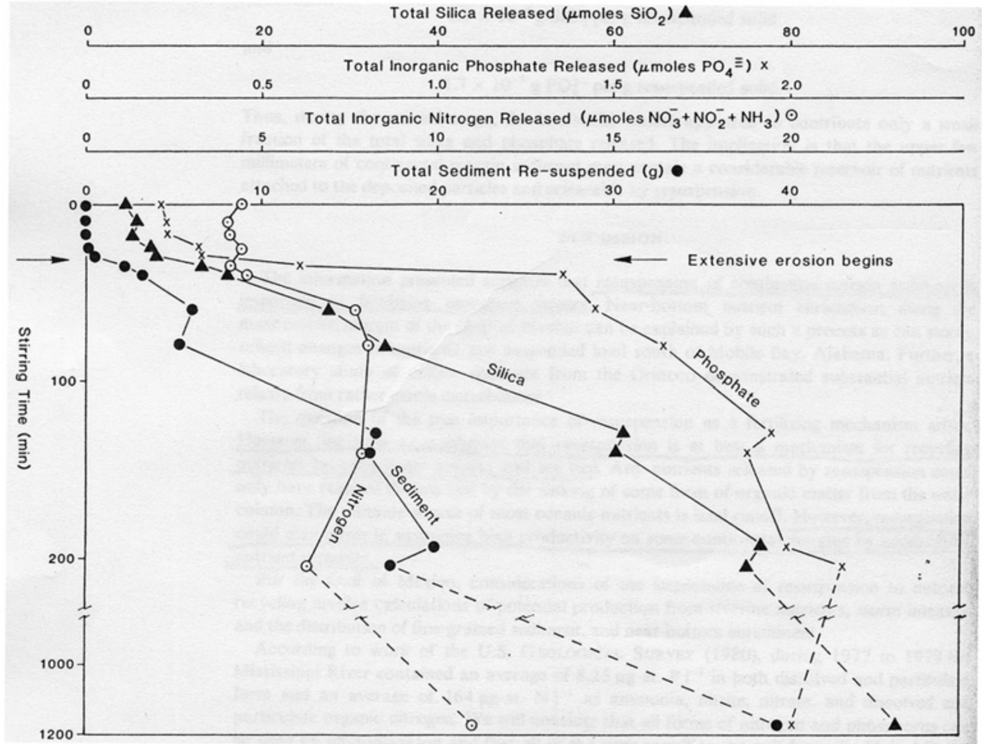

Figure 9. The time course of the release of silica, inorganic phosphate, inorganic nitrogen, and suspended matter during laboratory resuspension of sediment from the Venezuelan continental shelf (from Fanning et al.1982).

A study by Morris and Howarth (1998) examined sediment resuspension in the North Sea at a seasonally stratified water column of mean depth 47 meters with weak tidal currents and a muddy sea bed. Their study suggests that the chemical consequences of resuspension are more significant in fine cohesive sediments, because contaminants have little affinity for coarser materials. However, another study at two sites also in the North Sea found contradictory results when examining trace metal concentrations released into the water column from tidally-induced sediment resuspension. Site A with sandy sediments and a permanently well-mixed water column showed temporary changes in particulate and trace metal concentrations of bottom waters for Mn, Pb, and Zn. At site B, composed of muddy sand and a seasonally stratified water column, tidal resuspension of particulate metals was surprisingly negligible (Millward et al., 1998). These results suggest that the chemical consequences of resuspension are determined by many different variables at a study site.

Implications for phytoplankton and microbial communities

Diverse benthic, pelagic, free, and attached microorganisms inhabit both the water column and marine sediments. Colloidal particles suspended in the water column contain densities of bacteria 100-2000 times greater than the surrounding water (Herndl, 1988), and adherent species distinct from the surrounding water column (Rath et al., 1998). Benthic microbial biofilms in sediments form complex communities due to steep gradients of oxygen and nutrients diffusing into the sediment (Fenchel, 2002). These pelagic phytoplankton and benthic microbial communities may respond to the trawling-induced disturbance of a marine environment.

Pelagic primary productivity

Nutrients such as phosphorus, silica, nitrogen, and iron released into the water column in abnormally large pulses could accelerate nutrient turnover and increase overall productivity of the water column (Fanning et al., 1982). Studies from Jordan and Wilkinson basins in the western Gulf of Maine indicate that resuspension of one millimeter of sediment could double or triple nutrient fluxes to the photic zone in pulses, augmenting productivity by 100-200%, and altering phytoplankton from picoplankton to diatom-dominated populations (Pilskaln et al., 1998).

Productivity of pelagic bacteria, however, depends on whether they are auto or heterotrophic. The suspended load may suppress autotrophic activity through the attenuation of light at depth (Morris and Howarth, 1998). The growth of heterotrophs, in contrast, may actually be stimulated in the benthic turbidity zone following the resuspension of marine sediments from a storm event (Ritzrau and Graf, 1992). In a simulation of sediment resuspension, suspended microheterotrophs increased 2.6 times in biovolume after 32 hours. Although free-living pelagic heterotrophic bacteria showed the largest increase, particles in suspension also increased in attached bacterial biomass. Results indicate joint benefits of increased nutrients and substrate for both free and attached microbes (Wainright, 1987).

Benthic metabolism

Benthic decomposition at the depositional interface controls the amount of detrital organic matter available to macroconsumers, the amount buried in sediment, and the rate of nutrient release to the overlying water column. The rate of benthic metabolism is partially controlled by sediment composition (Balzer, 1984). When defining the Gulf of Maine as 100% fine sediment and Georges Bank as 100% coarse sediment, benthic metabolism in the Gulf of Maine is estimated to be five times that of Georges Bank. Estimates of benthic metabolism in the Gulf of Maine when hypothetically composed entirely of coarse sediments is estimated to be 2.66 times less than the present rate (Grant et al., 1991). These results indicate that the relative effects of changes in benthic metabolism in fine-grained communities may be greater than that of coarse-grained environments.

Two studies on the Damariscotta River Estuary in midcoast Maine quantified the impact of a scallop drag on the microbial metabolism of a silty sand community (Mayer et al., 1991; Watling et al., 2001). Effects following the experimental drags included lowered food quality of the sediment, measured by microbial populations, enzyme hydrolysable amino acids, and chlorophyll a. Total phospholipid phosphate and fatty acids, indicative of total biomass, decreased by 50-60% in the first centimeter, 27% in the four to five centimeter horizon, and showed no changes in microbial biomass at five to six centimeters depth (Fig. 10).

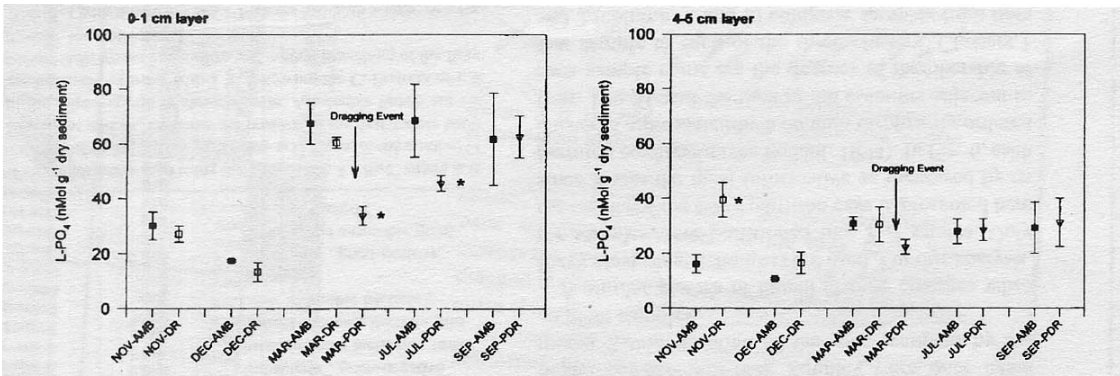

Figure 10. Changes in total microbial biomass of the 0-1 and 4-5 cm layers. Sampling periods are listed by month followed by AMB for ambient site, DR for the site to be dragged, and PDR for samples taken one day after dragging. Values plotted are means ± s.e. The closed symbols represent the ambient site and the open symbols the site to be dragged (from Watling et al. 2001).

Prior to the scallop drag, microbial communities in ambient surficial sediments were enriched in fatty acids typical of phototrophic microeukaryotes, while ambient sediments below the sediment-water interface were enriched in fatty acids indicative of anaerobic prokaryotes. Following the scallop drags, the contribution of anaerobic bacteria to the surficial microbial community increased, while the relative populations of photosynthetic microeukaryotes decreased, and shifted towards heterotrophs.

Microbial communities dominated by anaerobic bacteria may reduce nitrogen concentrations in post-trawl sediments. Sulfate reduction is the predominant pathway of anaerobic metabolism of organic carbon in marine sediments. The end-product of sulfate reduction – sulfide – completely inhibits nitrification at certain concentrations (Seitzinger et al., in press). In addition, denitrification is the anaerobic bacterial oxidation of organic matter using nitrogen as the terminal electron acceptor. This process converts nitrate and ammonium to biologically unavailable nitrogen gas, stripping available nitrogen from pore waters of sediments and from the water column (Sowles, 2001) (Mayer et al., 1998). Enclosed shelf areas like the Gulf of Maine tend to have high rates of sedimentary denitrification, and sediments enriched in anaerobes would certainly contribute to this rate.

Redox oscillation and water circulation rate

The causes of changes in benthic community structure are difficult to quantify. However, one major influence may be oscillations in redox conditions when surface sediments are resuspended, exposing anoxic sediments to an oxygenated water column. Microbial communities create vertical zonations in sediment layers caused by the successive depletion of electron acceptors for respiratory metabolism. Oxygen is often depleted within a few millimeters below the sediment-water interface by both aerobic microbes, and by the limitations of oxygen diffusion from above. Beneath the oxic zone, anaerobic metabolism depends on electron acceptors such as NO_3^-, Mn^{4+}, Fe^{3+}, and SO_4^{2-}. However, some anaerobes prefer periodic exposure to low oxygen levels rather than absolute anoxia, which may explain the proliferation of anaerobes in post-trawl sediments (Fenchel, 2002).

A study by Aller (1994) suggests that remineralization processes and internal nutrient dynamics may be distinct in sediments undergoing periodic redox oscillation when compared with sediments under completely oxic or anoxic conditions. This study found that brief exposure to O_2 results in increased net NH_4^+ release and storage of NH_4^+ and PO_4^{3-} in readily exchangeable forms relative to continuously oxic conditions.

However, the relative frequency and duration of redox change governs the response of organic matter decomposition and nutrient release.

In addition to redox oscillations through the removal of surficial sediment, movement of the overlying water column in the wake of trawl doors may alter benthic community respiration. A study investigated the relationship between water circulation rate and benthic community respiration using *in situ* chambers with variable speed pumps over a broad range of sediment characteristics, from mud to sand (Boynton et al., 1981). Both aerobic respiration, representing 65-90% of total sediment oxygen demand, and chemical oxygen demand accounting for 10-35%, increased when the overlying waters were stirred at velocities up to 20 cm s^{-1}. When water velocities exceeded an erosion threshold, the scouring of sediments resulted in a pulsed oxygen demand. Half of this total sediment oxygen demand was attributed to the chemical oxidation of reduced substances diffusing through the sediment.

Since sediment resuspension is a common characteristic of shallow water environments, estimates of total sediment oxygen demand would include these pulses through disturbed sediments. However, in deep, low-energy environments less prone to suspension, or during summer months, when storm-induced suspension is less frequent, respiration rates are higher, and stratified water columns reduce oxygenated water concentrations below the pycnocline, enhanced demands on dissolved oxygen as a result of resuspension could deplete benthic zones of oxygen (Wainright and Hopkinson, 1997).

Conclusions

Bottom fishing gear acts as a disturbance to the seabed, but quantifying the implications of this disturbance on a scale encompassing the Gulf of Maine and surrounding New England marine environments remains a complex task. Examining the relative proportions of natural and fishing-induced disturbance in localized areas, however, is a reasonable way to assess changes in benthic and pelagic metabolism. Less than 12% of Jordan Basin, for example, is trawled every month according to estimates in figure 2, but even storm-driven currents and waves cannot rework the seabed of this basin. Bottom trawling, therefore, represents a true disturbance. In contrast, the northeast flank of Georges Bank may be trawled a total of 300% its area every month. However, frequent seabed reworking from tidal and storm-induced currents also represents a substantial year-round disturbance to the seabed, so bottom fishing may not put a relatively abundant quantity of sediment into suspension.

To further complicate the assessment, relative implications of sediment resuspension also depend upon the residence time of a turbid plume, and perhaps the sedimentary characteristics of the areas fished. Plumes generated in Jordan Basin would presumably settle far faster than those of Georges Bank due to the differences in hydrodynamics of the two areas. However, a plume in residence for twenty minutes in Jordan Basin may release more nutrients, trace metals, and organic matter into the water column than a plume in residence for three days on Georges Bank due to chemical sediment properties, and adjustment of a system to disturbance. Quantifying the overall effects of disturbance on benthic and pelagic metabolism, as well as implications for carbon budgets, is equally difficult.

The 1996 amendments to the Magnuson-Stevens Fishery Conservation and Management Act include an ecosystem-based approach to fishery management with provisions to protect “essential fish habitat” (EFH). The National Marine Fisheries Service (NMFS) interprets EFH to include the physical, chemical, and biological properties of water, as well as benthic sediment characteristics and substrate affected by mobile fishing gear. Since characteristics of both water column and bottom substrate are highly heterogeneous in the Gulf of Maine, perhaps fishery management plans could be adapted for different regions of the Gulf and its surrounding waters (Kurland, 1998).

These adaptive fishery management plans would require classifying sea floor types according to vulnerability to mobile fishing gear, implementing rotating closures of fishing grounds, and assessing effects of mobile gear over various spatial and temporal scales (Dorsey and Pederson, 1998). They may also require mobile gear designed specifically for the habitat fished. For example, designs have been proposed to raise a trawl 18-24 inches off the bottom, thereby avoiding contact with the seafloor and reducing turbulence in areas of fine sediment. In addition, lighter sweeps are proposed for scallop dredges to reduce the depth of disturbance depending on bottom substrate (Carr and Milliken 1998).

Inquiry on the effects of mobile fishing gear to the seafloor, engineering of trawls and dredges to reduce impact on the benthos, and improved understanding of the relative contributions of human impacts and natural disturbance are essential to future management of fisheries in and around the Gulf of Maine.

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