Resuspension of Sediment by Bottom Trawling in the Gulf of Maine and Potential Geochemical Consequences

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Abstract: *The benthic environment of the Gulf of Maine is characterized by a thick and basin-wide nepheloid layer, classically defined as a near-bottom region of permanent sediment resuspension. The high frequency of commercial bottom trawling in particular regions of the Gulf of Maine, documented by records compiled by the National Marine Fisheries Service, may strongly affect measured resuspension fluxes and contribute to the maintenance of the nepheloid layer. Indirect evidence of the effects of bottom trawling on sediment resuspension is observed in the seasonal collection of large, benthic infaunal worms, along with substantial amounts of resuspended bottom sediment, in a sediment trap deployed 25 m off the bottom in the western gulf region of Wilkinson Basin. These collections appear to be coincident with seasonal periods of intensive bottom trawling in this area. By comparison, the western gulf region of Jordan Basin is typified by significantly reduced annual bottom-trawling activity, and very few infaunal worms are found in the seasonal collections of a sediment trap located 25–30 m off the bottom. The extent to which trawling-induced bottom sediment excavation and resuspension occurs has important implications for regional nutrient budgets in terms of the input of sedimentary nitrogen and silica into the water column via this anthropogenic activity. Sediment mixing and frequent bottom disturbance from trawling activity may also produce changes in the successional organization of soft-sediment infaunal communities. The potential effects of trawling require serious examination and quantification to accurately determine the impact of such anthropogenic activity on the benthic ecosystems of continental margin environments.*

Resuspensión de Sedimentos por Arrastres de Fondo en el Golfo de Maine y sus Consecuencias Geoquímicas Potenciales

Resumen: *El ambiente bentónico del Golfo de Maine esta caracterizado por una capa gruesa y amplia de nefeloide, clásicamente definida como una región de resuspensión permanente de sedimentos cercana al fondo. La alta frecuencia de arrastres comerciales de fondo en regiones particulares del Golfo de Maine documentadas por datos compliados por el Servicio Nacional de Pesquerias Marinas, puede afectar drástricamente los flujos de resuspensión de sedimentos que contribuyen con el mantenimiento de la capa nefeloide. Evidencias indirectas de los efectos de arrastres de fondo en la suspensión de sedimentos se observan en la colecta de gusanos bénticos infaunales grandes, a lo largo de una cantidad sustancial de sedimento del fondo resuspendido en una trampa de sedimentos colocada a 25 m del fondo en la región oeste del golfo de la Cuenca Wilkinson. Estas colectas aparentemente coinciden con la temporada de intensa actividad de arrastres en la zona. Como comparación, la región Este de la Cuenca Jordan es tipificada por una reducción anual significativa de arrastres de fondo con muy pocos gusanos infaunales encontrados en las colectas estacionales de una trampa colocada a 25-30 m del fondo. La extensión de la excavación inducida por arrastres en el sedimento del fondo y la resuspensión tiene implicaciones importantes en la disponibilidad de nutrientes de la región en términos de la entrada de nitrógeno sedimentario y sílica a la columna de agua vía esta actividad antropogénica. Adicionalmente, la mezcla de sedimentos y la frecuente perturbación del fondo por ar-*

Paper submitted October 12, 1997; revised manuscript accepted July 7, 1998.

rastres puede producir cambios en la organización sucesional de las comunidades infaunales de sedimentos suaves. Los efectos potenciales del arrastre requieren de una examinación seria y su cuantificación para determinar con precisión el impacto de estas actividades antropogénicas en ecosistemas bénticos de ambientes continentales marginales.

Introduction

A number of studies conducted over the past 5–10 years have identified commercial bottom trawling on continental shelves as an important mechanism of sediment resuspension and have resulted in discussions of the potential effects of this activity on the marine environment (Churchill et al. 1988; Churchill 1989; Churchill et al. 1994; Auster et al. 1996; Dayton et al. 1995; and references therein). Of the variety of natural forces, such as bioturbation or sediment mixing by burrowing benthic organisms, waves and tidal currents, and iceberg scour, and anthropogenic forces, such as dredging, mining, fishing, and wetland filling, that are responsible for the physical disturbance of the benthos, the use of mobile fishing gear is unique in that it encompasses a broad region, often the entire continental shelf, and produces locally intense effects. In a recent analysis of the physical disturbance agents acting on the benthic habitats in the Gulf of Maine, a region with a highly active fishing industry, Watling and Norse (this issue) concluded that trawling activity represents the most intense (defined as force per unit area) mechanism of bottom disturbance. As an initial step in assessing the effects of trawling on the biogeochemistry and benthic biodiversity in the Gulf of Maine, it is important to examine the frequency of trawling and the extent of sediment resuspension in this particular area to determine if any cause-and-effect relationships exist.

Frequency of Bottom Trawling in the Gulf of Maine

In the Gulf of Maine, bottom-trawling intensity has been greater in the Georges Bank and western Wilkinson Basin regions of the gulf than in the eastern Jordan Basin area during the years 1990–1993, for which the most current, compiled trawling records are available from the National Marine Fisheries Service (NMFS, unpublished data). January through April are the predominant months of bottom-trawling activity, with substantial areas of the western gulf and the northern Georges Bank region completely trawled one to four times per year (Fig. 1). Percent area trawled was calculated as the ratio of area trawled to bottom area, using the total number of trawl days in a year within each square, as obtained from monthly NMFS records, and realistic estimates of trawl speed (5.5 km/hour) and width of trawl track (40 m, equal to distance between the two trawl doors that effectively hold the trawl net open and represent the mouth of the net; Churchill 1989). It is clear from the 1993 map that trawling activity is not evenly distributed throughout the gulf; intensely trawled squares are adjacent to squares that experience a minimal amount of trawling.

Sediment Resuspension in the Gulf of Maine and Evidence of Trawling Impacts

There is a pervasive bottom nepheloid layer in the Gulf of Maine and, in particular, within the deep offshore basins (Spinrad & Zaneveld 1982; Spinrad 1986; Townsend et al. 1992). Water-column turbidity profiles obtained from Sea Tech transmissometers (25-cm path length; 660-nanometers wavelength) and reported as percent light transmission or beam attenuation due to particles (c_p) show seasonally persistent bottom nepheloid layers extending tens of meters above the bottom in both Wilkinson and Jordan Basins (Fig. 2). The increase of c_p values by two- to four-fold below 190–200 m is evidence of strong bottom nepheloid layers of 20–40 m thickness in both basins (Fig. 2). Suspended particle mass (SPM) values compiled in 1995–1996 associated with these nepheloid layers ranged from 2–4 mg/L in Jordan Basin and 2–8 mg/L in Wilkinson Basin (C.H.P., unpublished data). Separately obtained mineralogic and textural data from Jordan Basin indicate that the nepheloid layer in this basin may be maintained and fed primarily by substantial sediment influx from the Bay of Fundy region. Specifically, new data support the probable transport of kaolinite-rich mud to Jordan Basin by strong tidal currents in excess of 50 cm/second measured near the northern edge of Jordan Basin and the mouth of the Bay of Fundy (Moody et al. 1984; C.H.P., unpublished data).

Because we know that bottom trawling occurs in the gulf basins, and it appears to be particularly intense in the case of Wilkinson Basin (e.g., Fig. 1), the question arises as to what extent this activity affects or augments the height and suspended particle mass of the basin nepheloid layers. Preliminary evidence from time-series sediment traps deployed in Wilkinson and Jordan Basins suggests that bottom trawling may contribute substantially to sediment resuspension in the near-bottom water column of the Gulf of Maine (Fig. 1). Biweekly trap samples collected during March-December 1995 at 250 m

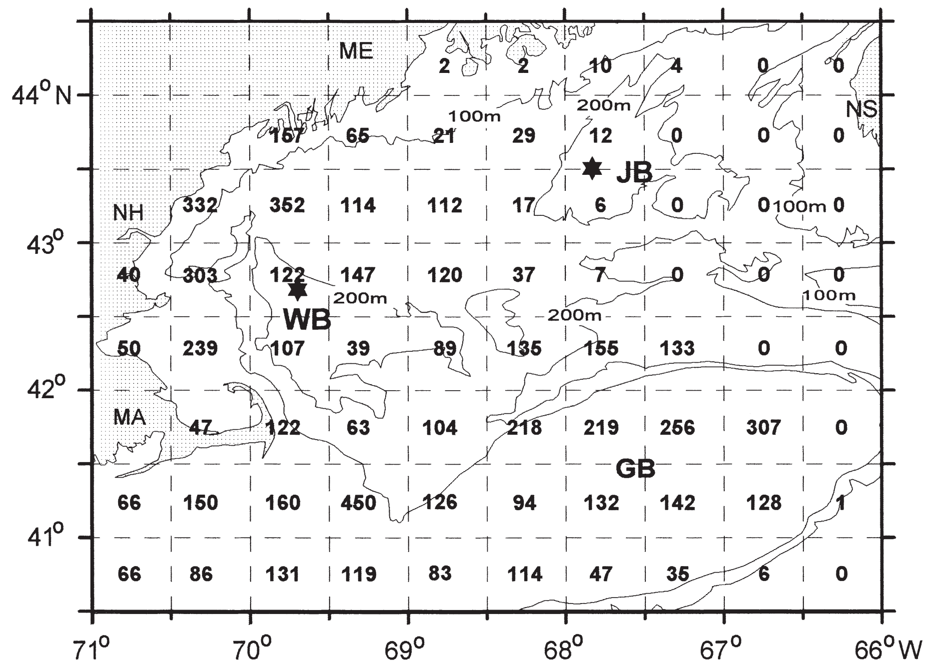

Figure 1. Monthly bottom trawling activity in the Gulf of Maine for 1993 (the most recent year for which such data were available) given as percent area trawled of each dotted line square, with each square representing 810 nm² (zeros indicate Canadian regions for which no National Marine Fisheries Service bottom trawling data were available and areas closed to trawling on the eastern edge of Georges Bank, GB). Stars are locations of time-series sediment trap moorings deployed in Wilkinson Basin (WB in the western gulf) and Jordan Basin (JB in the eastern gulf), 1995–1997. The trap systems were deployed to quantify biogeochemical particulate fluxes and regeneration within the Gulf of Maine offshore water column and to determine the impact of sediment resuspension on these processes (C.H.P., unpublished data).

(25–35 m above the bottom in each basin) contained large (3.5–14.0 cm in length) polychaete worms, which are infaunal organisms that live in the sediment (Fig. 3). These post-larval adult cirratulid and arabellid worms occur in appreciable numbers in the Wilkinson Basin 250-m trap samples, especially during the early part of the year, and are absent or present only in very low numbers in the 250-m Jordan Basin trap samples. The fact that the trap-collected polychaetes are benthic, infaunal worms for which there is no documentation of swimming activity far above the sediment-water interface suggests that they may be artificially resuspended by the bottom excavation action of mobile fishing gear. Either the worms are immediately resuspended from the sea floor into the resuspension plume created as the trawl net is dragged along the bottom, or they are discharged as the net is brought to the surface near the trap site.

If this anthropogenic mechanism of sediment excavation is responsible for resuspending large benthic worms tens of meters up into the water column, it is not surprising that the number of worms trapped in Wilkinson Basin is much greater than that in Jordan Basin, considering the substantially higher levels of bottom trawling activity in Wilkinson. Comparison of the 1995 biweekly trap-collected polychaete numbers (Fig. 3) to the 1993 month-to-month bottom trawling activity within the 810-nm² (nm, nautical miles) block area in Fig. 1 (where the Wilkinson basin trap mooring site was located) reveals some temporal similarities (Fig. 4). Both data sets display major peaks in the spring and less pronounced peaks in the summer, with the fall trap samples not showing a collection of infaunal worms coincident with the enhanced September-October trawling activity in this region (Figs. 3 & 4). This observation may be a reflection of the seasonal polychaete worm abundance in the bottom sediments for which no data presently exist. Although the two data sets presented in Figs. 3 and 4 were not collected in the same year, the seasonal trend may be representative, and a comparison of the trapped worm counts relative to the 1995 monthly bottom trawling activity in the western gulf will be completed as soon as such data are made available by the NMFS.

Seasonal fluxes to the 250-m Wilkinson Basin sediment trap in 1995 of lithogenic material (primarily clay sediment) measured in milligrams per square meter per day, reveal peaks in March and April and a broad peak from June to October (C.H.P., unpublished data). Because the sediment trap was deployed in the nepheloid layer of the basin, it would be expected to collect fine resuspended mud throughout the year, with the likelihood that enhanced fluxes might occur during periods of intensive bottom trawling in the region. For several

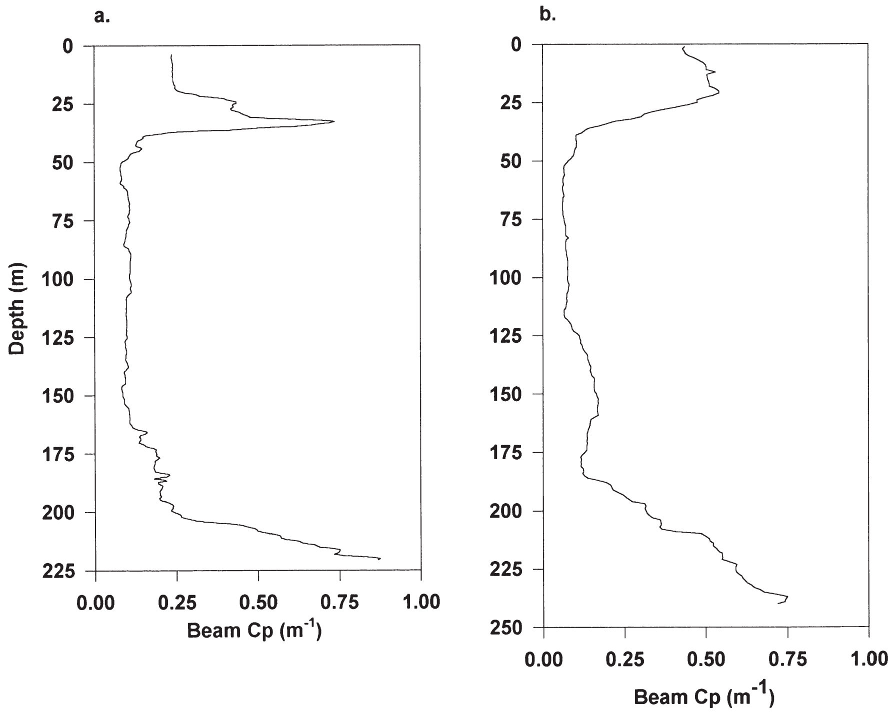

Figure 2. Particle attenuation (c_p) profiles showing bottom nepheloid layers in Wilkinson Basin in August 1995 (a) and Jordan Basin in September 1995 (b) obtained from transmissometer casts (c_p = total light attenuation minus attenuation due to water and dissolved organic matter).

reasons, the temporal collection of large infaunal worms in the traps displaying collection peaks that are basically coincident with peak seasonal periods of bottom trawling activity is more noteworthy as an indirect indicator of trawling effects on sediment excavation and resuspension than of general trends in lithogenic material collection by the trap. First, fine sediment plumes created by bottom trawling are laterally advected some distance by tidal currents before settling because such plumes consist primarily of micron-sized clay particles with negligible sinking velocities (Churchill et al. 1988; Churchill 1989). Second, if one considers the infaunal worms as large particles with measured sinking rates of 1–5 cm/second (C.H.P., unpublished data), the probability that they will settle rapidly within the area where they were resuspended is substantially higher than that of the clay particles that are resuspended at the same time. Thus we might expect to see a stronger temporal relationship between the trap collection of the fast-sinking worms than the very slowly settling clays, if we assume that the worms were resuspended by trawling activity in close proximity to the sediment trap.

Biogeochemical Implications of Trawling-Induced Benthic Habitat Excavation and Sediment Resuspension

Trawler-induced resuspension has important implications for nutrient cycling in bottom-trawled areas. Continental shelf environments in which trawling activity is concentrated typically receive about half their nutrients for primary production from the sediment. This nutrient input is derived from organic matter decay and nutrient remineralization within sediments, followed by upward physical transport driven by processes such as molecular diffusion and biological irrigation.

Trawling can be expected to affect sedimentary organic matter decay and nutrient fluxes or budgets in several ways. One effect will be burial of fresh, labile organic matter into subsurface horizons from its normal position at the sediment-water interface (Mayer et al. 1991). This burial could shift organic matter decay from aerobic, eukaryotic populations at the sediment-water interface toward anaerobic, prokaryotic metabolism in the subsurface. It follows that the reverse situation would also occur: deeper, anaerobic sediment would be exposed to aerobic conditions via trawling-induced sediment mixing. The degree to which anaerobic versus aerobic sediments, and their organic matter remineralizing populations, are affected by bottom trawling will depend upon the depth and thickness of the sedimentary reduction-oxidation zones and to what depth within the sediments trawling-induced mixing occurs.

A second effect of bottom trawling on sedimentary nutrient budgets is a simple physical enhancement of upward flux of remineralized (dissolved) nutrients already in the interstitial pore waters of the sediments; hence, nutrients will be delivered to the water column in a large pulse rather than by the usual slower and more steady mechanisms. The magnitude of this pulse can be

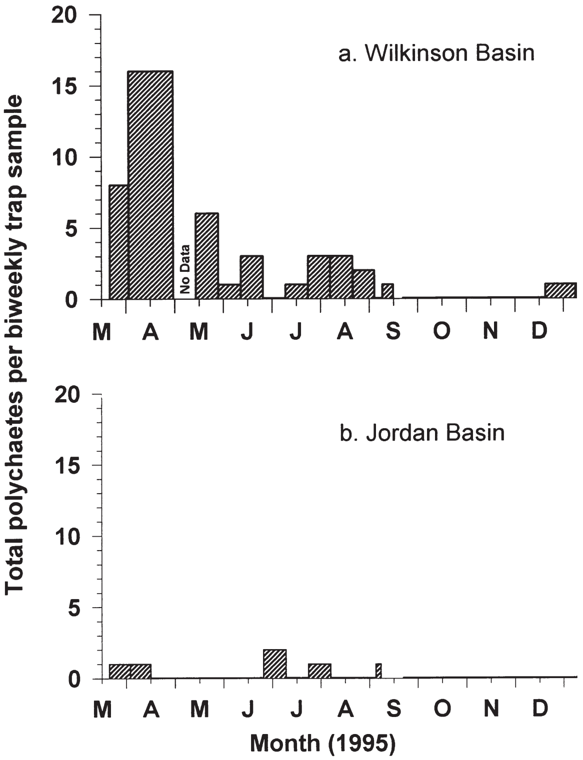

Figure 3. Number of benthic polychaete worms collected in Gulf of Maine sediment traps deployed at 250 m in Wilkinson Basin (a) and Jordan Basin (b). Each vertical bar represents the total benthic infaunal worm count in one 2-week trap sample.

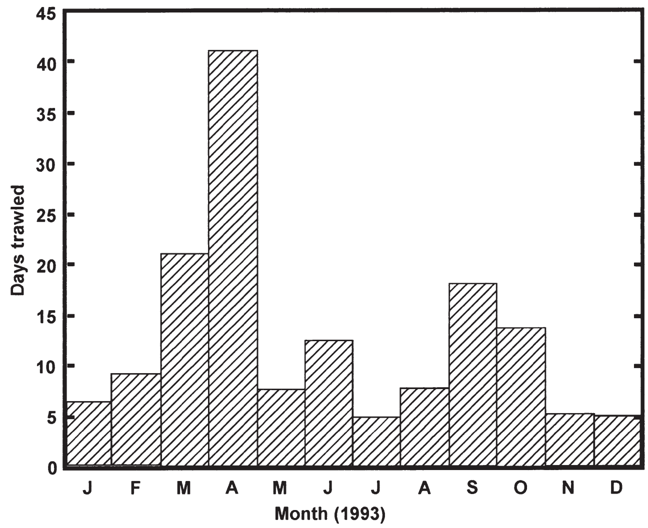

Figure 4. Number of bottom trawl days per month occurring in 1993 within the 810-nm^2 dashed line block containing the 1995 Wilkinson Basin sediment trap mooring shown in Fig. 1 (National Marine Fisheries Service, unpublished data).

gauged by the calculations of Fanning et al. (1982) on storm resuspension: they estimated that resuspension of only 1 mm of sediment could double or triple the nutrient flux into the photic zone. This pulse can have important implications for the type and rates of primary production. For example, seasonal changes in nutrient inputs to temperate coastal systems tend to shift phytoplankton populations from a late fall-winter picoplankton population to a spring-summer diatom-dominated community, resulting in an overall increase in primary productivity and organic carbon export rates (Chavez 1996; Pilskaln et al. 1996). Because bottom trawling tends to be concentrated during the high-productivity spring and summer months in temperate coastal environments, it would be difficult in the field to distinguish between the effects on phytoplankton production and community structure of trawling-induced nutrient input versus that due to upwelling or thermocline mixing. Quantifying these effects, however, might be well-suited to a laboratory mesocosm experiment in which factors such as sediment and water-column mixing rates and nutrient levels could be controlled and manipulated with a systematic monitoring of changes in phytoplankton community composition and production levels.

A third impact on sedimentary nutrient fluxes involves a change in infaunal benthic metabolism that results from trawling. Sedimentary environments are spatially organized into successions of metazoan and prokaryotic communities in complicated geometries. The geometric arrangements of these successions can have a strong influence on the rates and pathways of nutrient regeneration. Aller (1982, 1988) has demonstrated that the density and size of animal burrows in sediments can substantially affect both the direction and magnitude of nitrogen flux across the sediment-water interface. The effects are strongly influenced by the relative roles of nitrification and denitrification, which vary with changes in burrow spacing or abundance and burrow size. An example of this from Aller (1988) is that NO_3^- fluxes out of the sediment appear to increase substantially with increasing burrow wall thickness, defined as burrow abundance divided by burrow radius. Bottom trawling may produce a significant change in burrow spacing and geometry, with the replacement of late-stage successional assemblages of polychaetes (fewer and larger burrows) by more-opportunistic assemblages (more numerous but smaller burrows), and thus may result in an increase in the ratio above and a net increase in nitrate fluxes out of the sediments.

Another example of how bottom trawling may alter the structure and function of the remineralizing community within the sediments concerns the role of denitrifying bacteria. Denitrification converts remineralized nitrogen derived from the decay of organic matter (e.g., NH_4^+ and NO_3^-) into N_2 gas, which is then unavailable for further participation in primary production. In sediments, denitrification typically removes several tens of percentages of regenerated nitrogen before its return to the water column (Seitzinger 1988). The bacteria responsible for denitrification require the low oxygen conditions found in sediments. Trawling resuspension will introduce both regenerated ammonium and its nitrified product, nitrate, into the well-oxygenated water column, where it is not subject to bacterial denitrification and hence will be more available to the aerobic ecosystem.

A preliminary calculation for the Gulf of Maine of the amount of sediment and contained water volume that are annually excavated by bottom trawling (C.H.P., unpublished data) indicates that these amounts are 9.08 kg/m^{-2} of sediment and 6.14×10^9 m^3 of interstitial pore water. The calculation uses a 1990–1993 average from the NMFS of the percentage of the total gulf area that is trawled annually, a conservative value of 5 cm as the depth of excavation into the bottom by the trawl gear (Churchill 1989), and sediment porosity data from Christensen et al. (1987). Applying previously published values for the average integrated concentration of ammonium within the upper 5 cm of Gulf of Maine sediments (Christensen 1989), it is estimated that the annual release into the overlying water column of nitrogen as ammonium from sediments, via bottom trawling activity, is equal to 306×10^6 μm N. Measured summer concentrations of NH_4^+ in the water column of the Gulf of Maine range from 1.0 μM in the upper water column nutrient maximum to 0.1 μM in the intermediate and deep waters of the gulf (Townsend & Christensen 1986; Townsend, unpublished data). Considering these concentrations, an input of ammonium by trawling-induced sediment excavation might represent an unrecognized but important factor in the annual nitrogen budget, possibly helping to fuel bacterial nitrification of NH_4^+ (and thus the production of nitrite) within the water column (Ward et al. 1989). Similarly, trawling activity may be important in supplying significant inputs of silica (as dissolved silicate) to the overlying water column from the underlying sediments, especially in the highly trawled western gulf region where elevated silicate concentrations cannot be completely accounted for by river input (Donoghue 1993). Annual gulf-wide nutrient budgets for nitrogen and silica are now being determined, and nutrient input calculations based on trawling activity will certainly be examined within the context of these budgets.

The net changes in nutrient regeneration described above can lead to desirable or undesirable ecosystem impacts. Biasing phytoplankton populations toward diatoms with an increase in nitrate fluxes to the water column may be beneficial for fisheries, whereas changing nutrient ratios has the potential to stimulate noxious phytoplankton. It is difficult to predict both the direction and magnitude of these changes at this time, but it is clear that study of their nature and consequent effects on water column processes should be an important part of research on the effects of trawling.

Acknowledgments

We thank C. Lehmann, W. Arnold, and P. Brickley for assistance in collecting the sediment trap and transmissometer data, and the National Marine Fisheries Service in Woods Hole, Massachusetts, for providing statistics on commercial bottom trawling for the Gulf of Maine. Recent results presented here were supported by National Oceanic and Atmospheric Administration Regional Marine Research Program grant award NA46RM0451 to C.H.P. This paper is MCBI contribution 18.

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