2006 outfall benthic monitoring report

Massachusetts Water Resources Authority

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2006 Outfall Benthic Monitoring Report

Submitted to

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EXECUTIVE SUMMARY

The benthic surveys discussed in this report began in 1992 as part of the Benthic (Sea-Floor) Monitoring component of the MWRA Harbor and Outfall Monitoring (HOM) program. The benthic program has four major components, including the annual late-summer measurement of

- geochemical properties, contaminants, and sewage tracers in sediments
- the apparent redox potential layer in sediment profile images (SPI) taken in the nearfield
- benthic infaunal (soft-bottom) community structure
- hard-bottom community structure

In 2003, the MWRA received permission from the USEPA to modify the benthic sampling, including reduction in the number of stations sampled each year, as well as a reduction in the sediment chemistry parameters measured at each station. The nearfield and farfield stations were randomly binned into two subsets, to be sampled in alternate years. In August 2006, all of the SPI and hard-bottom stations were visited, whereas the soft-bottom benthos and sediment geochemical parameters were sampled at roughly half the number of stations that had been evaluated annually through 2003.

Contingency Plan Thresholds

The offshore outfall is regulated under a permit issued to MWRA by the United States Environmental Protection Agency (USEPA) and Massachusetts Department of Environmental Protection (DEP), under the National Pollutant Discharge Elimination System (NPDES). The permit stipulates that MWRA must monitor the outfall effluent and the ambient receiving waters to test for compliance with NPDES permit requirements; specifically, whether the impact of the discharge on the environment is within the bounds predicted by the SEIS (USEPA 1988), and whether any changes within the system exceed any of the Contingency Plan thresholds, including those for sediment redox depth, toxic contaminant concentrations, community structure, or abundance of opportunistic species (MWRA 2001).

The Contingency Plan (MWRA 2001) is an attachment to the MWRA's Discharge Permit. Warning level thresholds listed in the plan are based on effluent limits, observations from baseline monitoring, national water quality criteria, state standards, and, in some cases, best professional judgment. Contingency plan threshold values (Table 1) for benthic monitoring were originally based on averages calculated for the period 1992 through 2000, *i.e.*, from the beginning of the monitoring program through September 2000, when diversion of highly treated effluent to the new outfall was initiated. Benthic community thresholds were adjusted to reflect the stations sampled in alternate years (Williams *et al.* 2005). No thresholds were exceeded in 2005.

Monitoring Questions

The benthic monitoring program was designed to address a series of questions (MWRA 2001) regarding sediment contamination and tracers, and the benthic communities:

- *What is the level of sewage contamination and its spatial distribution in Massachusetts and Cape Cod Bays sediments before discharge through the new outfall?*
- *Has the level of sewage contamination or its spatial distribution in Massachusetts and Cape Cod Bays sediments changed after discharge through the new outfall?*
- *Have the concentrations of contaminants in sediments changed?*
- *Have the sediments become more anoxic; that is, has the thickness of the sediment oxic layer decreased?*
- *Has the soft-bottom community changed?*
- *Are any benthic community changes correlated with changes in levels of toxic contaminants (or sewage tracers) in sediments?*
- *Has the hard-bottom community changed?*

Table 1. Contingency plan thresholds established by MWRA for monitoring potential impacts of the offshore outfall. Benthic thresholds adjusted for stations collected in even- and odd-numbered years (Williams *et al.* 2005).

Location	Parameter	Caution Level	Warning Level
Sediment toxic contaminants, nearfield	Acenaphthene	None	500 ppb dry
	Acenaphylene	None	640 ppb dry
	Anthracene	None	1100 ppb dry
	Benz(a)pyrene	None	1600 ppb dry
	Benzo(a)pyrene	None	1600 ppb dry
	Cadmium	None	9.6 ppm dry
	Chromium	None	370 ppm dry
	Chrysene	None	2800 ppb dry
	Copper	None	270 ppm dry
	Dibenzo(a,h)anthracene	None	260 ppb dry
	Fluoranthene	None	5100 ppb dry
	Fluorene	None	540 ppb dry
	Lead	None	218 ppm dry
	Mercury	None	0.71 ppm dry
	Naphthalene	None	2100 ppb dry
	Nickel	None	51.6 ppb dry
	p,p'-DDE	None	27 ppm dry
	Phenanthrene	None	1500 ppb dry
	Pyrene	None	2600 ppb dry
	Silver	None	3.7 ppm dry
	Total DDTs	None	46.1 ppb dry
	Total HMWPAH	None	9600 ppb dry
	Total LMWPAH	None	3160 ppb dry
	Total PAH	None	44792 ppb dry
	Total PCBs	None	180 ppb dry
	Zinc	None	410 ppm dry
Sediments, nearfield	RPD depth	1.18 cm	None
Even Years Benthic diversity, nearfield	Species per sample	<48.41 or >82.00	None
	Fisher's log-series *alpha*	<9.99 or >16.47	None
	Shannon diversity	<3.37 or >4.14	None
	Pielou's evenness	<0.58 or >0.68	None
Odd Years Benthic diversity, nearfield	Species per sample	<46.52 or >79.95	None
	Fisher's log-series *alpha*	<9.95 or >15.17	None
	Shannon diversity	<3.30 or >3.91	None
	Pielou's evenness	<0.56 or >0.66	None
All Years Species composition, nearfield	Percent opportunists	10%	25%

Sediment Geochemistry and Sewage Tracer

- ♦ *What is the level of sewage contamination and its spatial distribution in Massachusetts and Cape Cod Bays sediments before discharge through the new outfall?*
- ♦ *Has the level of sewage contamination or its spatial distribution in Massachusetts and Cape Cod Bays sediments changed after discharge through the new outfall?*

Abundances of the sewage tracer *Clostridium perfringens* measured in surface sediments throughout Massachusetts and Cape Cod Bays have ranged from undetected to 24,100 colony forming units per grams dry weight (cfu/g dry) (Figure 1). In general, *Clostridium* abundances were low throughout the bay, with slightly higher levels observed closer to Boston Harbor. Abundances generally decreased with distance from the harbor, with farfield sediments located far away from Boston Harbor (>20 km) having the lowest *C. perfringens* abundances.

Following diversion of effluent discharge to the new outfall in September 2000, *C. perfringens* abundances were within the general range of samples collected during the baseline period (Figure 1, left), although annual mean abundances (normalized to percent fines) decreased in the late 1990s while treatment upgrades were implemented (Figure 1, right). A localized increase in abundances of *C. perfringens* (normalized to percent fines) was apparent in the nearfield the first five years following effluent diversion compared to 2000 pre-diversion values (Figure 1, right). Abundances decreased sharply in 2006, however, and returned to 2000 pre-diversion values. The 2006 decrease could reflect that a cleaner effluent is being discharged, or perhaps physical processes such as bioturbation or sediment layering are diluting the abundances of *C. perfringens* by mixing the surface sediments with deeper, clean sediments.

The post-diversion mean abundances of *C. perfringens* decreased significantly (at the 95% confidence level) compared to the baseline means in the transition area (*i.e.,* between the mouth of Boston Harbor and the outfall) and the farfield.

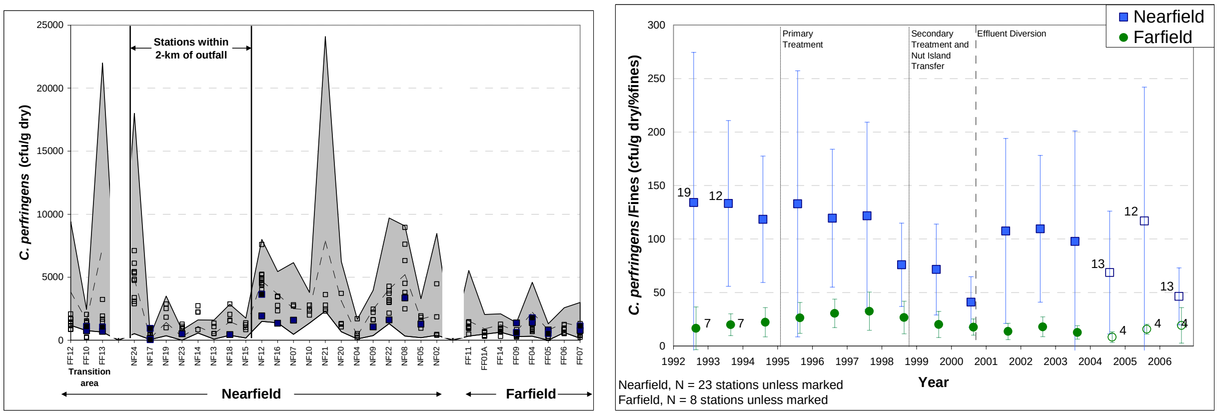

Figure 1. Abundances of *Clostridium perfringens* (left) in nearfield and farfield sediments during baseline (1992–2000 range of values, gray band) and post-diversion (□ 2001-2005 and the ■ 2006) periods. (The baseline mean values are indicated by a dashed line within the gray band.) Yearly mean abundance of *Clostridium perfringens* (normalized to percent fines, right) in nearfield and farfield sediments, 1992–2006 (open symbols represent years under the revised monitoring program and the number (N) of stations sampled is indicated).

Sediment Contaminants

- ♦ *Have the concentrations of contaminants in sediments changed?*

The long-term monitoring data from 1992 to 2006 show that concentrations of anthropogenic contaminants in surface sediments at nearfield and farfield regions of Massachusetts and Cape Cod Bays are spatially and temporally variable and reflect differences in bulk sediment characteristics such as grain-size distributions and TOC content rather than an outfall impact. For example, storm-induced impacts to the sediment bed following the May 2005 nor'easters likely contributed to a coarsening of grain size and a corresponding decrease in 2005 in concentrations of aluminum, chromium, iron, and nickel, which are primarily crustal in nature (distribution of nickel concentrations at the nearfield from 1992 to 2006 is shown in Figure 2, left).

Post-diversion mean concentrations of total DDT, total PCB, cadmium, and nickel decreased significantly (at the 95% level of confidence) at farfield regions of the Massachusetts and Cape Cod Bays compared to the baseline. Post-diversion mean concentrations of total DDT also decreased significantly at nearfield stations located within 2 km of the outfall (Figure 2, right) and cadmium decreased significantly at the transition area between Boston Harbor and the outfall. Decreases in total DDT and total PCB may be associated with the banning of these chemicals in the 1970s and 1980s. Overall, sediment data to date indicate that post-diversion (2001–2006) concentrations of most anthropogenic contaminants have not changed substantively compared to the baseline (1992–2000).

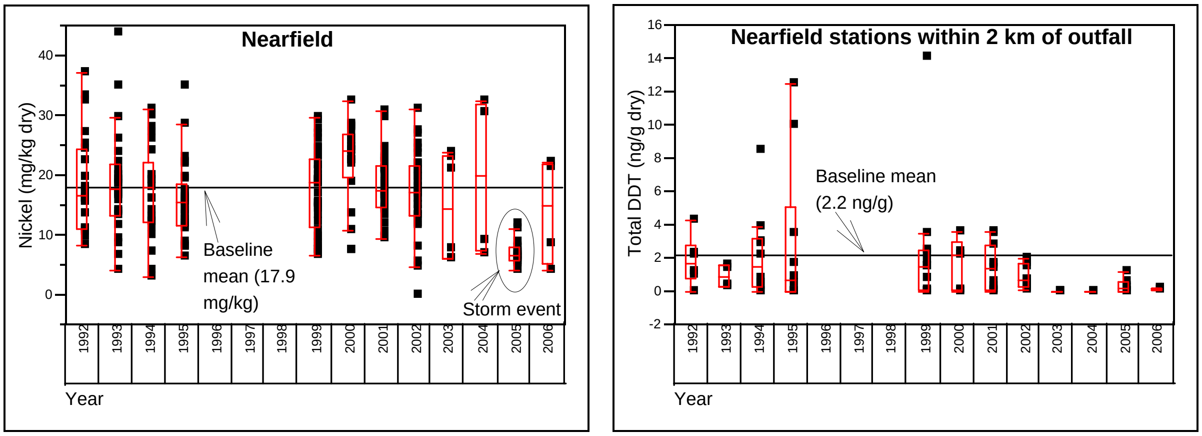

Figure 2. Distribution of nickel (left) and total DDT (right) concentrations in the nearfield from 1992 to 2006. The ends of the box represent the 25th and 75th quartiles, the line across the middle represents the median value, and the reference line represents the baseline mean. The lines are "whiskers" that extend from the ends of the box to the outermost data point that falls within the distances computed (a distance of 1.5 times the interquartile range, difference between 25th and 75th quartiles). Data points above or below the whiskers represent possible outliers.

Sediment Redox Potential Layer

- ♦ *Have the sediments become more anoxic; that is, has the thickness of the sediment oxic layer decreased?*

The general pattern in RPD layer depths in 2006 was similar to both the baseline and previous post-diversion years (Figure 3). In 2006, the average apparent color RPD layer depth ranged from >1.1 cm to 5.3 cm, with a grand mean of 3.0 cm (SD = 1.09 cm) (Figure 4). Statistical analysis determined that there was a significant increase in the depth of the apparent color RPD layer depth between baseline years and 2006. The difference between 2006 and the baseline was a deepening of the RPD by an average of 0.7 cm or 32%. When the six baseline years were compared to the six discharge years, the discharge years had significantly deeper RPD layers. If the same analysis is restricted to the nine stations with only measured RPD layers (Figure 3) for all 12 years of data, the post-diversion years have even deeper RPD layers.

For assessing outfall effects, the MWRA (1997) set a 50% reduction in the apparent color RPD layer depth over the study area as a critical trigger level. Similarly, a 50% increase in apparent color RPD over the baseline would be noteworthy. The fact that in 2006 the RPD was deeper than baseline would indicate that the RPD threshold was not exceeded. The average RPD for 2006 was at the high end of the range of annual RPDs, with 1998 being the shallowest year at 1.6 cm and 1995 the deepest year, also at 3.0 cm (Figure 4).

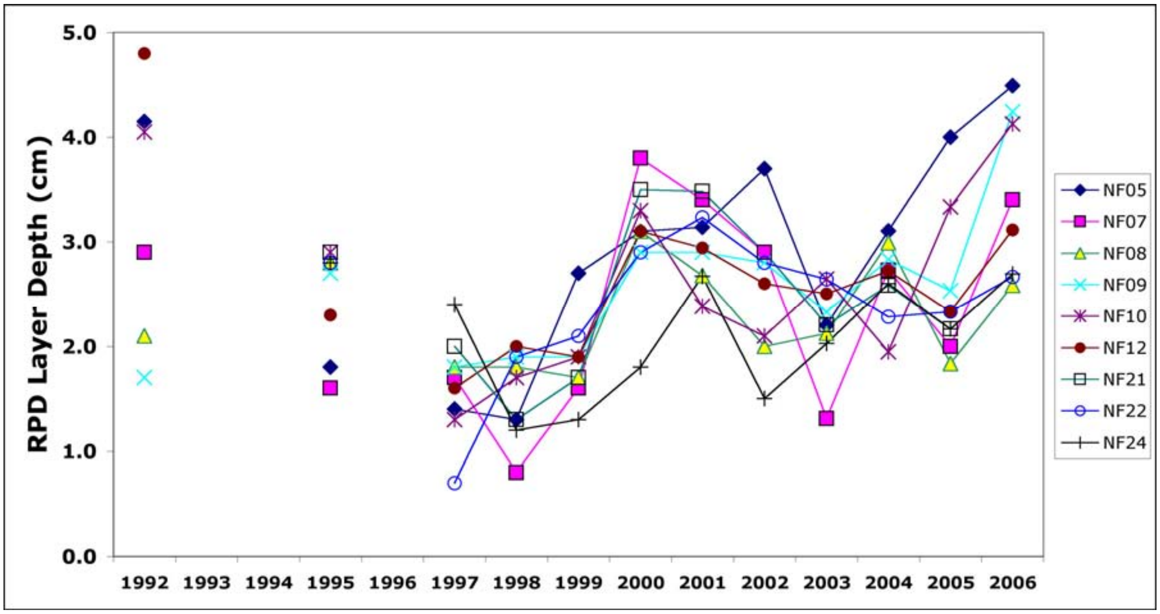

Figure 3. Apparent color RPD layer depth (cm) for the nine nearfield stations that had measured values for all years.

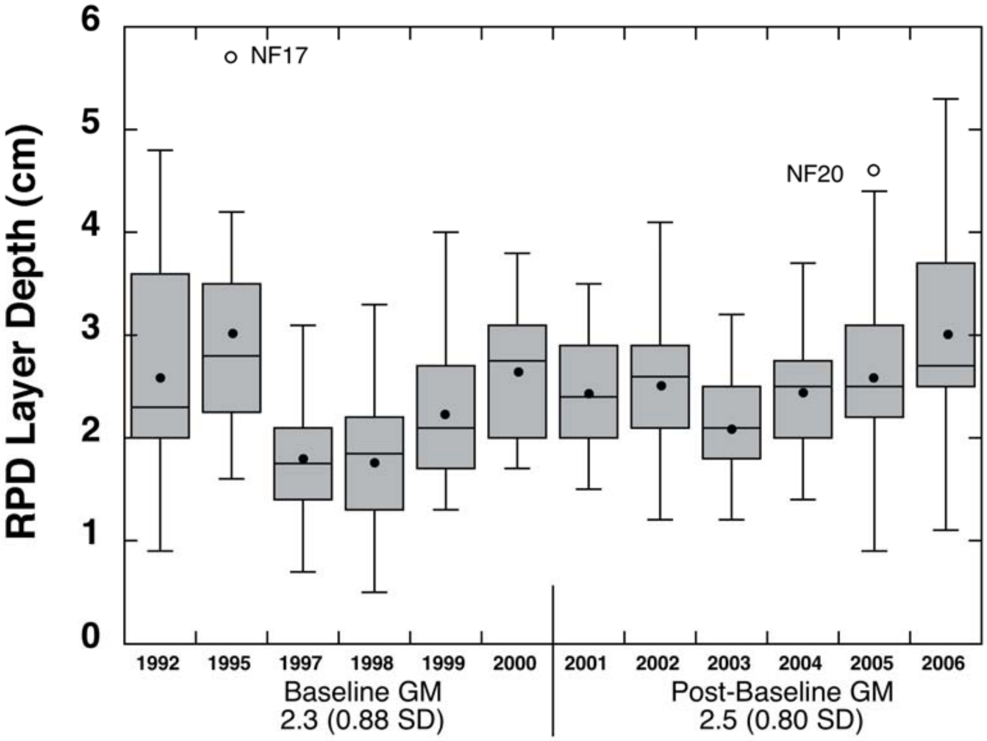

Figure 4. Apparent color RPD layer depth (cm) summarized by year for all data from nearfield stations. Box is interquartile range (IR), bar is median, circle is mean, and whiskers are data range. Outliers are >(2*IR).

Soft-Bottom Benthic Infaunal Communities

♦ *Has the soft-bottom community changed?*

There have been clear temporal changes in the soft-bottom benthic infaunal community over the time period of the monitoring program, including changes in total infaunal density, species composition and richness, and, to a lesser extent, diversity. Annual fluctuations in the population densities of several species and the occasional scouring of the bottom by storms both contribute to the overall invertebrate densities recorded from the benthic grab samples. The high variability at some stations, which contrasts with the stability of other stations over time, suggests that several processes, biological as well as physical, operate in this system.

The highest mean infaunal density per nearfield sample was recorded in 2002, when it was roughly 60% higher than abundances recorded in the early years of the program. Since then, mean abundance has declined every year, and the 2006 mean was the second lowest recorded in the program, with only 1993 being slightly lower. In 2006, all three diversity measures—Shannon H, Pielou's evenness, and log-series *alpha*—indicated a small, insignificant increase in diversity compared with 2005 results, but a decline compared with the 2004 values for this subset of stations.

The dominant species at the nearfield stations have been consistent over the past several years, although changes in their absolute numbers, and numerical rank in the samples, have changed from year to year. The spionid polychaete *Prionospio steenstrupi* has been the numerical dominant in Massachusetts Bay for the past several years, and is a numerical dominant in all sediment types, which range from 5 to 70 % fines, found at the nearfield stations. In spite of reduced densities beginning in 2004 (Figure 5), in 2006, *P. steenstrupi* accounted for 27 percent of all infaunal organisms collected and was the numerical dominant at eight of the 11 nearfield stations, where it accounted for 15–53 percent of the organisms in a sample. Other polychaete species, including *Levinsenia gracilis*, *Mediomastus californiensis*, and *Ninoe nigripes*, often co-occur with *P. steenstrupi* as numerical dominants at the majority of nearfield stations.

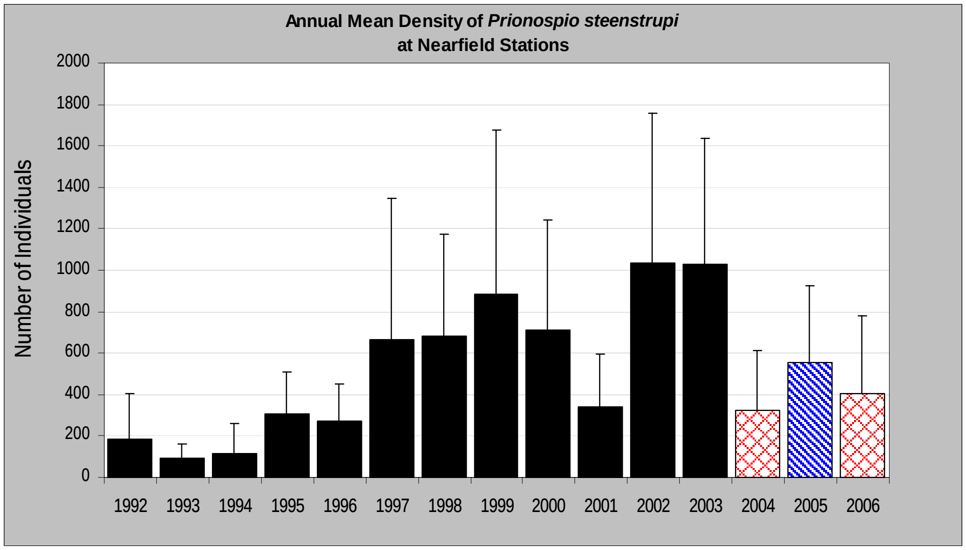

Figure 5. Annual mean density of P*rionospio steenstrupi* at nearfield stations. Two subsets of stations were sampled, one in 2005 and the other in 2004/2006.

A different suite of species is found at the coarse-grained stations, where percent fines are only 2–8% of the sediments. At those stations, the bivalves *Ensis directus* and *Cerastoderma pinnulatum*, the ascidian *Molgula manhattensis*, amphipods such as *Crassicorophium crassicorne*, and the sand dollar *Echinarachnius parma* are the dominant species. These sandy communities have also been consistent throughout the course of the monitoring program.

The larger patterns elucidated over time for the Massachusetts Bay stations have remained stable throughout the program. In similarity tests, the farfield stations have always differed from the nearfield, *e.g.*, the Cape Cod Bay stations comprise a suite of species that gives them a unique signature. Nearfield stations FF10, FF12, and FF13 can be distinguished from the remaining nearfield stations, reflecting the transitional sediment texture at those stations; similarly, the nearfield sandy stations can be distinguished from nearfield fine-grained stations. These patterns have held whether the entire station set is sampled, or whether the even-year (2004 and 2006) or odd-year (2005) subsets are considered.

- ♦ *Are any benthic community changes correlated with changes in levels of toxic contaminants (or sewage tracers) in sediments?*

Detailed investigation of individual stations has not suggested any localized outfall impact, even at stations within 2 km of the outfall, where, in previous years, elevated levels of the sewage tracer *Clostridium perfringens* suggested a modest impact of the discharge. None of the changes that have been documented in the benthic infaunal communities, either for individual species or for calculated parameters, appear to be related to the operation of the outfall.

Hard-Bottom Benthic Communities

- ♦ *Has the hard-bottom community changed?*

The hard-bottom benthic communities near the outfall remained relatively stable over the baseline period, and have not changed substantially with activation of the outfall in September 2000. Major departures from baseline conditions have not occurred during the post-diversion years; however, some modest changes have been observed, including a decrease in the number of upright algae at some stations and increases in sediment drape and a decrease in percent cover of coralline algae at several sites on the top of the drumlin north of the outfall and at the two northernmost reference sites.

It is unlikely that the decrease in upright algae is attributable to diversion of the outfall, since abundances of upright algae were found to be quite variable throughout the baseline period, reflecting temporal as well as spatial heterogeneity. The decline, which started in the late 1990s and now appears to be reversing at a number of stations, has been quite pronounced at the northern reference stations and may, in part, reflect an increase in anchoring frequency of LNG tankers at these locations after September 11, 2001. Evidence of substantial disturbance to the seafloor, such as turned over boulders and a large area of shell lag, was observed this year at northern reference site T7-2 (Figure 6).

The decrease in percent cover of coralline algae has been noticeable in all six post-diversion years, especially in 2005, when it extended to eight additional stations located both north and south of the outfall. Mechanisms relating the decrease in coralline algae to outfall diversion are not clear, since the impact was noted further from the outfall rather than nearby. It is possible that some of the decreases noted at the northern reference stations are related to the increased anchoring activity at these stations, and that the decreases closer to the outfall are related to the diversion. However, it is also possible that we are observing long-term changes in sedimentation patterns and hence in coralline algae.

The outfall might be expected to alter the amount of particulate material reaching the seafloor, possibly accounting for the increase in sediment drape. A continued increase of sediment drape, and/or a continued decrease in the percent cover of coralline algae might be expected if the discharge from the outfall were causing accumulation of materials in the vicinity of the drumlins. Changes might also be expected in the depth distribution of coralline algae and upright algae if discharges from the outfall alter those properties of the water column that affect light penetration. If water clarity is reduced, it is expected that the lower depth limit of both coralline and upright algae would be reduced. Conversely, if water clarity were increased, then it is expected that high coralline algal coverage or upright algae could extend into some of the deeper areas. However, no noticeable changes in the depth distribution of coralline algae have been observed since discharge began and the decline of upright algae observed in recent years appears to be reversing.

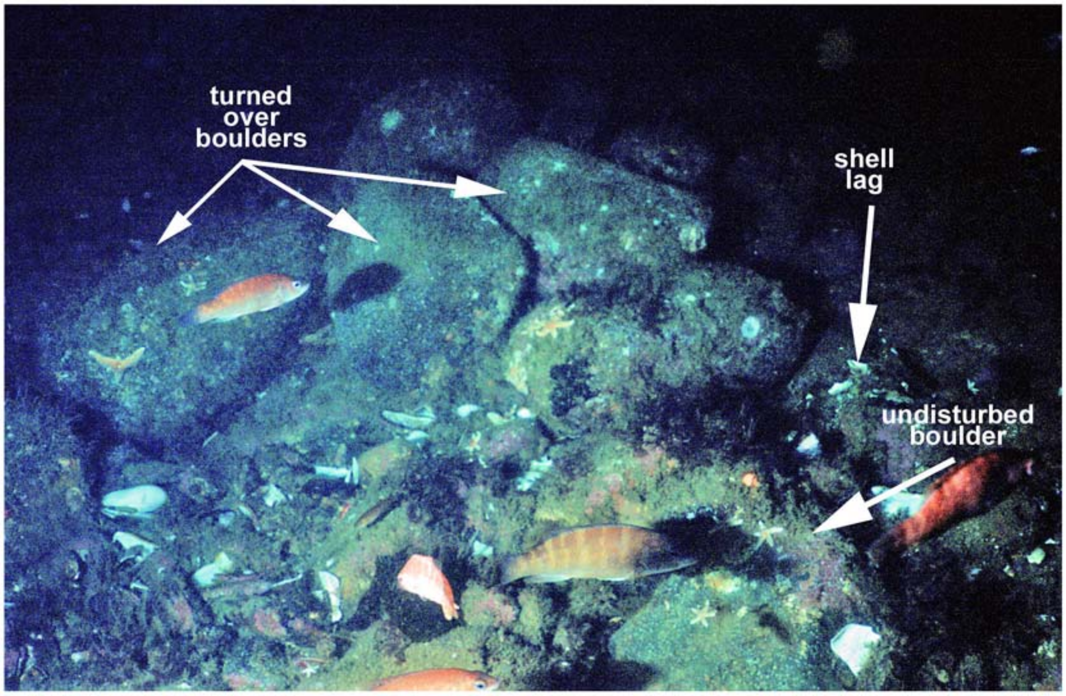

Figure 6. Evidence of increased disturbance to the seafloor, attributed to increased anchoring activity at the northern reference site.

The first six years of discharge monitoring have shown modest changes suggestive of an outfall impact at a subset of five stations, and some additional subtler changes at a number of other stations. However, two of the five stations in this subset may have been compromised as “reference” stations by post-9/11 increases in anchoring activity of LNG tankers, which caused physical disturbances of the seafloor at these sites. Lush epifaunal growth continues to thrive on the diffuser heads surveyed for this study and throughout many of the other stations visited (Figure 7). However, despite the fact that outfall impacts appear to be minimal at this time, changes in the hard-bottom communities could be chronic and/or cumulative, and may take a longer time to manifest themselves.

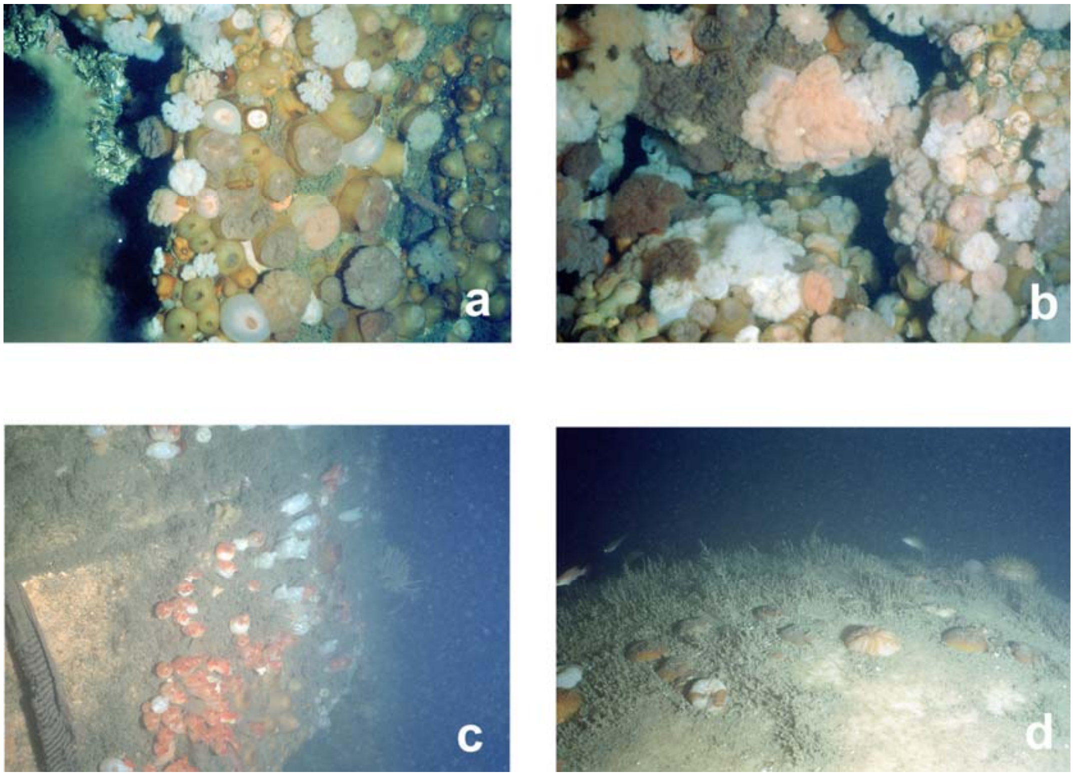

Figure 7. Photographs showing colonization of the MWRA outfall. Numerous frilled anemones colonize all surfaces of the active diffuser head #2 (a and b). In contrast, the sides of the inactive diffuser head #44 are colonized by numerous sea peach tunicates *Halocynthia pyriformis* (c), while the top supports only a sparse colonization by *Metridium senile* (d).

Summary

The MWRA offshore outfall has been discharging treated effluent into Massachusetts Bay since September 2000. Annual monitoring of the benthic environment at both nearfield and farfield locations has indicated only modest impacts at stations closest to the discharge, and no evidence of outfall-related changes in the farfield. The only change that appears to have been directly related to the operation of the outfall was a localized increase in the abundance of the sewage tracer *Clostridium perfringens* at stations located within 2 km of the discharge, and this increase was reversed in 2006. Other changes, such as levels of anthropogenic contaminants, deepening of the apparent color-RPD layer, and changes in the numbers of certain benthic species, appear to be related to processes such as storm-induced shifts in sediment composition or the natural fluctuations of biological populations. Some changes seen at hard-bottom reference stations may be related to physical disturbances caused by increased anchoring activities in the farfield.

1. INTRODUCTION

by Nancy J. Maciolek

1.1 Background

A burgeoning population and the impacts of industrialization throughout the first half of the twentieth century increasingly stressed Boston Harbor and Massachusetts Bay, as it did many urbanized coastal areas (Stolzenbach and Adams 1998). In response, federal legislation was passed in the early 1970s mandating that wastewater facilities be upgraded to secondary treatment, providing substantially greater removal of most chemical and domestic wastes. Further federal regulation of toxic chemicals and banning of contaminants, such as polychlorinated biphenyls (PCBs) and DDTs, in the 1970s and 1980s led to the continued reduction in toxic discharges over the past 30 years. Against this backdrop, the Massachusetts Water Resources Authority (MWRA) was created in 1985 with a mandate to implement both short-term and long-term remediation activities to decrease anthropogenic contamination discharge into the harbor.

Major improvements to the water and sediment quality in Boston Harbor began with the abatement of sludge discharge into the harbor in late 1991. Also, from 1991 to the start of outfall operation in 2000, a series of regional events transpired that influenced both Boston Harbor and the nearfield area. Climatologically, a severe storm passed over the region in October 1991, representing the highest bottom stress winter on record (Butman *et al.*2005). Freshwater flow was also elevated over long-term averages for much of the baseline period except for 1995, which was a low flow year (Taylor 2005).

In 1995, a new primary treatment facility at the Deer Island plant was brought online. In 1998, all wastewater was transferred to the Deer Island treatment plant and discharged off Deer Island at the mouth of the harbor. By this time, loadings from wastewater were reduced to about 4,000 mt C/yr from a high of about 11,400 mt C/yr. Secondary treatment was achieved in phases, with the final phase completed in 2000 and becoming fully operational in 2001.

In September 2000, the effluent from Deer Island was diverted to a new outfall approximately 15 km offshore, in 32 m water depth in Massachusetts Bay. All of these improvements—the improved effluent treatment, the complete cessation of sludge discharge to the harbor in 1991, and the transfer of wastewater discharge offshore—were implemented to improve the water quality in Boston Harbor and to increase effluent dilution with minimal impact on the environment of Massachusetts and Cape Cod Bays. Overall, the changes in wastewater discharge and improved treatment from 1995 to 2001 resulted in about a 90% decrease in loadings to Boston Harbor to about 1,200 mt C/yr. The operation of the offshore outfall diverted about 2,800 mt C/yr directly to the nearfield, which represents about 70% of the annual regional loadings (Taylor 2005). As a comparison to carbon fixed by primary production in the nearfield, which is about 400 g C/m^2/yr (Keller *et al.* 2001) or about 1 mt C per 2,500 m^2, the amount of carbon delivered to the nearfield via the outfall would be equal to the primary production in an area of about 7 km^2. This is a significant carbon input at scales of kilometers squared and might be expected to account for some changes in the study area.

The offshore outfall is regulated under a permit issued to MWRA by the United States Environmental Protection Agency (USEPA) and Massachusetts Department of Environmental Protection (DEP), under the National Pollutant Discharge Elimination System (NPDES). The permit stipulates that MWRA must monitor the outfall effluent and the ambient receiving waters to test for compliance with NPDES permit requirements; specifically, whether the impact of the discharge on the environment is within the bounds predicted by the SEIS (USEPA 1988), and whether any changes within the system exceed any of the

Contingency Plan thresholds, including those for sediment redox depth, toxic contaminant concentrations, community structure, or abundance of opportunistic species (MWRA 2001).

The Contingency Plan (MWRA 2001) is an attachment to the MWRA's Discharge Permit. Warning level thresholds listed in the plan are based on effluent limits, observations from baseline monitoring, national water quality criteria, state standards, and, in some cases, best professional judgment (Table 1-1). The Contingency Plan also details the process of how the MWRA would respond to any exceedances of the threshold values. Threshold values for benthic monitoring were originally based on averages calculated for the period 1992 through 2000, *i.e.*, from the beginning of the monitoring program through September 2000, when diversion of highly treated effluent to the new outfall was initiated. In 2003, the MWRA received permission to redesign the sampling program, and, beginning in 2004, a different subset of the original stations are sampled in even-numbered and odd-numbered years (see Section 1.3 below). The benthic community thresholds were adjusted to reflect the stations actually sampled in alternate years (Williams *et al.* 2005).

The studies included in the monitoring plan (MWRA 1991, 1997) are more extensive than necessary to calculate the Contingency Plan threshold values or to meet the NPDES permit requirements (MWRA 2003). Relocating the outfall raised concerns about potential effects of the discharge on the offshore benthic (bottom) environment. These concerns focused on three issues: eutrophication and related low levels of dissolved oxygen; accumulation of toxic contaminants in depositional areas; and smothering of animals by particulate matter. Extensive information collected over a nine-year baseline period and a five-year post-diversion period has allowed a more complete understanding of the bay system and has provided data to explain any changes in the parameters of interest and to address the question of whether MWRA's discharge has contributed to any such changes.

Table 1-1. Contingency plan thresholds established by MWRA for monitoring potential impacts of the offshore outfall. Benthic thresholds adjusted for stations collected in even- and odd-numbered years (Williams *et al.* 2005).

Location	Parameter	Caution Level	Warning Level
Sediment toxic contaminants, nearfield	Acenaphthene	None	500 ppb dry
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All Years Species composition, nearfield	Percent opportunists	10%	25%

1.2 Design of the Benthic Monitoring Program

The benthic surveys discussed in this report began in 1992 as part of the Benthic (Sea-Floor) Monitoring component of the MWRA Harbor and Outfall Monitoring (HOM) program (MWRA 1991). The benthic program has four major components, including the measurement of

- the apparent redox potential layer in sediment profile images (SPI)
- geochemical properties, contaminants, and sewage tracers in sediments
- benthic infaunal (soft-bottom) community structure
- hard-bottom community structure

Although SPI are taken only in the nearfield, the other three technical components are carried out at both nearfield (defined as being within 8 km of the outfall) and farfield locations.

The benthic monitoring program was designed to address a series of questions (MWRA 2001) regarding sediment contamination and tracers:

> *Have the concentrations of contaminants in sediments changed?*
>
> *What is the level of sewage contamination and its spatial distribution in Massachusetts and Cape Cod Bays sediments before discharge through the new outfall?*
>
> *Has the level of sewage contamination or its spatial distribution in Massachusetts and Cape Cod Bays sediments changed after discharge through the new outfall?*

and benthic communities:

> *Have the sediments become more anoxic; that is, has the thickness of the sediment oxic layer decreased?*
>
> *Has the soft-bottom community changed?*
>
> *Are any benthic community changes correlated with changes in levels of toxic contaminants (or sewage tracers) in sediments?*
>
> *Has the hard-bottom community changed?*

Achieving a good monitoring design for the nearfield was difficult because of the heterogeneity of habitats in the vicinity of the outfall. As a result, the sampling protocol has been modified several times to find the best approach. Shifts in station design have presented some problems in comparing year-to-year trends because the 1993 nearfield design departed significantly from that of 1992 and 1994−2003. Nevertheless, the baseline data accrued from 1992−2000 are considered to be sufficient to assess long-term regional trends and to establish thresholds against which potential impacts from the effluent discharge can be measured.

Until 2003, 23 nearfield and 8 farfield stations were sampled (either replicated or as single-sample stations) for benthic infauna and chemical contaminants; SPI was taken at 23 locations in the nearfield, and the hard-bottom communities photographed using ROV-mounted cameras at 23 waypoints in both nearfield and farfield areas. Although the SPI and hard-bottom sampling have remained essentially unchanged, beginning in 2004, a reduced number of stations were sampled for soft-bottom infauna and chemical contaminants (see section 1.3 below).

1.3 Revision of the Benthic Monitoring Program

In 2003, the MWRA began an intensive review of all elements of the monitoring program and the results to date, including the four components of the benthic monitoring. The concentrations of contaminants and of sewage tracers in sediments changed only modestly and only in the immediate vicinity of the outfall in the first two years since the outfall came online, and no changes in any of the benthic community parameters that could be related to the outfall were detected (Maciolek *et al*. 2004). MWRA therefore proposed to reduce sampling effort in several program areas, and the proposed changes were reviewed and ultimately approved by the USEPA and the MADEP. A revised sampling plan was released in March 2004 by the MWRA (2004).

Several major and minor revisions to the monitoring program have therefore been implemented. Sampling in August 2003 reflected the discontinuation of the Nearfield Special Study (sediments around the outfall were sampled three times per year before and after outfall start-up to see if there would be rapid accumulation of contaminants there) and a reduction in the frequency of sediment chemistry measurements at all stations.

Additional modifications to the benthic sampling include a reduction in the number of stations sampled each year, as well as a reduction in the sediment chemistry parameters measured at each station (Table 1-2). Under the revised plan, the frequency of sampling for infaunal benthos and chemical constituents was reduced by at least 50 percent The revised plan included the following adjustments:

- SPI will be taken at all 23 nearfield stations.
- Infaunal stations were randomly split into two subsets that will be sampled in alternate years, with the result that all stations will be sampled every two years. Stations were binned by region and level of replication before the random selection (MWRA, 2003 briefing package).
- Sediment characteristics/tracers, including total organic carbon (TOC), sediment grain size, and *Clostridium perfringens* spore counts in the 0–2-cm depth fraction will be sampled annually at each of the stations sampled for infauna (Table 1-2).
- Chemical constituents, *i.e.*, PAHs, PCBs, pesticides, and metals, will be sampled at a variable number of stations, depending on the year (Table 1-2).
    - Stations NF12 and NF17 will be sampled annually for all parameters
    - Every three years, starting in 2005, all stations sampled for infauna will be sampled for all chemical constituents
- The only modification to the hard-bottom sampling was to drop two locations and add two new ones. The details of this station placement are discussed in Chapters 2 and 6 of this report.

The sewage tracer and organic carbon data, and sediment trap data from a companion US Geological Survey (USGS) study, will be evaluated to ensure that there continue to be no sudden changes in sediment chemistry over the next few years. If the sediments are still not accumulating contaminants, and effluent toxic contaminant concentrations remain low, the MWRA might propose to further reduce chemistry sampling.

Table 1-2. Revised benthic station sampling and replication (from MWRA 2004).

Station Group	Stations	Year sampled	Replication: biology	Replication: metals and organic contaminants	Replication: TOC/grain size
Core (2 stations to be sampled every year)	NF12, NF17	2004, 2005, 2006	3	2	2
Even years replicated nearfield (2 stations)	FF10, FF13	2004, 2006	3	0	2
Even years unreplicated nearfield (9 stations)	NF05, NF07, NF08, NF09, NF16, NF18, NF19, NF22, NF23	2004, 2006	1	0	1
Even years farfield (4 stations)	FF04, FF05, FF07, FF09	2004, 2006	3	0	2
Odd years replicated nearfield (2 stations)	FF12, NF24	2005	3	2	2
Odd years unreplicated nearfield (8 stations)	NF02, NF04, NF10, NF13, NF14, NF15, NF20, NF21	2005	1	1	1
Odd years farfield (4 stations)	FF01A, FF06, FF11, FF14	2005	3	2	2

2. 2006 FIELD OPERATIONS

by Isabelle P. Williams

2.1 Sampling Design

2.1.1 Soft Bottom

Sediment Samples—Benthic monitoring surveys are conducted each year in August. The nearfield station array was designed to provide detailed spatial coverage of the infaunal communities inhabiting depositional sediments within about 8 km of the diffuser (Figure 2-1). Farfield stations, located more than 8 km from the diffuser, serve primarily as reference areas for the nearfield; these stations are located throughout Massachusetts and Cape Cod Bays (Figure 2-2). Sampling in the Stellwagen Bank National Marine Sanctuary (Station FF04 and FF05) was conducted under sampling permit SBNMS-2006-002. Target locations for all soft-sediment stations are given in Table 2-1. The actual station data for each biology and chemistry grab sample, along with a brief description of each, are in Appendix A1. In 2006, sediment grab samples were collected at 13 nearfield and 4 farfield stations.

Sediment Profile Images—The Sediment Profile Image (SPI) surveys are conducted in August of each year at the 23 nearfield stations (Figure 2-1). The SPI survey allows a rapid comparison of benthic conditions to the triggering threshold for depth of the apparent RPD layer. SPI can also be integrated with the quantitative results from the infaunal and sediment chemistry analyses to aid in assessing outfall effects. Sediment profile imagery, using digital technology first implemented in 2002, permits a faster evaluation of the benthos than can be made by traditional infaunal analyses. The target locations for SPI stations are the same as those of the nearfield grab stations (Table 2-1). In 2006, sediment profile images were taken at all 23 nearfield stations. Specific locations of all sediment profile images collected in 2006 are listed in Appendix A2.

2.1.2 Hard Bottom

Because of the relative sparseness of depositional habitats in the vicinity of the diffusers and adjacent nearfield, a photographic study of hard-bottom habitats is conducted each June. The hard-bottom ROV (remotely operated vehicle) survey of the outfall area is designed to provide semi-quantitative data about the hard-bottom community and its responses to the operation of the outfall. Video and 35-mm photographic images were collected at 18 waypoints/stations along six transects and five additional waypoints (T9-1, T10-1, T11-1, T12-1, and Diffuser #44) (Figure 2-3). Target locations for hard-bottom survey waypoints are listed in Table 2-2. Station data taken at the arrival of each station are given in Appendix A-3.

2.2 Field Program Results

2.2.1 Vessel and Navigation

The soft-bottom, SPI, and hard-bottom surveys in 2006 were conducted on Battelle's research vessel, the R/V *Aquamonitor*. Vessel positioning was accomplished with the Battelle Oceans Sampling Systems (BOSS) Navigation system. BOSS consists of a Northstar differential global positioning system (DGPS) interfaced to an on-board computer. Data are recorded and reduced using NAVSAM© data acquisition software. The GPS receiver has six dedicated channels and is capable of locking onto six satellites at once. The system is calibrated with coordinates obtained from USGS navigation charts at the beginning and end of each survey day.

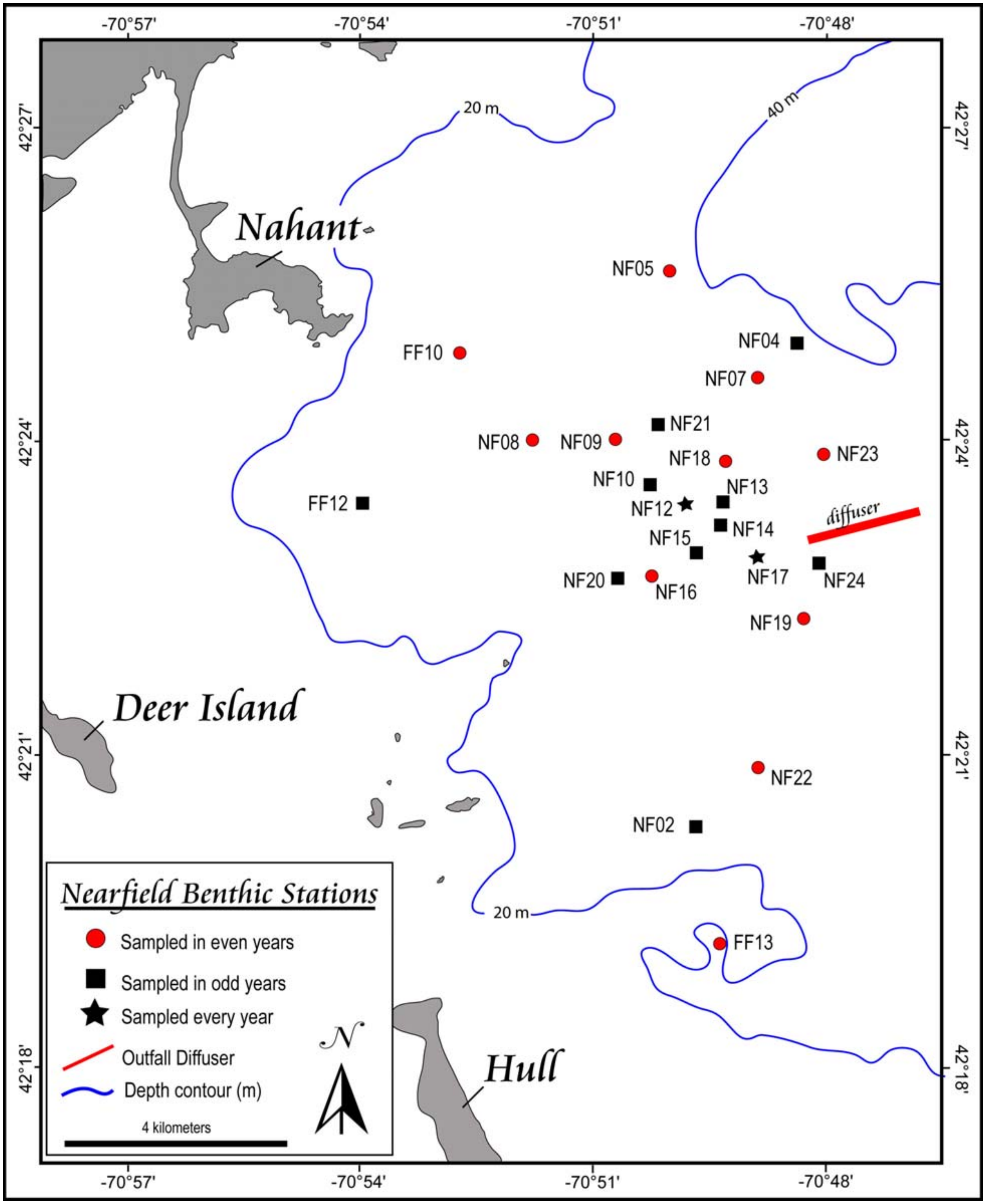

Figure 2-1. Locations of nearfield stations sampled in August 2006. All stations were sampled by SPI and those denoted by circles and star symbols were sampled by grab.

Table 2-1. Target locations for outfall survey grab and SPI stations.

Station	Latitude	Longitude	Depth (m)
Nearfield Stations			
FF10[1,2]	42°24.84′N	70°52.72′W	28.7
FF12[1]	42°23.40′N	70°53.98′W	23.5
FF13[1,2]	42°19.19′N	70°49.38′W	20.7
NF02[1]	42°20.31′N	70°49.69′W	26
NF04[1]	42°24.93′N	70°48.39′W	34
NF05[1,2]	42°25.62′N	70°50.03′W	36
NF07[1,2]	42°24.60′N	70°48.89′W	32
NF08[1,2]	42°24.00′N	70°51.81′W	28
NF09[1,2]	42°23.99′N	70°50.69′W	29
NF10[1]	42°23.57′N	70°50.29′W	32.9
NF12[1, 2]	42°23.40′N	70°49.83′W	34.9
NF13[1]	42°23.40′N	70°49.35′W	33.8
NF14[1]	42°23.20′N	70°49.36′W	34.1
NF15[1]	42°22.93′N	70°49.67′W	32.7
NF16[1,2]	42°22.70′N	70°50.26′W	31.1
NF17[1, 2]	42°22.88′N	70°48.89′W	30.6
NF18[1,2]	42°23.80′N	70°49.31′W	33.3
NF19[1,2]	42°22.30′N	70°48.30′W	33.2
NF20[1]	42°22.69′N	70°50.69′W	28.9
NF21[1]	42°24.16′N	70°50.19′W	30
NF22[1,2]	42°20.87′N	70°48.90′W	30
NF23[1,2]	42°23.86′N	70°48.10′W	36
NF24[1]	42°22.83′N	70°48.10′W	37
Farfield Stations			
FF01A[3]	42°33.84′N	70°40.55′W	35
FF04[2]	42°17.30′N	70°25.50′W	90
FF05[2]	42°08.00′N	70°25.35′W	65
FF06[3]	41°53.90′N	70°24.20′W	35
FF07[2]	41°57.50′N	70°16.00′W	39
FF09[2]	42°18.75′N	70°39.40′W	50
FF11[3]	42°39.50′N	70°30.00′W	88.4
FF14[3]	42°25.00′N	70°39.29′W	73.3

[1] Stations sampled by SPI in 2006 (all NF stations)

[2] Stations sampled by grab in 2006 (13 NF and 4 FF stations)

[3] Farfield stations not sampled in 2006

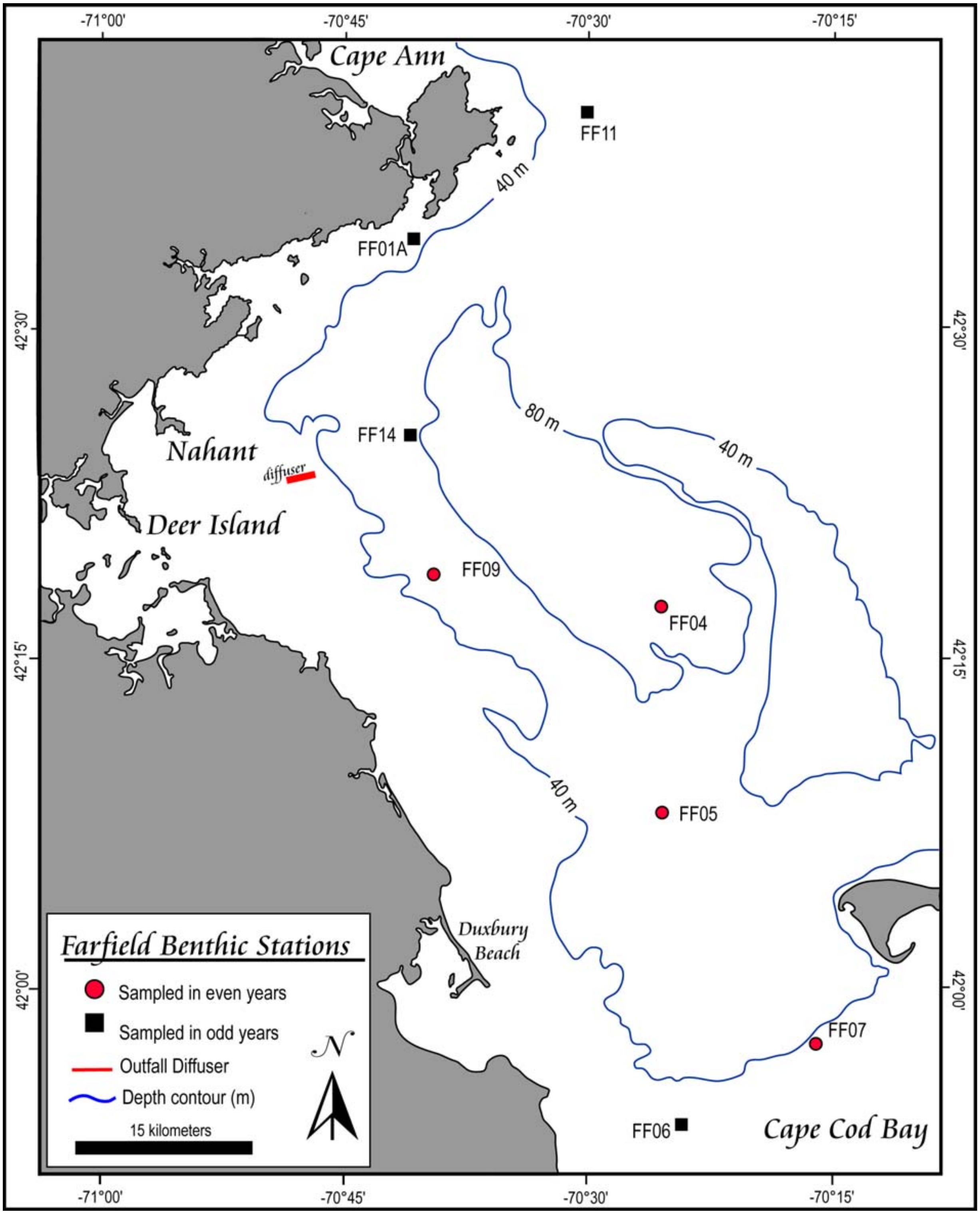

Figure 2-2. Locations of farfield grab stations sampled in August 2006 (circles).

Table 2-2. Target locations for hard-bottom survey waypoints.

Transect	Waypoint/ Station	Latitude	Longitude	Depth (m)
T1	1	42°23.606'N	70°48.201'W	25
T1	2	42°23.625'N	70°48.324'W	24
T1	3	42°23.741'N	70°48.532'W	22
T1	4	42°23.815'N	70°48.743'W	20
T1	5	42°23.869'N	70°48.978'W	27
T2	1	42°23.634'N	70°47.833'W	26
T2	2	42°23.570'N	70°47.688'W	27
T2	3	42°23.525'N	70°47.410'W	26
T2	4	42°23.457'N	70°47.265'W	32
T2	5 (Diffuser #2)	42°23.331'N	70°46.807'W	34
T4	2	42°23.012'N	70°46.960'W	29
T4/6	1	42°22.948'N	70°47.220'W	23
T6	1	42°22.993'N	70°47.712'W	30
T6	2	42°22.855'N	70°47.082'W	27
T7	1	42°24.565'N	70°47.015'W	23
T7	2	42°24.570'N	70°46.920'W	24
T8	1	42°21.602'N	70°48.920'W	23
T8	2	42°21.823'N	70°48.465'W	23
T9	1	42°24.170'N	70°47.768'W	24
T10	1	42°22.680'N	70°48.852'W	26
T11	1	42°14.405'N	70°34.373'W	36
T12	1	42°21.477'N	70°45.688'W	29
	Diffuser # 44	42°23.116'N	70°47.931'W	33

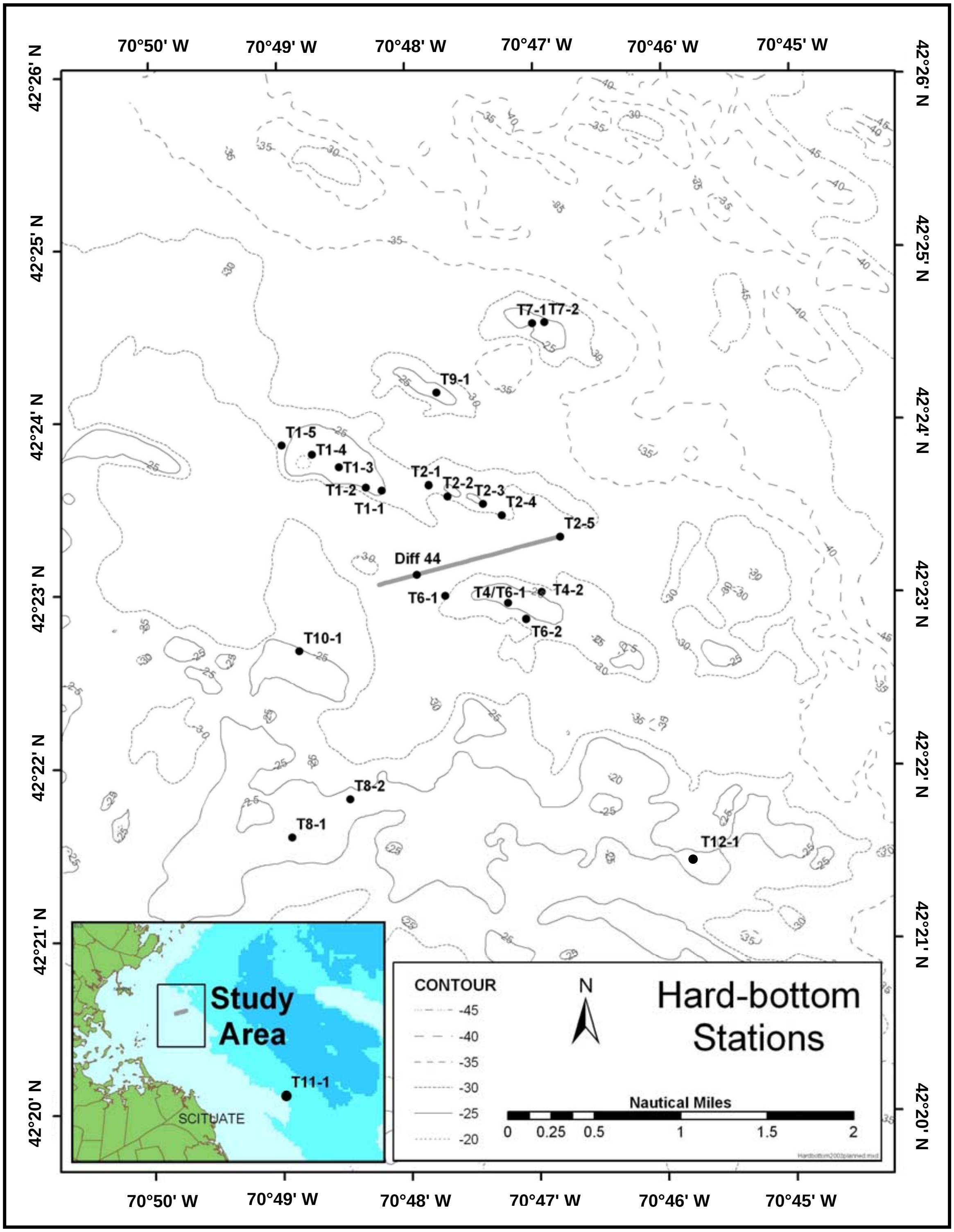

Figure 2-3. Hard-bottom stations sampled in June 2006.

At each sampling station, the vessel is positioned as close to target coordinates as possible. The NAVSAM© navigation and sampling software collects and stores navigation data, time, and station depth every 2 seconds throughout the sampling event, and assigns a unique designation to each sample when the sampling instrument hits bottom. The display on the BOSS computer screen is set to show a radius of 30 m around the target station coordinates (six 5-m rings) for all MWRA benthic surveys. A station radius of up to 30 m is considered acceptable for benthic sampling for this program.

2.2.2 Grab Sampling

Ms. Isabelle Williams was the Chief Scientist for collection of soft-sediment grab samples. In 2006, three sampling protocols were used for the 17 stations sampled during the Nearfield/Farfield Benthic Survey BN061/BF061.

- At two nearfield stations, (FF10 and FF13) and the four farfield stations (FF04, FF05, FF07, and FF09), three replicate samples for infaunal analysis, and two replicate samples for analysis of sedimentary parameters were collected.
- At two nearfield stations (NF12 and NF17), three replicate samples for infaunal analysis, and two replicate samples for chemical analysis of metals and organics in addition to the sedimentary parameters were collected.
- At nine nearfield stations (NF05, NF07, NF08, NF09, NF16, NF18, NF19, NF22, and NF23), one sample for infaunal analysis, and one sample for analysis of sedimentary parameters were collected.

Samples for the sedimentary parameters, which include total organic carbon (TOC), sediment grain size, and *Clostridium perfringens*, were collected from all 17 stations. Samples for metals and organics analyses were collected only from stations NF12 and NF17. Numbers of samples collected are summarized in Table 2-3. At all stations, samples were collected with modified van Veen grab samplers; specifically, a 0.04-m^2 grab for infaunal samples and a 0.1-m^2 Kynar-coated grab for chemistry samples.

Infaunal samples were sieved onboard with filtered seawater over a 300-μm-mesh sieve and fixed in 10% buffered formalin. For chemistry samples, the top 2 cm of the sediment in the grab was removed by using a Kynar-coated scoop and homogenized in a clean glass bowl before being distributed to appropriate storage containers. The TOC, metals, and organics samples were frozen, whereas the *C. perfringens* and grain size samples were placed on ice in coolers.

Table 2-3. Benthic samples collected in 2006.

Survey Type	Survey ID	2006 Date(s)	Samples Collected									
			Inf	TOC	GS	Cp	Org	TM	SPI	35	V	DVD
Nearfield Benthic	BN061	31 July–1 Aug	21	17	17	17	4	4				
Farfield Benthic	BF061	3 Aug	12	8	8	8						
SPI	BR061	28 Aug							75			
Hard-bottom	BH061	26–30 June								~750	~460	8

Key: Inf: Infauna; TOC: total organic carbon; GS: grain size; Cp: *Clostridium perfringens*; Org: organic contaminants; TM: trace metals; SPI: individual sediment profile images; 35: 35-mm slides; V: minutes of video; DVD: digital video discs.

2.2.3 Sediment Profile Imagery (SPI)

Dr. Pamela Neubert was Chief Scientist and Dr. Robert Diaz was SPI Specialist for the 2006 SPI Survey (BR061). The digital camera used for this survey captured a 5.2-megapixel image that produced a 14.1-megabyte RGB image that was then recorded to an IBM 1-gigabyte microdrive. The digital camera was also equipped with a video-feed used to send images to the surface via cable so that prism penetration could be monitored in real-time. In addition, the camera frame supported a video-plan camera mounted to view the surface of the seabed. These images were also relayed to the surface via the video cable and permitted the camera operator to see the seafloor and know exactly when the camera had reached the bottom. The camera operator then switched to the digital still camera and, while viewing the camera penetration, chose exactly when to record sediment profile images. Each time the camera was on the bottom, a series of 2–4 photographs was taken, generally within the first 12 seconds after bottom contact. This sampling protocol helped ensure that at least one usable photograph was produced during each lowering of the camera.

At each station, the camera was lowered to the seafloor three or four times to ensure that at least three replicate images, suitable for analysis, were obtained. Thus, at least three replicate samples were collected at each station (Table 2-3; Appendix A2-2). It was necessary to take a fourth replicate image at only six nearfield stations. The video signal showing the surface of the seafloor was recorded on 8-mm videotape for later review. The date, time, station, water depth, photo number, and estimated camera penetration were recorded in a field log, with each touch down of the camera also marked as an event on the NAVSAM©.

The microdrive was capable of recording more images than could be collected during a day of sampling and the system employed was very conservative on energy consumption. Nor was it necessary to take test shots on deck because loss of battery power to the strobe or camera would have been noticed immediately when the video cable failed to relay any images. Consequently, the camera housing did not have to be opened during this survey, except at the end of each day when images were downloaded from the microdrive to the laptop computer. This digital capability allowed a review of the collected images within 20 min of downloading; all images were then copied to a compact disc (CD) for archiving.

2.2.4 Hard-Bottom Sampling

Dr. Neubert was Chief Scientist and Dr. Barbara Hecker was Senior Scientist for the 2006 Hard-Bottom Nearfield Survey (BH061) during which 23 waypoints were visited (Table 2-2; Appendix A-3). An Outland Technology "Outland 1000" ROV equipped with a UWC-360D, low-light, dual camera on 360° tilt was deployed from the survey vessel to obtain the necessary video, DVD, and photographic images. The ROV was guided as close to the bottom as possible so that the clarity of the video and photographs was maximized. Approximately 20–30 minutes of video footage per waypoint were recorded along a randomly selected heading (Table 2-3). Along this route, still photographs were taken as selected by Dr. Hecker, until an entire (36 exposure) roll of 35-mm film was exposed at each waypoint.

The date, time, and ROV depth were recorded on the videotapes and appeared on the video monitor during the recording. The beginning and end of each video tape, the start of each roll of film, and the capture of each 35-mm image were recorded as separate events on the NAVSAM© system. The time displayed on the video monitor (and recorded on the tape) was synchronized with the NAVSAM© clock. When a still photograph was taken, the event and frame-identifying observations (made by Dr. Hecker) were recorded on the videotape. The NAVSAM© produced barcode labels for the videotapes (attached directly to the videotape cartridge) and photographic film (attached to the Battelle survey logbook). All slides were developed onboard to monitor camera performance, then mounted and labeled upon return to ENSR. Additionally, each 35-mm slide was digitized and copied onto a compact disc (CD) for archival. Digital Video Discs (DVDs) were also produced as the ROV was filming the hard-bottom stations.

3. 2006 CHEMISTRY

by Deirdre T. Dahlen and Carlton D. Hunt

3.1 Status of the Bay

A recent review of toxic contaminant issues in Boston Harbor and Massachusetts and Cape Cod Bays (Hunt *et al.* 2006) documents that the remediation activities, including source reduction actions and improvements to sewage treatment, have contributed to major improvements to the water and sediment quality in Boston Harbor. Notably, these improvements have resulted in reductions in contaminant loadings and a five-fold decrease in effluent solids discharge (Hunt *et al.* 2006). Since many contaminants readily bind onto solid particles, the magnitude of the solids reduction is mirrored for most chemicals of concern in the MWRA effluent. Improvements to other MWRA facilities have also resulted in smaller contaminant loadings from the MWRA waste collection system.

Consistent with predictions made in the Supplemental Environmental Impact Statement (SEIS) for the Massachusetts Bay outfall (EPA 1988), major findings from the benthic monitoring program (Hunt *et al.* 2006 and Maciolek *et al.* 2005 and 2006) show that contaminant-related impacts have not been detected in the regional coastal environment from the diversion of effluent into Massachusetts Bay in September 2000. A signature of the Massachusetts Bay outfall discharge has been found in nearby sediments, but has not caused substantive local or regional changes in the quality of the environment nor has the discharge acutely impacted marine life in the vicinity of the outfall and Bay at large.

This chapter presents the 2006 sediment chemistry data and incorporates these data into the understanding of the Massachusetts and Cap Cod Bay system. Monitoring year 2006 represents the 6th year following effluent diversion to Massachusetts Bay, and an 'even' sampling year under the revised monitoring program (MWRA, 2004). Results from the 2006 monitoring are evaluated in the context of the larger monitoring period (1992–2005), the conclusions reached in Hunt *et al.* (2006) and Maciolek *et al.* (2005 and 2006), and with respect to severe weather events, if any. Sediment chemistry data from the 1992–2006 monitoring period are also discussed in the context the 'even' and 'odd' sampling years approach implemented under the revised monitoring program (MWRA 2004).

3.2 Methods

Massachusetts Bay benthic investigations have been conducted by MWRA annually in August since 1992. Surface (top 2 cm) sediment samples were generally collected at 23 nearfield and 8 farfield stations located throughout Massachusetts and Cape Cod Bays. Consistent with recent revisions to the monitoring program (MWRA 2004), a reduced set of stations was sampled beginning in 2003 for anthropogenic[1] contaminants, and beginning in 2004 for sediment grain-size distribution, total organic carbon (TOC) content, and *Clostridium perfringens* abundance as described in Section 1.3. Monitoring year 2006 represents an even sampling year under the revised program, with approximately half of the nearfield (FF10, FF13, NF05, NF07, NF08, NF09, NF12, NF16, NF17, NF18, NF19, NF22, and NF23) and farfield (FF04, FF05, FF07, and FF09) stations sampled for sediment grain size, TOC, and *C. perfringens*, and two nearfield stations (NF12 and NF17) sampled (in duplicate) for anthropogenic contaminants (Figures 2-1 and 2-2).

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[1] Anthropogenic analytes are generated or enriched in the environment by human activity. They are functionally defined in this analysis as TPAH, TPCB, TDDT, and CPERF. In addition, they include metals like Al, Cd, Cr, Cu, Fe, Pb, Hg, Ni, Ag and Zn. All of these can be enriched by anthropogenic activities. However, Al and Fe are crustal metals that do not typically spike unless there is a nearby metallurgical industry (e.g., steel mill or aluminum smelter). Under normal circumstances, Al and Fe can be used as reference values for comparing the metal composition of samples collected at different locations.

Surface sediment samples collected in 2006 were analyzed for sediment grain size, TOC, and *C. perfringens,* and anthropogenic parameters according to Prasse *et al.* (2007). The testing procedures are summarized in Sections 3.2.1 and 3.2.2. Section 3.2.3 describes how the data were evaluated to characterize the sediments and assess changes in sediment quality that may have resulted from diversion of effluent discharge to the Massachusetts Bay outfall. Complete details regarding the data analyses and those data excluded from the evaluation are provided in Appendix B1.

3.2.1 Grain Size, Total Organic Carbon, and *Clostridium perfringens*

Grain Size—Samples were analyzed for grain-size distribution by a sequence of wet- and dry-sieving methodologies following Prasse *et al.* (2007) and Folk (1974). Data were presented as weight percent by size class. In addition, the gravel:sand:silt:clay ratio and a numerical approximation of mean particle size and standard deviation were calculated. Grain-size analyses were performed by Azimuth Geo Services, of Austin, Texas.

Total Organic Carbon (TOC)—Samples were analyzed for TOC by using a DC-190 analyzer following Prasse *et al.* (2007). Data were presented as percent dry weight. TOC analyses were performed by the Department of Laboratory Services (DLS), MWRA.

***Clostridium perfringens*—**Sediment extraction methods for determination of *C. perfringens* spores followed Prasse *et al.* (2007) and are based on Emerson and Cabelli (1982), as modified by Saad (1992). Data are reported as colony-forming units (cfu) per gram dry weight of sediment. This analysis was performed by BAL Laboratory, Cranston, Rhode Island.

3.2.2 Anthropogenic Contaminants

Sediment samples were analyzed for a suite of anthropogenic contaminants including polycyclic aromatic hydrocarbons (PAH), polychlorinated biphenyls (PCBs), pesticides, and inorganic constituents following Prasse *et al.* (2007). PAH, PCB, and pesticide analyses were conducted by using gas chromatography with mass spectrometry detection. Sediment data for 4,4'-DDT were qualified as 'suspect' because of a co-eluting compound. The analysis method will be modified for monitoring year 2007 to eliminate the interference.

Inorganic constituents, aluminum, chromium, copper, iron, and zinc were analyzed using flame atomic absorption; cadmium, nickel, lead, and silver were analyzed using graphite furnace atomic absorption; and mercury was analyzed using cold vapor atomic absorption. Anthropogenic contaminant analyses were performed by the DLS, MWRA.

3.2.3 Data Analyses

Microsoft® Excel 2003 and JMP (The Statistical Discovery Software, a business unit of SAS Institute, Inc.) were used to analyze the sediment chemistry data from system-wide and station-specific perspectives. Graphical representations of the results were presented as ternary plots, box plots, histograms, range, and variability gage plots. The total concentration for each contaminant class studied (see Appendix B1) was used in the data evaluations, including total PAH, total PCB, and total DDT. In cases where an individual analyte was not detected, a value of zero (0) was used in the summation. Linear alkyl benzene (LAB) data were not evaluated here because sediments have not been analyzed for these chemicals since 2004; the most recent evaluation of LAB sediment data was presented in Maciolek *et al.* (2006).

Abundances of the sewage tracer *C. perfringens* were normalized to percent fines because the distribution of *C. perfringens* has been found to vary with the proportion of fine-grained material in the sediments (Parmenter and Bothner, 1993), and normalization provides a more conservative means of evaluating the data for trends.

Sediment data for the even and odd year station groupings were compared to determine if apparent trends between the two data groupings are similar. Similar trends and concentrations would suggest that stations sampled during a given monitoring year are representative of the system and able to detect change under the revised sampling regime. Sediment data for the even and odd year comparison were evaluated from a system-wide perspective in terms of nearfield and farfield regions of Massachusetts and Cape Cod Bays. Nearfield data were also evaluated as a function of distance from the outfall and Boston Harbor. Nearfield data were grouped into three categories, including 1) nearfield stations located within 2 km of the outfall; 2) nearfield stations located greater than 2 km from the outfall; and 3) transition area stations. Nearfield stations NF12 and NF17 were excluded from the comparison because these stations were sampled every year.

Sediment data were also statistically evaluated by using Tukey-Kramer means comparisons and Pearson pair-wise correlation analyses. Prior to statistical evaluations, the sediment data were checked for normality with the Shapiro-Wilk test, and where appropriate the data used in the statistical tests were log-transformed (*i.e., C. perfringens*, total PAH, total PCB, total DDT, cadmium, chromium, copper, lead, mercury, silver and zinc). Tukey-Kramer was used to test system-wide and station-specific differences in group means, that is differences between the baseline and post-diversion means. Output from the test is a comparison circles plot, which is a visual representation of group means. Circles for means that are significantly different (at the 95% level of confidence) either do not intersect or intersect slightly so that the outside angle of intersection is less than 90 degrees. If the circles intersect by an angle of more than 90 degrees or if they are nested, the means are not significantly different at the 95% confidence level (see Appendix B1, Figure B1).

The relationship between sediment variables was determined using Pearson pair-wise correlation analyses; station mean values were used in the analysis. The Pearson product-moment correlation coefficient (r) measures the degree to which two variables have a linear relationship if the variables have normal distributions. Values near 1 indicate that the two variables have a strong positive correlation, values near -1 indicate that the two variables have a strong negative correlation, and values near 0 indicate that the two variables are unrelated. Strong correlation coefficients do not necessarily indicate a direct dependence of the variables.

Finally, nearfield and farfield sediment data were also compared to Sediment Quality Guidelines (SQG) (Long *et al.* 1995) to evaluate whether changes in sediment quality have occurred in the system since the early 1990s or between baseline and post-diversion periods. For this analysis, station means were compared with published marine effects range-low (ER-L) and effects range-median (ER-M) (Long *et al.* 1995) concentrations for 27 chemicals. The total number of ER-L and ER-M exceedances for each year was summed by station and by chemical.

3.3 Results and Discussion

This section describes findings from the evaluation of sediment chemistry data collected from the 1992 to 2006 monitoring period. Sediment chemistry data are first discussed in context of the even and odd sampling years implemented under the revised monitoring program. Sediment data for 2006 are discussed in context of the larger monitoring period (1992–2005), the conclusions reached in Hunt *et al.* (2006) and Maciolek *et al.* (2005 and 2006), and with respect to severe weather events, if any. System-wide and station-specific sediment data are also discussed with focus on how the post-diversion data (2001–2006) compare to the baseline data (1992–2000). All sediment results are discussed in terms of dry weight.

3.3.1 Evaluation of Revised Sampling Program

Under the revised monitoring program, nearfield and farfield stations were divided among even and odd sampling years as described in Section 1.3. Long-term monitoring data are evaluated here to determine how well the even and odd year sampling groups represent the Massachusetts and Cape Cod Bays system, in terms of identifying potential trends and/or changes in the sediment data following effluent diversion. Results from the evaluation are summarized below; detailed results are provided in Appendix B2.

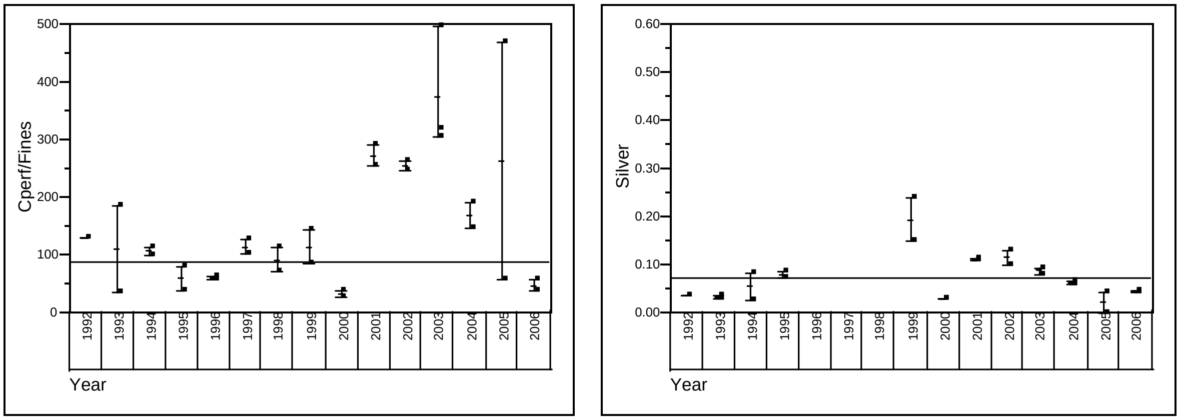
Overall, it was difficult to discern differences in trends among the sediment data for the even and odd year station groups because of the high variability among the data, which often reflects differences in bulk sediment characteristics (i.e., percent fines and TOC content). Moreover, limited anthropogenic chemical data are available for post-diversion years 2003, 2004, and 2006, which further confounded the even and odd year data comparison. Where trends were observed, they were usually similar for both the even and odd year station groups, although some subtle differences in the responses of *C. perfringens*, total PCB, cadmium, and silver were observed, especially at sub-regions within the nearfield. For example, annual mean abundances of *C. perfringens* at even and odd year stations located within 2 km of the outfall have decreased steadily since the initial post-diversion increase in 2001. Results from the most recent sampling events, however, are not consistent between the even and odd year stations. Annual mean abundances of *C. perfringens* continued to decrease in 2006 at even year stations, whereas abundances increased in 2005 at odd year stations (Figure 3-1). A coincident increase in percent fines or TOC was not observed that could explain the 2005 increase in *C. perfringens* abundances at the odd year stations (Figure 3-2). There were also some subtle differences in concentrations of total PCB and cadmium at transition area stations between the even and odd year stations. Since 1999, concentrations of total PCB and cadmium (except in 2005) at the odd year stations were consistently below the baseline mean, whereas, a coincident decrease was not observed at the even year stations (Appendix B2). Finally, there were some subtle differences in silver trends between the even and odd year station groups for nearfield stations located within 2 km of the outfall. Annual mean concentrations of silver decreased since 2000 at the odd year stations (Figure 3-1, concentrations also decreased at NF17), which likely reflects reduced inputs to the system associated with regional source reduction efforts and a cleaner effluent (Werme and Hunt 2006). A decreasing trend in silver concentrations was not evident at the even year stations, however, this may be an artifact of the limited data available for even year stations (Figure 3-1). A statistical analysis showed that any apparent regional decreases in silver were not significant (see Section 3.3.3).

The even and odd year data comparison confirmed earlier evaluations (Maciolek *et al.* 2005 and 2006), which illustrated that differences among the *C. perfringens* and contaminant data, either in variability or concentration, were largely influenced by differences in bulk sediment characteristics (i.e., grain size and TOC content). Stations divided between even and odd year station groups, therefore, should have comparable bulk sediment characteristics representative of the overall system to facilitate data evaluations and interpretation. The evaluation showed that from a system-wide perspective (i.e., nearfield and farfield regions) there were no obvious or substantive differences among bulk sediment characteristics between the even and odd year station groupings. However, substantive differences were apparent at sub-regions within the nearfield, particularly stations located within 2 km of the outfall as shown in Figure 3-2 (note the difference in percent fines between the even and odd year station groups) and stations located at the transition area (Appendix B2). Close examination of the data, however, suggests that the substantive 'differences' are probably an artifact either of a single station with markedly different grain size or TOC (i.e., NF24 is the only station located within 2 km of the outfall that is comprised of fine-grained sediment with variable grain-size distributions; see Section 3.3.2 and Figure 3-3) or the smaller number of stations that could be divided among the even and odd year station groups (i.e., transition area, n=3).

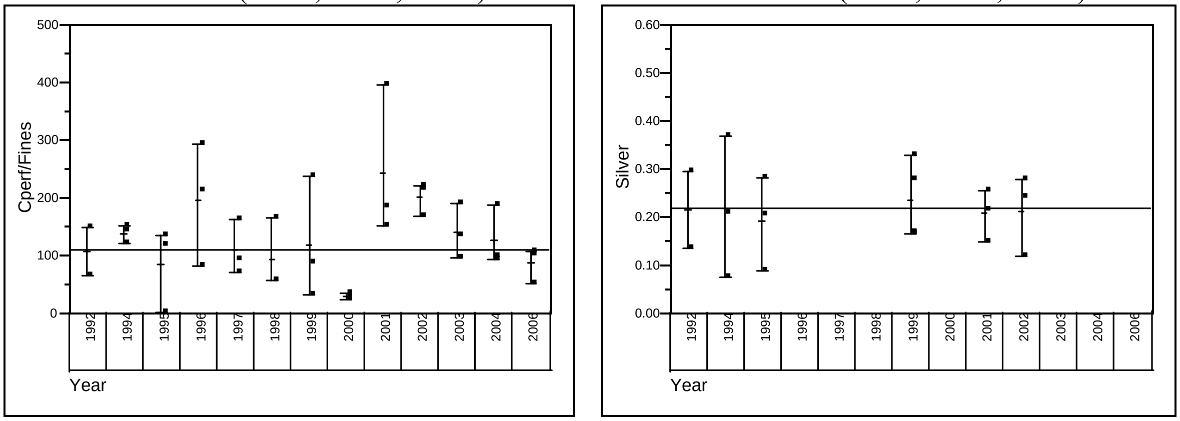
In summary, division of the stations between even and odd sampling years revealed some subtle differences in apparent trends for *C. perfringens* and silver at stations located near the outfall and in total PCB and cadmium concentrations at stations located in the transition area between the harbor and the offshore outfall. More often, however, differences among the sediment data (e.g., variability) reflected differences in bulk sediment characteristics between the even and odd station groups. Overall, the even and odd year evaluation indicates that annual monitoring of one consistent set of stations that is representative of the overall system would be more useful in discerning potential trends among the data and detecting potential impacts associated with effluent diversion. Annual monitoring at one consistent set of stations would also ensure that impacts, if any, to the system from severe events (e.g., major storms) could be detected and properly considered.

***C. perfringens*/Fines (cfu/g dw/%fines)** **Silver (mg/kg dry)**

Station NF17 Station NF17



Even Year Stations (NF18, NF19, NF23) Even Year Stations (NF18, NF19, NF23)



Odd Year Stations (NF13, NF14, NF15, NF24) Odd Year Stations (NF13, NF14, NF15, NF24)

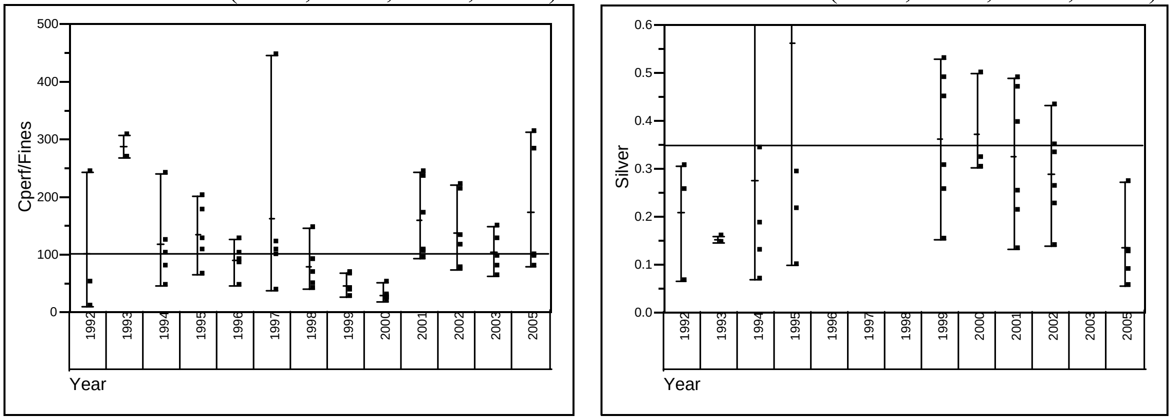
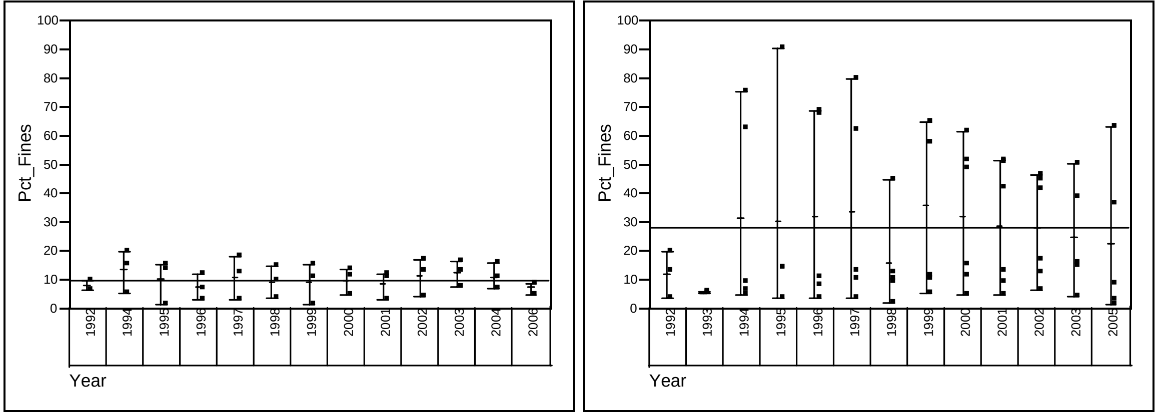


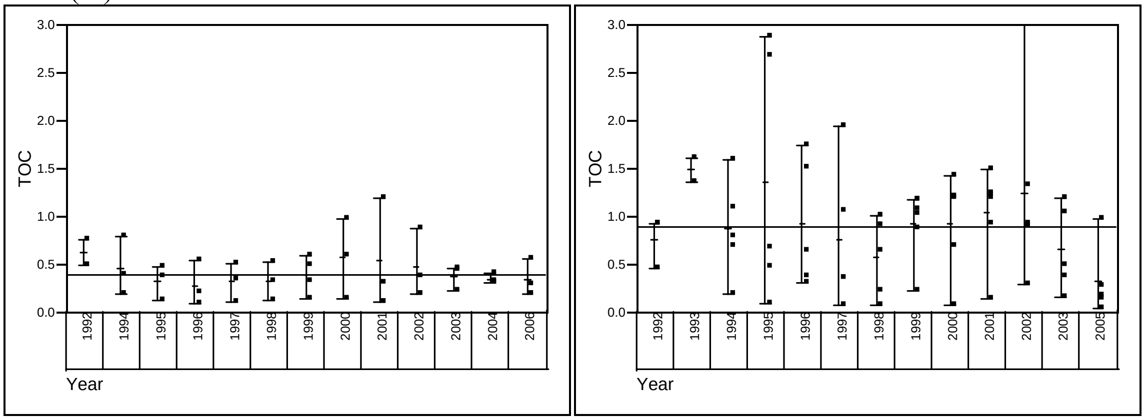
Figure 3-1. Comparison of *C. perfringens* (normalized to percent fines) and silver at stations located within 2 km of the outfall, including station NF17 (sampled every year), even, and odd year station groupings, from 1992 to 2006. Individual data points are represented by the points, the vertical bars represent the range in values by year, the annual mean is represented by the dash ('-'), and the baseline mean is represented by the reference line.

Even Year Stations (NF18, NF19, NF23) **Odd Year Stations (NF13, NF14, NF15, NF24)**

Percent Fines (%)



TOC (%)



Mercury (mg/kg dry)

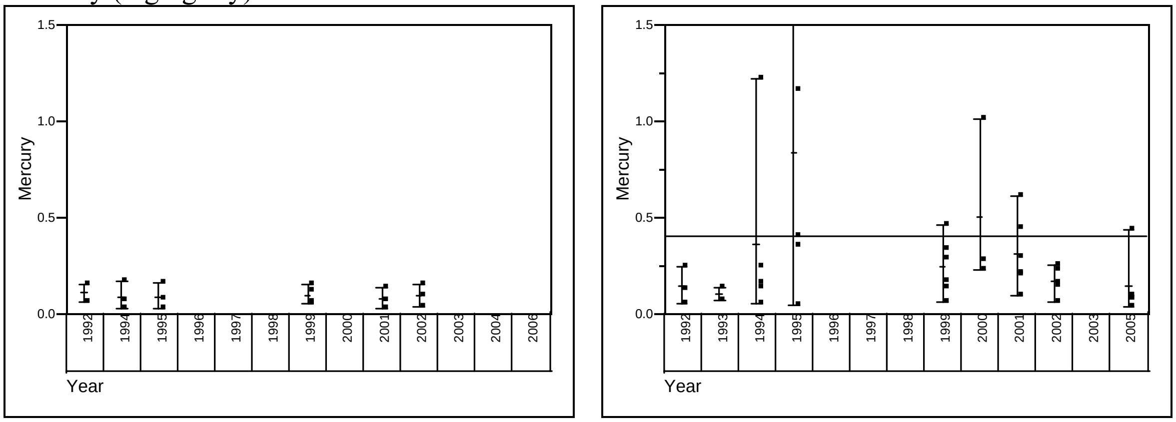


Figure 3-2. Comparison of percent fines, TOC content, and mercury between even and odd year station groupings for nearfield stations located within 2 km of the outfall, from 1992 to 2006. Individual data points are represented by the points, the vertical bars represent the range in values by year, the annual mean is represented by the dash ('-'), and the baseline mean is represented by the reference line.

3.3.2 Sediment Grain Size and Total Organic Carbon 1992–2006

Grain-size distributions and TOC content in 2006 were consistent with the larger monitoring period (1992–2005). Unlike in 2005, storm-induced impacts to the sediment bed were not evident in the 2006 data, which is expected since there were no major storms prior to the 2006 sampling event.

Long-term data (1992–2006) reveal that monitoring stations include a series of locations having heterogeneous sediments (Figure 3-3) located throughout Massachusetts and Cape Cod Bays. Surface sediments sampled at nearfield stations located within 2 km of the offshore outfall were, with the exception of NF24, consistently coarse-grained (Figure 3-3; median value[2] is 91% gravel+sand) with low concentrations of organic carbon (Figure 3-4; median value[1] is 0.38% TOC). Station NF24 was comprised of fine-grained sediments (median value is 52% silt+clay) with higher concentrations of organic carbon (median value is 1.2% TOC). Although grain-size distributions were more variable from year to year at station NF24, sediments appear to be coarser during the post-diversion period compared to baseline as shown by an increase in percent sand and decrease in percent silt during the post-diversion period (Figure 3-3).

Surface sediments sampled at nearfield stations located more than 2 km from the outfall (including the transition-area stations), had a wide range of grain-size distributions (Figure 3-3) and TOC content (Figure 3-4). Surface sediments were comprised of coarse-grained sediments with low TOC content (e.g., NF04) to fine-grained sediments with higher TOC content (e.g., NF08, NF12) (Figure 3-3; see Appendix B3 for ternary plots by station). Surface sediments sampled at the farfield regions of Massachusetts and Cape Cod Bays were generally fine-grained (median value[1] is 72% fines) with higher concentrations of organic carbon (median value[1] is 1.4% TOC), except stations FF01A and FF09, which contained coarse-grained sediments (Figure 3-3) with lower organic carbon (median values using 1992–2006 data for FF01A and FF09 are <0.5% TOC).

System-wide changes in grain-size distributions and TOC content, between the baseline and post-diversion periods, were difficult to discern because of the high variability among the data. Substantive changes, however, were observed at selected stations. For example, significant changes in grain-size distributions were observed at stations FF05, FF09, FF10, NF08, NF12, NF17, and NF24; the post-diversion mean value for percent fines increased significantly (at the 95% level of confidence) compared to the baseline mean at all but two of the stations (percent fines decreased at NF08 and NF24; note that post-diversion grain-size distributions for NF24 cluster closer to the gravel+sand axis in the ternary plot shown in Figure 3-3 compared to the pre-diversion data) (see Tukey-Kramer means comparison results Appendix B3). Significant changes between the baseline and post-diversion mean values for TOC content were also observed at stations FF04, FF05, FF07, FF13, and FF14; post-diversion TOC concentrations increased at all stations except FF13 (see Tukey-Kramer means comparison results Appendix B3). The observed changes in grain-size distributions and TOC content do not appear to be outfall related, as there were no clear trends (e.g., increasing fines and TOC) observed at stations located close to the outfall. For example, following effluent diversion there was a significant increase in percent fines at NF17, but a significant decrease in percent fines at NF24. Changes in grain-size distributions and TOC content are more likely associated with natural fluctuations in the bay, which are expected in a dynamic system influenced by physical forces such as severe weather events as demonstrated in the 2005 MWRA data following the May 2005 nor'easters (Maciolek *et al.* 2006).

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[2] Median values were determined by using data from the entire monitoring period (1992–2006) and all stations within each group classification (transition area, <2 km from outfall, >2 km from outfall, and farfield).

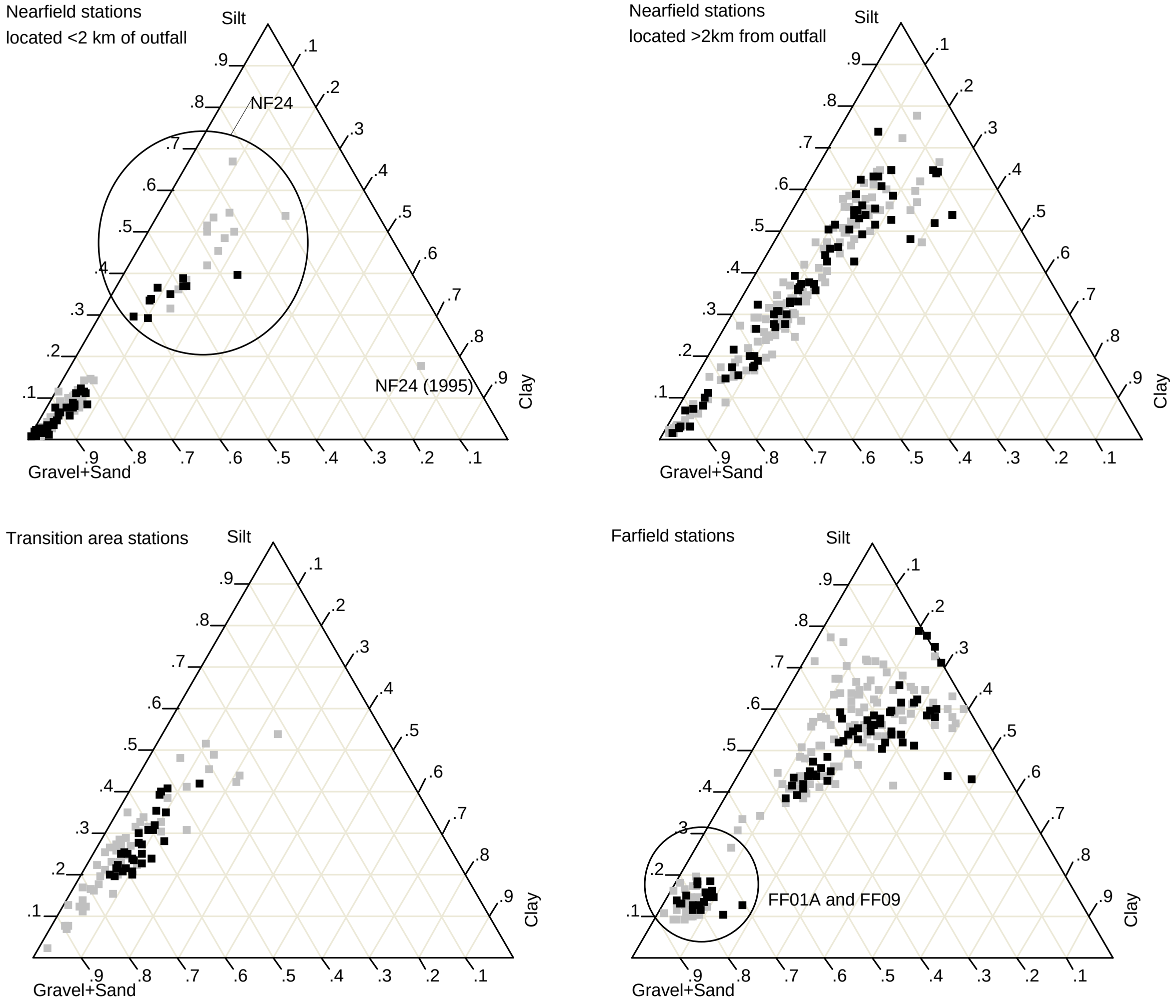


Figure 3-3. Ternary plots showing the distribution of percentages gravel + sand, silt, and clay at nearfield and farfield stations during baseline (1992-2000, gray filled squares) and post-diversion (2001-2006, black filled squares) periods. Nearfield data are grouped according to three distance categories: <2 km from the outfall, > 2 km from the outfall, and transition area stations located between Boston Harbor and the outfall. (Station-specific ternary plots are provided in Appendix B3).

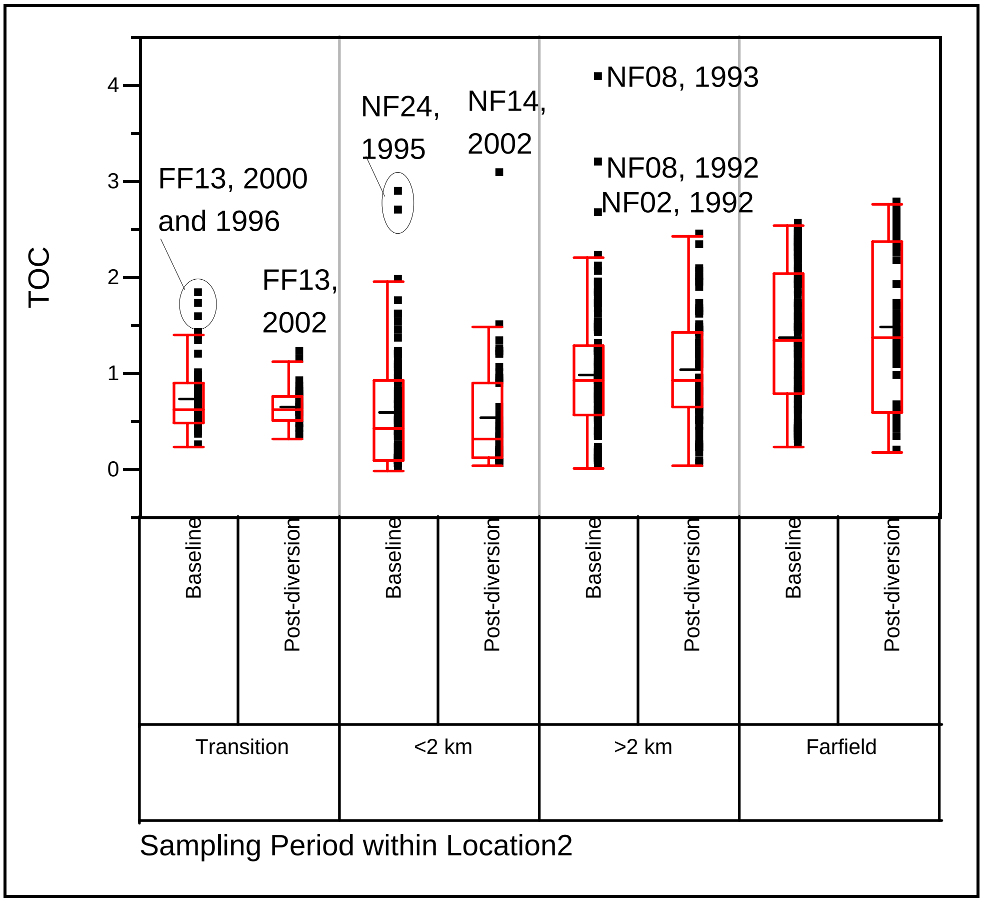


Figure 3-4. Distribution of TOC in nearfield and farfield sediments during baseline (1992–2000) and post-diversion (2001–2006) sampling periods. Nearfield data are grouped according to three distance categories: <2 km from the outfall, > 2 km from the outfall, and transition area stations located between Boston Harbor and the outfall. (Station-specific data distributions are provided in Appendix B3). The ends of the box represent the 25th and 75th quartiles, the line across the middle represents the median value, and the dashed line across the middle represents the mean value. The vertical lines are "whiskers" that extend from the ends of the box to the outermost data point that falls within the distances computed (a distance of 1.5 times the interquartile range, difference between 25th and 75th quartiles). Data points above or below the whiskers represent possible outliers**.**

3.3.3 Anthropogenic Contaminants 1992–2005

System-wide and station-specific concentrations of anthropogenic contaminants in 2006 were within the range of values measured over the larger monitoring period (1992–2005) (total PAH and nickel are shown in Figure 3-5; all data in Appendix B4). Storm-induced impacts to the sediment bed can alter chemical concentrations, which have been observed in the MWRA data. For example, concentrations of aluminum, chromium, iron, nickel, and silver decreased considerably in 2005 at nearfield and farfield locations compared to the 2001–2004 post-diversion data (nickel is shown in Figure 3-5; all data in Appendix B4). The observed decrease was attributed to the May 2005 nor'easters that were believed to have contributed to a loss of fines, resulting in a coarsening of sediment grain size (Maciolek *et al.* 2006). No differences in the sediment data between 2006 and previous years were observed that were attributable to severe weather events, which is consistent with the lack of any substantive storm systems moving through the area prior to the 2006 monitoring event.

The long-term monitoring data (1992–2005) showed that concentrations of anthropogenic contaminants in surface sediments at nearfield and farfield regions of Massachusetts and Cape Cod Bays are highly variable (total PAH and nickel are shown in Figure 3-5; all data in Appendix B4), which often reflects differences in bulk sediment characteristics such as grain-size distribution and TOC content (see Section 3.3.1). A chemometric assessment of 1992–2002 sediment data (grain size, TOC, *C. perfringens*, organic contaminants, and metals) by principal components analysis (PCA) confirmed that the primary factor associated with the variance in the nearfield and farfield chemistry data was sand content, and that secondary factors were associated with anthropogenic analytes and fine particles (Maciolek *et al.* 2003).

Annual mean concentrations of anthropogenic analytes (*i.e.*, total PCB, total PAH, silver, mercury, lead, copper and cadmium) are typically higher in nearfield sediments, which are located in closer proximity to Boston Harbor, and lowest in farfield sediments, which are more distant from Boston Harbor (total PAH shown in Figure 3-5; all data in Appendix B4). For most of the baseline and post-diversion periods, annual mean concentrations of aluminum, iron, nickel, and zinc were slightly higher in farfield sediments than in nearfield sediments (nickel shown in Figure 3-5; all data are in Appendix B4). These findings were consistent with the PCA, which showed that most farfield sediments contained high silt and clay without a large anthropogenic chemical content (Maciolek *et al.* 2003).

The PCA also showed that anthropogenic inputs appear to decrease over time, suggesting that nearfield sediments are no longer receiving organic and inorganic compounds associated with the historical discharges of untreated or inadequately treated sewage from Boston Harbor (Maciolek *et al.* 2003). A statistical analysis confirmed that the post-diversion mean concentrations of total DDT, total PCB, cadmium, and nickel decreased significantly (at the 95% level of confidence) compared to the baseline mean value at farfield regions of Massachusetts and Cape Cod Bays. Significant decreases in post-diversion mean concentrations of total DDT were also observed at nearfield stations located within 2 km of the outfall and in cadmium at the transition area. The observed post-diversion decreases in total DDT and total PCB are likely associated with reduced inputs resulting from the banning of these chemicals in the 1970s and 1980s. Post-diversion mean concentrations of aluminum, however, increased significantly compared to baseline at nearfield stations located closer to Boston Harbor (i.e., nearfield stations >2 km from the outfall and transition area stations). An explanation for the increase is not evident.

A station-specific evaluation of the sediment data showed that most of the post-diversion data were within the general range of samples collected during the baseline period, except aluminum, which was above the baseline in 2002 at most stations and nickel, which was below the baseline in 2005 at all but two of the stations sampled (representative contaminants including total PAH and nickel are shown in Figure 3-5; all data in Appendix B4). Localized increases and/or decreases in post-diversion contaminant concentrations at one or more stations have been observed in the MWRA data, and are described in detail in Maciolek *et al.* (2006). Briefly, observed decreases in contaminant concentrations have been attributed to severe weather events, which can coarsen sediment grain size, and method changes which can reduce or eliminate interferences thereby decreasing concentrations of selected chemicals. Observed increases in post-diversion contaminant concentrations at one or more stations have also been attributed to analytical interferences, random spikes, or unknown contamination. An outfall effect appears unlikely in these cases because contaminant concentrations generally returned to baseline in subsequent surveys (Maciolek *et al.* 2005 and 2006).

While the ability to draw definitive conclusions is confounded by the large intra- and inter-annual variability observed in the data, overall the system response six years since outfall startup suggests that diversion of treated effluent discharge to the Massachusetts Bay outfall has not caused widespread or systematic increases in anthropogenic contaminants of environmental concern to the bay system.

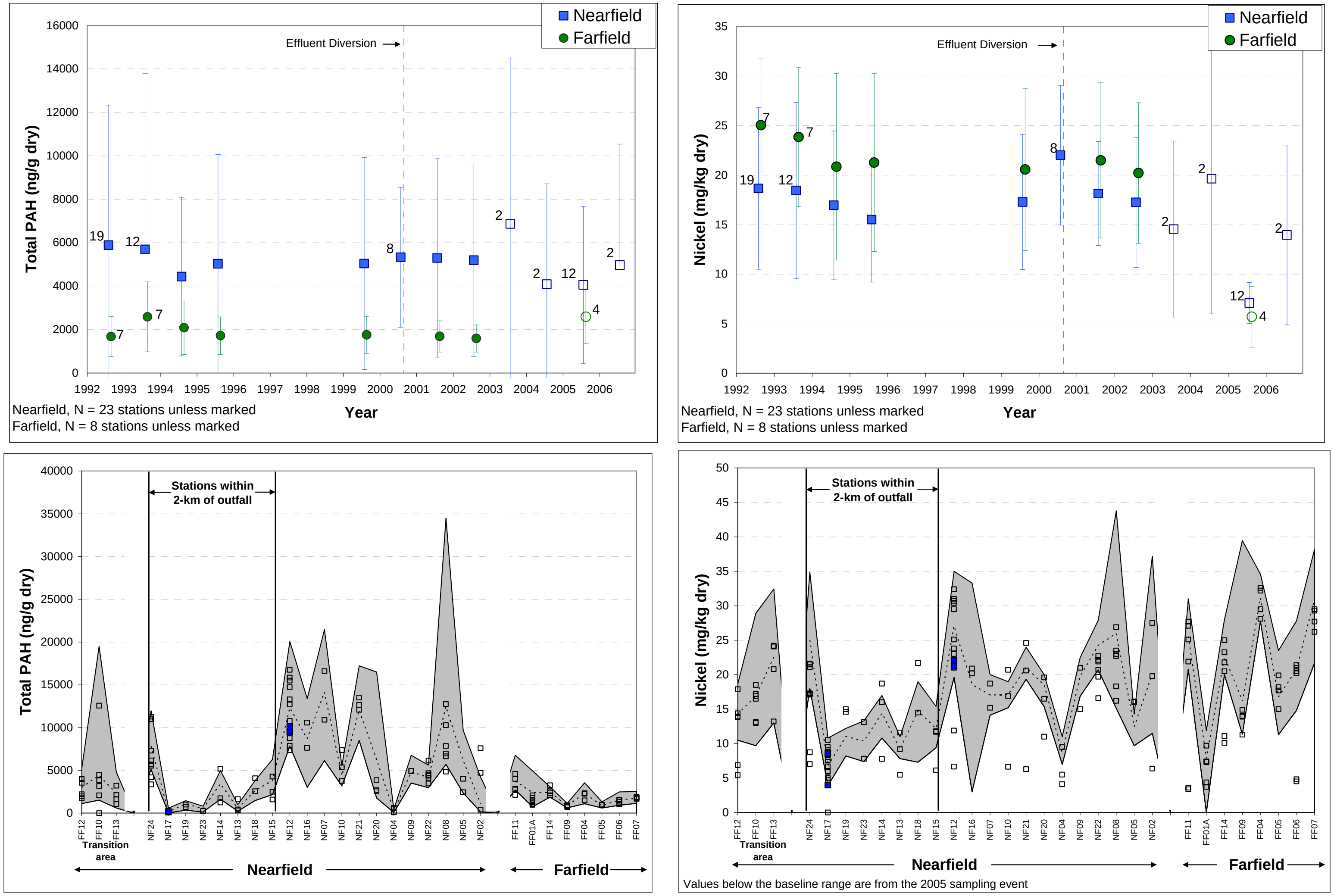


Figure 3-5. Temporal (top) and spatial (bottom) trends in total PAH and nickel in the nearfield and farfield regions of Massachusetts and Cape Cod Bays, 1992 to 2006. Temporal trends (top) are illustrated using the yearly mean abundance (i.e., the average of all stations and replicates for a given year, by region); vertical bars represent one standard deviation and open symbols represent years under the revised monitoring program. Spatial trends (bottom) are illustrated using range plots, where the range of values during baseline (1992–2000) is represented by the grey band and post-diversion data are represented by square symbols (☐ 2001-2005 and ■ 2006). The baseline mean values (1992–2000 mean) are indicated by a dashed line within the gray band.

3.3.4 Sewage Tracer *Clostridium perfringens* 1992–2005

The 2005 Toxics Issue Review (Hunt *et al.* 2006) indicated that understanding the response of sewage tracers in sediments to the Boston Harbor cleanup effort provides a means of evaluating how the system reacted when the intensity of sewage sources was reduced in the 1990s. One of the most commonly used tracers of sewage-derived sources in marine systems is *Clostridium perfringens,* an anaerobic bacterium common to the intestinal tract of mammals (Emerson and Cabelli 1982).

Abundances of *C. perfringens* were less variable and decreased with increasing distance from Boston Harbor (Figures 3-6 and 3-7). Farfield stations located more than 20 km from Deer Island Light had the lowest abundances, frequently fewer than 50 cfu/g dw/% fines (Figure 3-6). Abundances of *C. perfringens* increased in nearfield sediments one year after effluent diversion (*i.e.*, 2001) compared to 2000 pre-diversion values (Figures 3-6 and 3-7). This pattern has generally held from 2002 to 2005, although abundances appeared to decrease over time and by 2006 returned to 2000 pre-diversion values (Figure 3-7). Abundances of *C. perfringens* also decreased in 2006 at harbor locations (Figure 3-6) sampled in support of the Combined Sewer Overflow study (Durell *et al.* in progress).

From a system-wide perspective, *C. perfringens* abundances were generally higher and more variable in the nearfield region of Massachusetts Bay than in the farfield (Figure 3-7). Mean abundances of *C. perfringens* decreased in the late 1990s at nearfield locations (Figure 3-7), likely from the Boston Harbor cleanup efforts (*e.g.*, secondary treatment). Nearfield abundances increased one year after effluent diversion, remained elevated through 2005, and then decreased sharply in 2006 returning to 2000 pre-diversion values (Figure 3-7). The 2006 decrease could reflect that a cleaner effluent is being discharged, or perhaps physical processes such as bioturbation or sediment layering are diluting the abundances of *C. perfringens* by mixing the surface sediments with deeper, clean sediments. Available data is not sufficient to fully address these potential causes.

The nearfield-wide post-diversion increase is attributed, in large part, to increased abundances at stations located within 2 km of the outfall (Figure 3-7). A statistical analysis confirmed that the post-diversion increase in the nearby sediments is significant (see Tukey-Kramer mean comparison results in Appendix B5). These findings are consistent with conclusions drawn from the USGS sediment trap program (Bothner and Butman 2005), which showed statistically higher *C. perfringens* abundances in post-diversion samples collected about 1 km south of the outfall. The MWRA and USGS sediment trap data provide complementary evidence regarding the strength of the outfall signature in Massachusetts Bay and increase the confidence in the ability of the monitoring program to document the transport and fate of the effluent-related contaminants discharged in Massachusetts Bay. Sediment core data (surface 0-0.5 cm interval) from the same USGS study, however, showed no significant change in *C. perfringens* abundances following effluent diversion. The USGS sediment cores were collected at a single station, whereas MWRA's monitoring is based on a spatially replicated sampling design. The ability of MWRA's monitoring to detect this change documents the importance of the sampling design when evaluating the impact of a relatively clean discharge on coastal sediments with a history of modest levels of contamination.

A statistical analysis also showed that the post-diversion mean abundances of the sewage tracer *C. perfringens* (log transformed) decreased significantly (at the 95% level of confidence), compared to baseline, at the transition and farfield regions of Massachusetts and Cape Cod Bays (see Tukey-Kramer mean comparison results in Appendix B5). Clearly the long-term monitoring data for *C. perfringens* illustrates the major improvements in sewage treatment implemented by the MWRA over the last decade. Moreover, sediment data from 2006 suggest that the effluent may be having less influence on nearby sediments compared to the first five years following effluent diversion.

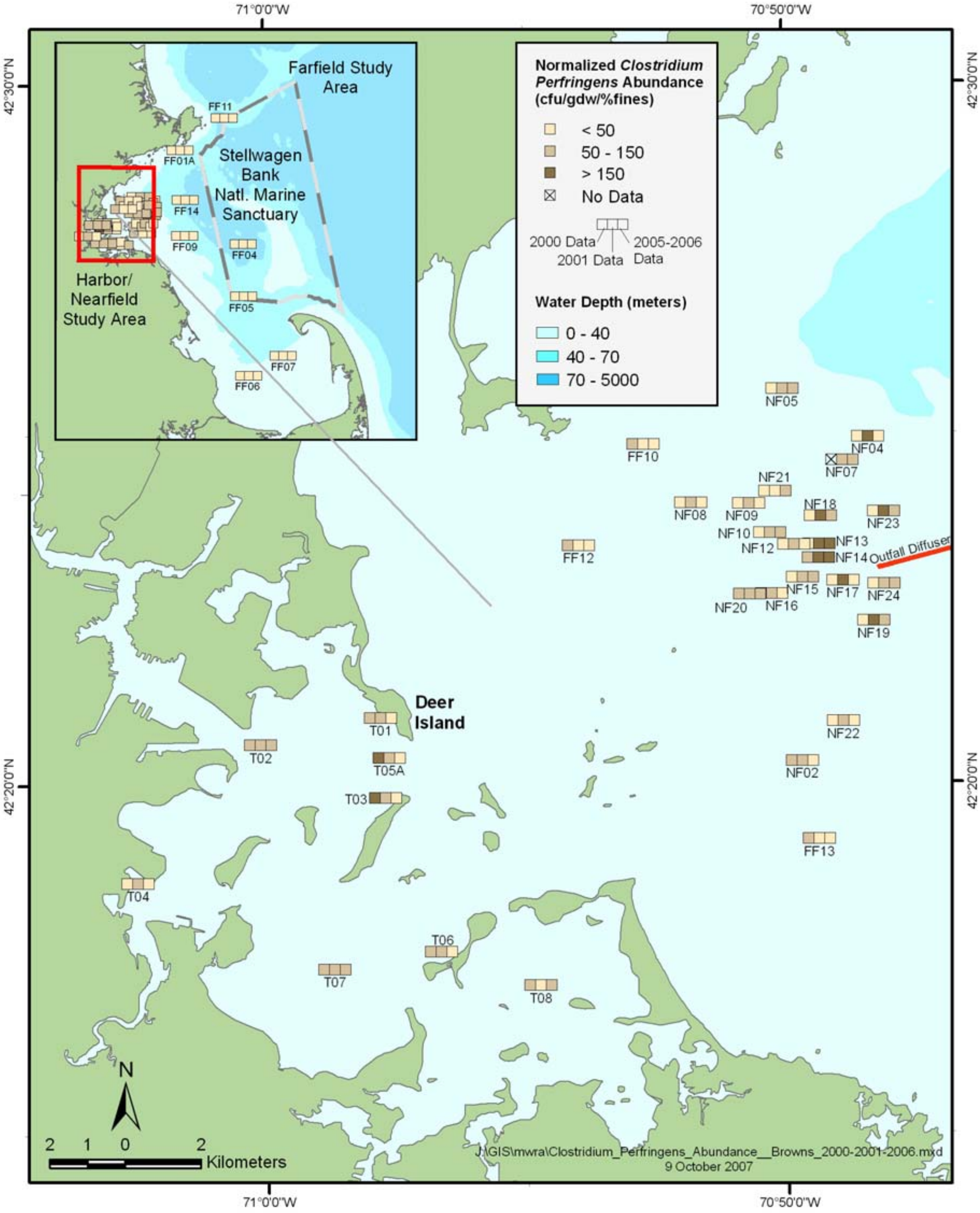


Figure 3-6. Distribution of pre-diversion (2000) and post-diversion (2001, 2006) station mean abundances of *Clostridium perfringens*, normalized to percent fines, in Boston Harbor and Massachusetts and Cape Cod Bays. Stations NF02, NF04, NF10, NF13, NF14, NF15, NF20, NF21, NF24, FF01A, FF06, FF11, FF12 and FF14 were not sampled in 2006, and the 2006 value reported is based on the 2005 station mean value.

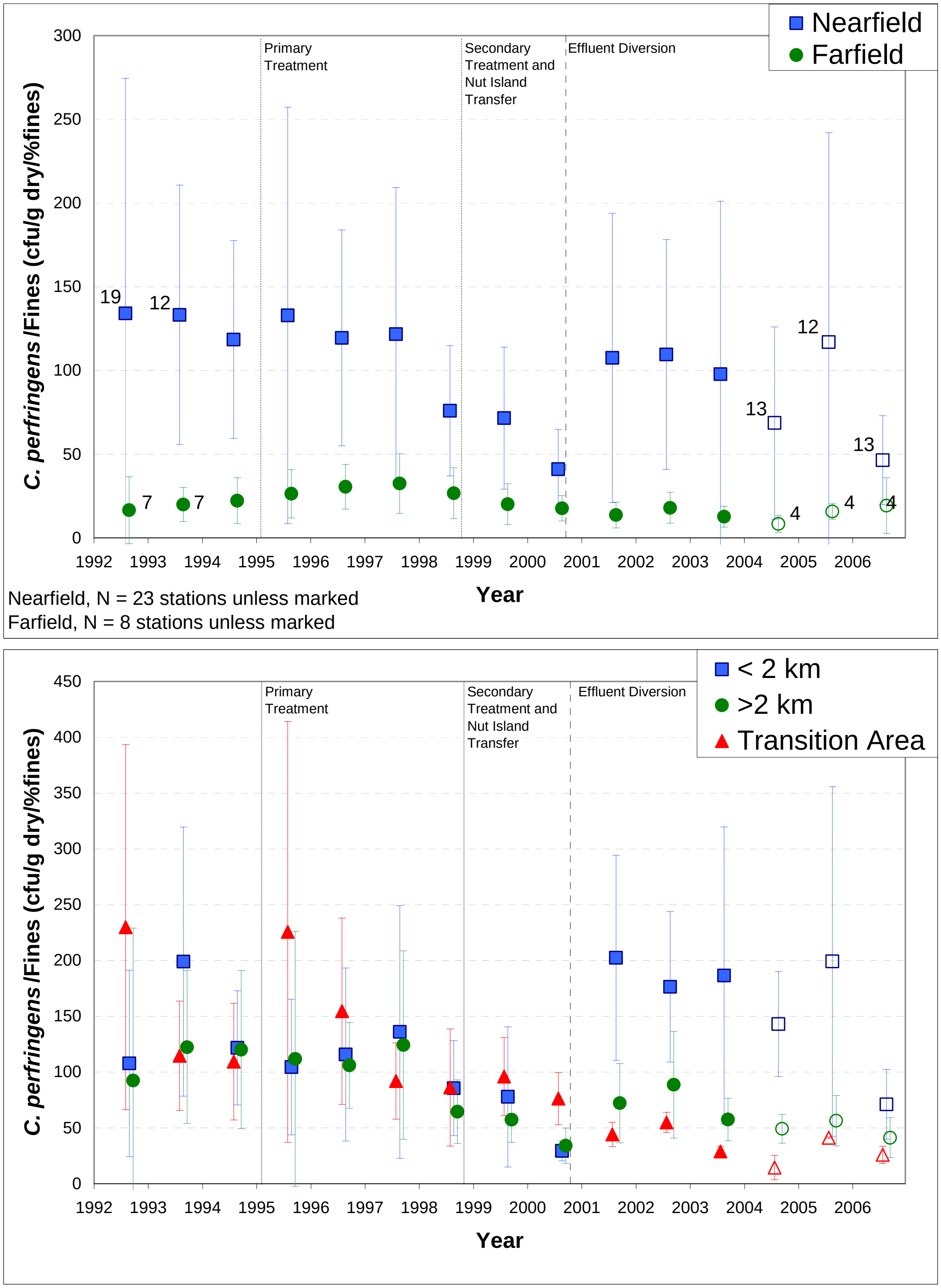


Figure 3-7. Yearly mean abundance of *Clostridium perfringens*, normalized to percent fines, in nearfield and farfield sediments, 1992 to 2006. The top plot illustrates the nearfield and farfield data following effluent diversion in 2000. The bottom plot shows that the nearfield increase is associated with stations located within two kilometers of the outfall, relative to the other nearfield and transition area stations. Yearly mean abundance is the average of all stations and replicates for a given year, by region. Vertical bars represent one standard deviation and open symbols represent years under the revised monitoring program.

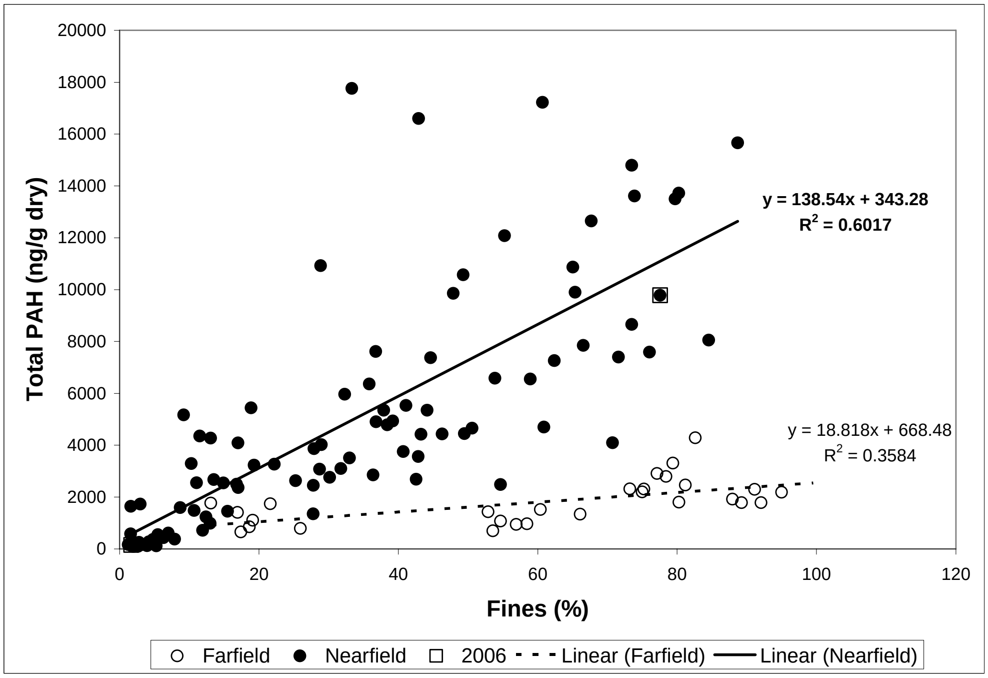
3.3.5 Sediment Correlations

Baseline (1999–2000) and post-diversion (2001–2006) sediment data were evaluated by using Pearson pair-wise correlation analyses to evaluate impacts of effluent diversion, if any, on the relationships between constituents of the sediment data at nearfield and farfield locations. Sediment data from 1999 and 2000 were used to represent the baseline because this sampling period represents the conditions after most of the improvements to wastewater treatment were complete (*i.e.,* primary and secondary treatment, Taylor 2005) and provide two years of data before effluent diversion to the new outfall. Correlation results for nearfield and farfield sediments are summarized below; detailed results are provided in Appendix B6.

Overall, the sediment constituents within the nearfield and farfield data sets were positively and significantly correlated, indicating that sediments with high concentrations of one variable (*e.g.*, percent fines) are associated with high concentrations of the second variable (*e.g.,* TOC, *C. perfringens* or anthropogenic contaminants). For example, the correlation between percent fines and TOC yielded *r* values ranging from 0.84 to 0.91 (Appendix B6, Tables B6-1, B6-2, and B6-3), which indicates that about 70% to 80% of the variation in the grain size and TOC data (at nearfield and farfield locations) is related. The correlation (*r*) between the sewage tracer *C. perfringens* and percent fines or TOC ranged from 0.44 to 0.88 (Appendix B6), which indicates that approximately 20% to 75% of the variation in the data is related. The correlations between anthropogenic analytes and percent fines or TOC were also moderate to moderately strong, with *r* values typically 0.5 or higher, indicating that 25% or more of the variation in the data is related. These findings indicated that fine-grained sediments with higher organic carbon content characteristic of depositional environments generally contained higher contaminant concentrations, and coarse-grained sediments with lower organic carbon content typically contained lower contaminant concentrations. These findings are also consistent with the PCA (conducted in 2002 using 1992–2002 data) which showed that the primary factor associated with the variance in the nearfield and farfield data was sand content (i.e., the higher the sand content the lower the contaminant concentrations), and that secondary factors were associated with fine particles and anthropogenic analytes (Maciolek *et al.* 2003).

There are some subtle differences in the correlations among sediment variables between nearfield and farfield regions, in terms of the 1999–2006 sampling period and between the baseline (1999–2000) and post-diversion (2001–2006) periods. For example, *C. perfringens* and organic contaminants have slightly stronger correlations with percent fines and TOC at nearfield locations during the 1999–2006 sampling period, whereas many metals have slightly stronger correlations at farfield locations (see Table B6-1 in Appendix B6). The correlations among sediment variables were also slightly stronger, at nearfield and farfield locations, during the baseline period compared to the post-diversion period (see Tables B6-2 and B6-3 in Appendix B6). For example, the correlation between the sewage tracer *C. perfringens* and bulk sediment characteristics degraded in farfield sediments following outfall activation (baseline *r* ranged are 0.88 (vs. percent fines) and 0.83 (vs. TOC) and post-diversion *r* values are 0.57 (vs. percent fines) and 0.44 (vs. TOC); Appendix B6, Table B6-3). The weaker correlation appears to be associated with an observed decrease (approximately 25% on average) in *C. perfringens* abundances with no corresponding change in grain size. Even so, the differences in the correlations among sediment variables between the nearfield and farfield regions and between the baseline and post-diversions periods were typically small (relative percent difference between *r* values <10% for most variables), suggesting that effluent diversion to the Massachusetts Bay outfall is not impacting the relationship among the sediment variables.

Finally, the correlation analyses also showed that the proximity to the primary historic source of contaminants, Boston Harbor, influenced the contaminant concentrations in nearfield and farfield sediments. Nearfield sediments, with grain size similar to farfield sediments, generally had higher concentrations of many anthropogenic contaminants compared to farfield values, especially for organic contaminants (total PAH shown in Figure 3-8; all data in Appendix B6). Anthropogenic concentrations present at levels above the underlying farfield signature are indicative of proximity to local sources (e.g., Boston Harbor, Salem Harbor), as evidenced by a higher slope value from the regression analysis for nearfield data compared with farfield data (total PAH shown in Figure 3-8; all data in Appendix B6). Anthropogenic concentrations at farfield locations are primarily influenced by widely distributed sources (e.g., atmospheric input, distant rivers). PCA (conducted in 2002 using 1992–2002 data) supported this and showed that the composition of sediments at farfield sampling may reflect regional inputs that are distinct from Boston Harbor (Maciolek *et al*. 2003).



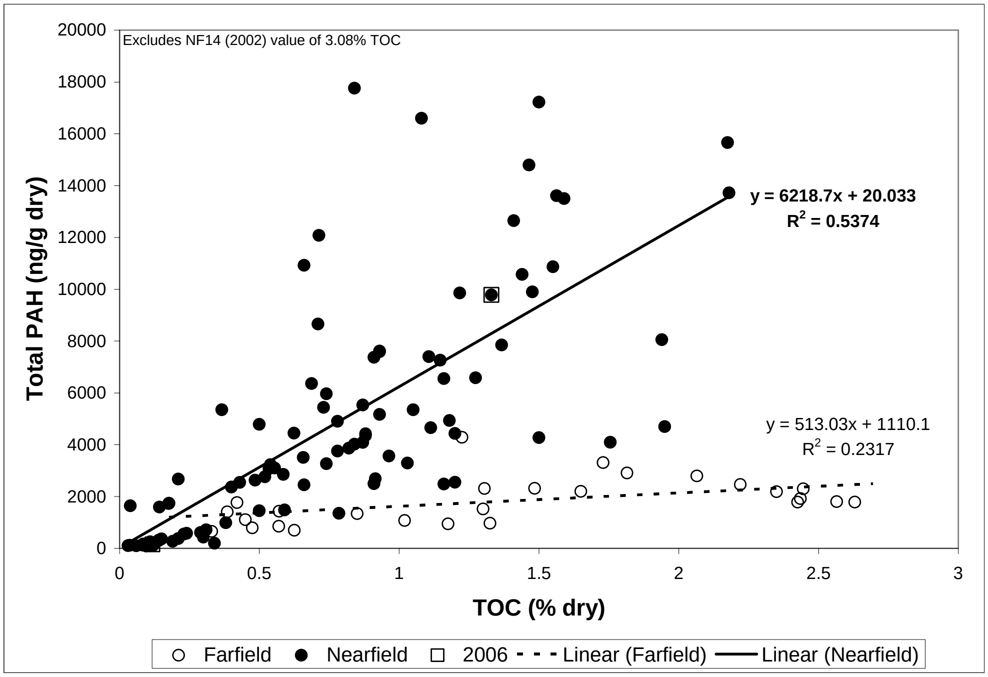


Figure 3-8. Correlation of total PAH against percent fines (top) and TOC content (bottom) in nearfield and farfield sediments, 1999–2006. Station mean values (i.e., average of all replicates, by station and year) were used in the correlation analysis.

3.3.6 Sediment Quality

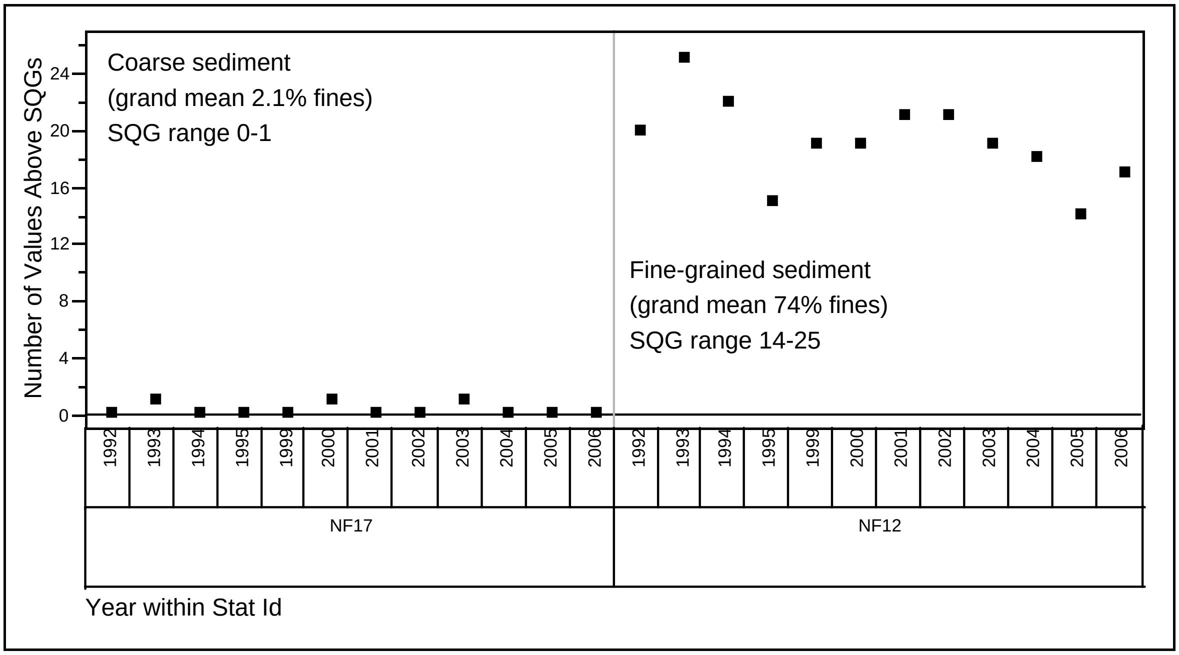
Complete sediment quality assessments are complex and can incorporate any of several measurement approaches, including biological characteristics, toxicological data, chemical data, and combinations of these attributes. The only long-term information on sediment quality in Massachusetts and Cape Cod Bays is the chemical and benthic infauna community data. The benthic infauna data have not revealed broad scale infaunal community impairment from outfall diversion (Chapter 5, this report). Lacking toxicological information, and clear contaminant-driven impacts to the benthic community, sediment data (station mean values) for 27 chemicals were compared against SQGs (Long *et al.* 1995) to evaluate potential changes or trends in sediment quality over the course of the monitoring period (1992–2006). Results are summarized below; complete details are provided in Appendix B7.

The number of chemicals with concentrations above the SQGs, at any given station or monitoring year, ranged from 0 to 25 out of a maximum potential of 27 SQG exceedances (27 chemicals compared to SQGs). The number of SQG exceedances appears to be influenced by proximity to the historic source of contaminants (Boston Harbor) and differences in bulk sediment characteristics (grain size and TOC). For example, nearfield sediments typically had more SQG exceedances than farfield sediments with similar grain-size distributions. Further, sediments with higher percentages of fines (silt + clay) typically had more SQG exceedances than coarse-grained sediments. For example, nearfield stations NF12, NF08, NF21, and NF24 had the highest number of SQG exceedances, and the highest percentages of fines (representative coarse- and fine-grained sediments from both nearfield and farfield locations are shown in Figure 3-9, all data in Appendix B7).

Most SQG exceedances were attributed to chemicals with concentrations above the ER-L. Chemical concentrations above the ER-M occurred rarely, and primarily during the early 1990s. Many chemicals contributed to the overall number of SQG exceedances; however, total DDT, mercury, and fluorene were among the most frequent chemicals to exceed the SQGs (Appendix B7, Table B7-1). Concentrations of cadmium and zinc were below the SQGs at all stations and during all sampling events.

Temporal trends in sediment quality are difficult to discern primarily because of the natural fluctuations in bulk sediment characteristics, and because monitoring revisions have reduced the station and sampling frequencies. Even so, the number of SQG exceedances appeared to decrease over time at station NF24 (Appendix B7) located near the outfall and station FF11 (Figure 3-9) located at Cape Anne. The decrease in numbers of SQG exceedances at station NF24 occurred following effluent diversion, whereas the decrease at station FF11 occurred in the mid 1990s. The decline in SQG exceedances at station NF24 may be associated with an apparent coarsening of grain size between baseline and post-diversion periods (Figure B3-3). Substantive changes in grain-size distributions or TOC content were not evident at FF11 between the early to mid 1990s, which suggests that the decline in SQG exceedances at the Cape Anne location may be associated reduced inputs to the system. Except for the observed decline at NF24, there were no substantive changes in the number of SQG exceedances between the baseline and post-diversion periods (representative stations NF17, NF12, FF09, and FF11 are shown in Figure 3-9, all data in Appendix B7), suggesting that sediment quality in Massachusetts and Cape Cod Bays has not been dramatically nor adversely impacted as a result of effluent diversion to the bay.

Location=Nearfield



Location=Farfield

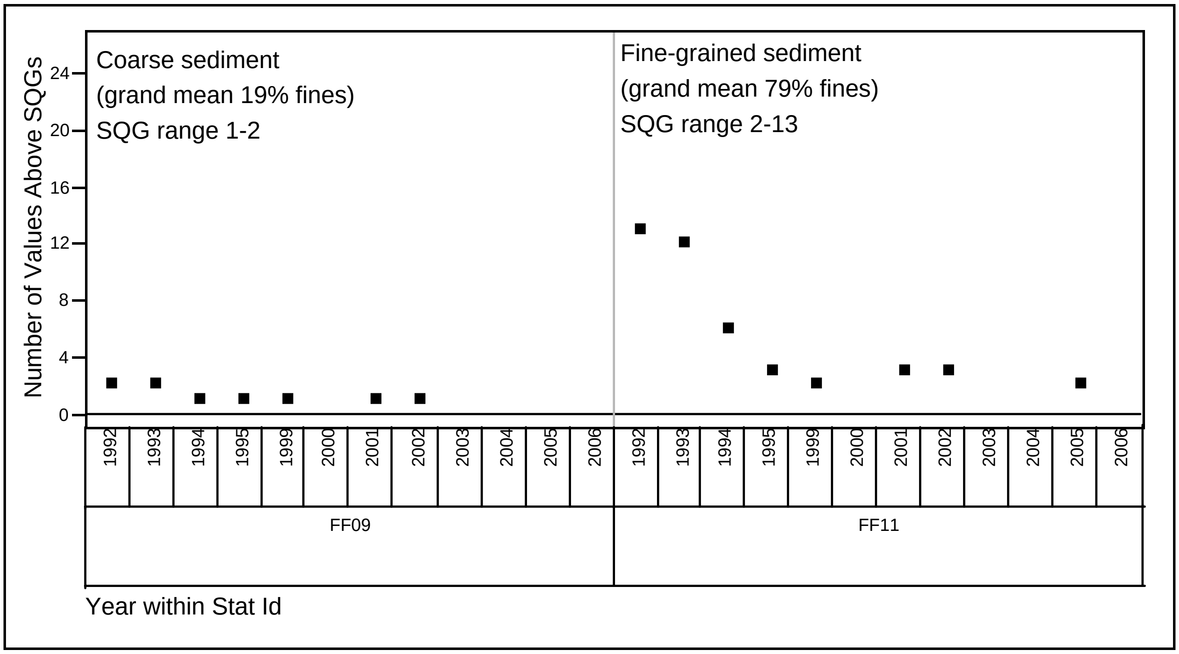


Figure 3-9. Distribution of SQG exceedances from 1992 to 2006 at representative nearfield and farfield stations comprised of coarse- and fine-grained sediments. The reference line represents no (0) SQG exceedances. (Data for all stations are provided in Appendix B7)

3.4 Summary and Conclusions

3.4.1 Monitoring Questions

Relocation of the MWRA outfall to Massachusetts Bay raised environmental concerns regarding potential effects of the diverted discharge on the seafloor. These concerns focused on three issues: eutrophication and related low levels of dissolved oxygen, accumulation of toxic contaminants in depositional areas, and smothering of animals by particulate matter (MWRA 1991, 1997). This section focuses on the second issue, accumulation of potentially toxic contaminants. Sediment monitoring conducted under the Benthic (Seafloor) Monitoring component of the MWRA HOM program was designed to address specific monitoring questions.

- *Have the concentrations of contaminants in sediment changed?*

The long-term monitoring data (1992–2006) show that concentrations of anthropogenic contaminants in surface sediments at nearfield and farfield regions of Massachusetts and Cape Cod Bays are spatially and temporally variable and reflect differences in bulk sediment characteristics such as grain-size distributions and TOC content rather than an outfall impact. For example, storm-induced impacts to the sediment bed following the May 2005 nor'easters likely contributed to a coarsening of grain size and a corresponding decrease in 2005 in concentrations of aluminum, chromium, iron, and nickel, which are primarily crustal in nature.

Post-diversion mean concentrations of total DDT, total PCB, cadmium, and nickel decreased significantly (at the 95% level of confidence) at farfield regions of the Massachusetts and Cape Cod Bays compared to the baseline. Post-diversion mean concentrations of total DDT also decreased significantly at nearfield stations located within 2 km of the outfall and cadmium decreased significantly at the transition area between Boston Harbor and the outfall. Decreases in total DDT and total PCB may be associated with the banning of these chemicals in the 1970s and 1980s. Overall, sediment data to date indicate that post-diversion (2001–2006) concentrations of most anthropogenic contaminants have not changed substantively compared to the baseline (1992–2000).

- *What is the level of sewage contamination and its spatial distribution in Massachusetts and Cape Cod Bays sediments before discharge through the new outfall?*

C. perfringens abundances (not normalized to percent fines) measured in surface sediments throughout Massachusetts and Cape Cod Bays have ranged from undetected (NF23 in 1995; FF05 and FF08 in 1992) to 24,100 cfu/g dry weight (NF21 in 1997). In general, *Clostridium* abundances were low throughout the bay, with slightly higher levels observed closer to Boston Harbor. Abundances generally decreased with distance from the harbor, with farfield sediments located far away from Boston Harbor (>20 km) having the lowest *C. perfringens* abundances.

- *Has the level of sewage contamination or its spatial distribution in Massachusetts and Cape Cod Bays sediments changed after discharge through the new outfall?*

Abundances of *C. perfringens* increased one year after effluent diversion at stations located within 2 km of the outfall. Abundances remained elevated through 2005, and then decreased sharply in 2006 returning to 2000 pre-diversion values.

The post-diversion mean abundances of *C. perfringens* (log-transformed) decreased significantly compared to the baseline means in the transition and farfield regions of Massachusetts and Cape Cod Bays. Most anthropogenic contaminant data did not show this response.

3.4.2 Monitoring Revisions

Revisions to the benthic monitoring plan implemented in 2003 reduced the number of stations sampled each year and the sediment chemistry parameters measured at each station. Further, beginning in 2004 the nearfield and farfield stations were randomly binned into two subsets, to be sampled in alternate (i.e., even and odd) years. From a nearfield- and farfield-wide perspective, sediment data between the two data groupings are generally similar, in terms of variability and concentration ranges, suggesting that stations sampled during a given monitoring year are representative of the larger system. There were some differences in the response of *C. perfringens*, total PCB, cadmium, and silver, however, between the two data groupings at sub-regions within the nearfield. Future design of the monitoring program should consider annual monitoring of one consistent set of stations that is representative of the overall system, which would be more useful in discerning potential trends among the data and detecting potential impacts associated with effluent diversion and severe events.

3.4.3 Conclusions

Consistent with predictions of the SEIS for the Massachusetts Bay outfall (EPA 1988), the transfer of the MWRA effluent discharge into Massachusetts Bay has not resulted in a widespread detectable increase of anthropogenic contaminants in the sediment generally, nor in depositional areas specifically. Moreover, comparison of the long-term monitoring data to SQGs for 27 chemicals suggests that the effluent has not caused substantive changes in the quality of the environment near to or far from the outfall location. While there was a clear signature of effluent discharge on nearby sediments through 2005, abundances of the sewage tracer *C. perfringens* decreased in 2006, returning to 2000 pre-diversion values. Post-diversion mean abundances of *C. perfringens* also decreased significantly in the transition area and farfield compared to the baseline mean values. The *C. perfringens* data clearly trace the major improvements to sewage treatment implemented by the MWRA, which have dramatically reduced the loading of contaminants under their control to coastal Massachusetts. Annual monitoring of one consistent set of stations that is representative of the overall system is essential when evaluating the impact of a relatively clean discharge on coastal sediments with a history of modest levels of contamination.

4. 2006 SEDIMENT PROFILE IMAGING

by Robert J. Diaz

4.1 Status of the Bay

The MWRA offshore outfall is located about 13 to 15 km off Boston Harbor along the inner edge of Massachusetts Bay in an area of complex and variable seafloor morphology and sediment texture that changes over a multitude of scales from a few kilometers to tens of meters (Butman *et al.* 2004). The area encompassing the outfall was designated as the nearfield (see Chapter 2 this report; Figure 4-1). Starting in 1992, Sediment Profile Images (SPI) were collected at a set of unconsolidated sediment stations to gather baseline data on benthic habitat conditions for infaunal communities and the depth of the apparent color redox potential discontinuity (RPD) layer as described in the MWRA's Contingency Plan (MWRA 2001). Multibeam mapping of the nearfield allowed for the analysis of the complex topography and how it may relate to benthic habitat quality. Ten of the nearfield stations were located in a relatively flat topographic feature, which included the outfall, west and south of the outfall at depths of 30–35 m (Figure 2-1, Figure 4-1). Another 13 stations were scattered around the outfall, primarily to the west. The baseline included six annual August collections from 1992 to 2000. In September 2000, the offshore outfall went into operation, thus annual August data collected from 2001 to 2006 represent post-diversion condition in the nearfield.

The dynamics of the RPD layer are related principally to the interaction of physical and biological processes that structured surface sediments and infaunal communities. During the baseline period, the mean RPD layer depth varied from a low of 1.8 cm (SE = 0.13 to 0.14) in 1997 and 1998 to a high of 3.0 cm (SE = 0.22) in 1995. In 1997, due to technical problems, sampling occurred in both August and October, which may have contributed to shallower RPD layers since the RPD layer becomes seasonally shallower in the fall. The largest deepening of the RPD layer between successive samplings was 0.5 cm from 1999 to 2000 and was associated with an increase in the levels of biogenic activity following the 1998 low storm frequency winter (Butman *et al*. In prep.) that allowed for the preservation of biogenic structures. The increased occurrence of Stage II communities in 1998 and 1999, and Stage III in 1999 (Figure 4-2), was a key factor in the deepening of the RPD. It appeared that successional Stage I pioneering communities dominated the nearfield stations from the start of SPI sampling in 1992 through 1997. Starting in 1998, it appeared that intermediate successional Stage II communities dominated to the end of the baseline period in 2000 and into 2004. In 2005 and 2006, there were indications that evidence of both pioneering Stage I and equilibrium Stage III communities had increased relative to Stage II (Figure 4-2). Most of the biogenic activity was related to burrowing organisms that created feeding mounds and pits in the sediment surface, and to small tube-building worms.

Factors responsible for the depth of the RPD layer in the nearfield appeared to be acting at regional scales with yearly patterns in RPD depth reasonably consistent across stations. From 1997 (*i.e.*, the start of annual sampling) to 2006, nine stations had measurable RPD layer depths for all years with a general concordance between these stations and time (Figure 4-3). There was a significant deepening trend in RPD from 1997 to 2000 throughout the nearfield area. This trend occurred among the four stations within the topographic feature that contains the outfall and the five stations in other topographic features surrounding the outfall (Figures 4-1 and 4-3). The post-diversion period, from 2001 to 2006, did not have significant trends in RPD layer depth for these nine stations (Table 4-1).

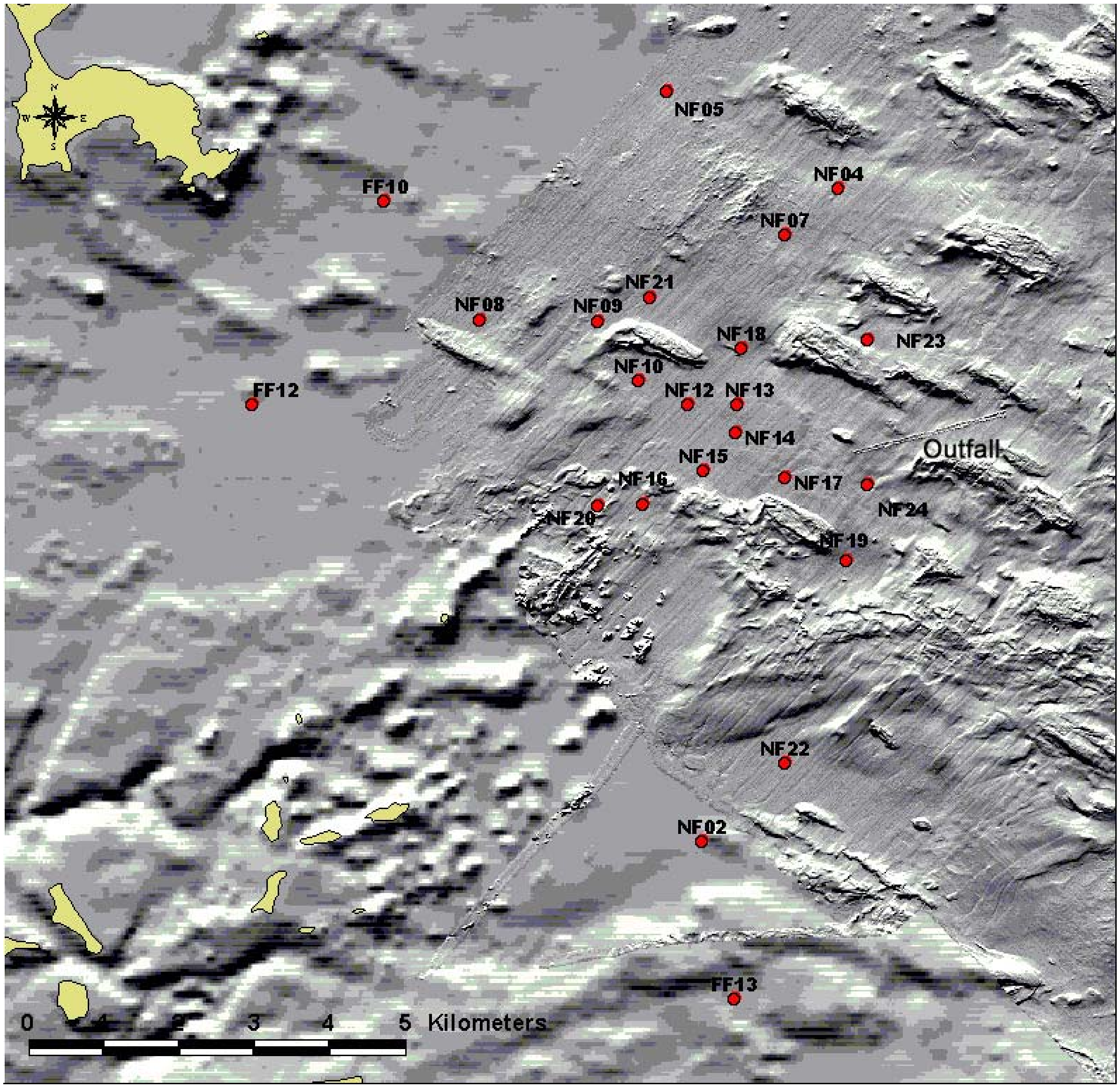


Figure 4-1. Locations of nearfield stations overlaid on multibeam bathymetry of Butman *et al.* (2004).

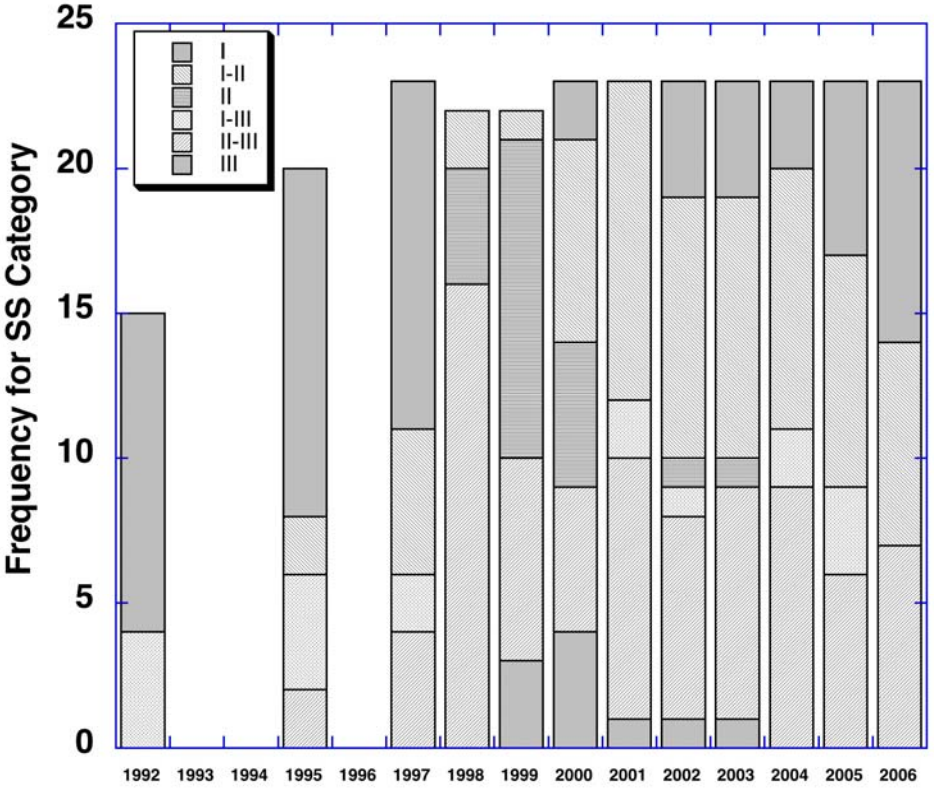


Figure 4-2. Estimated successional stage from nearfield SPI for all years.

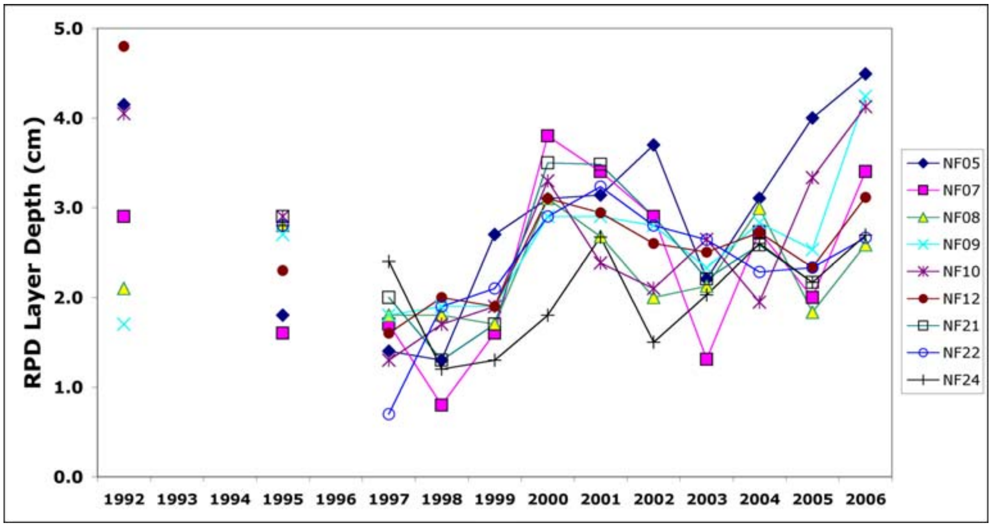


Figure 4-3. Apparent color RPD layer depth (cm) for the nine nearfield stations that had measured values for all years.

Table 4-1. Summary of repeated measures regression for RPD depth and OSI with year. Only stations with measured values for all years were included. Based on generalized estimating equations using identity link and normal distribution.

Selected Stations				
Flat Area near Outfall	NF10, NF12, NF21, NF24			
Other Areas	NF05, NF07, NF08, NF09, NF22			
RPD				
Period	**Topographic Feature**	**Multiplier**	**SE**	**p**
Baseline Years (1997–2000)	Flat Area near Outfall	0.345	0.15	0.024
Post-Diversion Years (2001–2006)	Flat Area near Outfall	0.550	0.07	<0.001
Baseline Years (1997–2000)	Other Areas	0.077	0.09	0.376
Post-Diversion Years (2001–2006)	Other Areas	0.097	0.06	0.099
OSI				
Period	**Topographic Feature**	**Multiplier**	**SE**	**p**
Baseline Years (1997–2000)	Flat Area near Outfall	1.272	0.529	0.016
Post-Diversion Years (2001–2006)	Flat Area near Outfall	0.136	0.16	0.380
Baseline Years (1997–2000)	Other Areas	0.640	0.22	<0.001
Post-Diversion Years (2001–2006)	Other Areas	0.052	0.04	0.262
All Stations Included				
Flat Area near Outfall	NF10, NF12, NF13, NF14, NF15, NF17, NF18, NF19, NF21, NF24			
Other Areas	FF10, FF12, FF13, NF02, NF04, NF05, NF07, NF08, NF09, NF16, NF20, NF22, NF23			
OSI				
Period	**Topographic Feature**	**Multiplier**	**SE**	**p**
Baseline Years (1997–2000)	Flat Area near Outfall	0.907	0.240	<0.001
Post-Diversion Years (2001–2006)	Flat Area near Outfall	0.145	0.1	0.139
Baseline Years (1997–2000)	Other Areas	0.640	0.22	0.004
Post-Diversion Years (2001–2006)	Other Areas	0.206	0.12	0.072

The Organism Sediment Index (OSI), a measure of benthic habitat condition, indicated that infaunal communities at 30% of the nearfield stations might have been stressed for three or more years during the baseline period. This assessment is based on applying the interpretation of OSI developed by Rhoads and Germano (1986) for inshore estuarine habitats, where an OSI <6 would be indicative of stressed conditions. The likely stressors in the nearfield were the physical processes shaping the dynamic sedimentary environment rather than water or sediment quality, since both water and sediment quality were consistently found to be good (see Chapter 3 this report, Libby *et al.* 2003, Tucker *et al.* 2005). In the long term, the annual OSI oscillated around a baseline grand mean of 6.4 (SD = 1.68), with the greatest departure in 1997 likely due to the shift in sampling dates from August to October. When stations were grouped by topographic feature (the flat area that contains the outfall and may be more prone to sedimentation versus other areas to the north, west, and east, see Figure 4-1) and only stations with measured OSI values for all years were considered, there was a significant increase in OSI through time for the baseline years (Table 4-1 and Figure 4-4). This increase was related to the deepening RPD layers and advancing estimated successional stages, the two factors used in OSI calculation. Post-diversion, from 2001 to 2006, there were no significant trends in OSI. This correspondence between defined topographic areas and OSI through time for the baseline period indicated that factors affecting OSI were acting at broader regional scales. For example, much of the increase in OSI during the baseline period may have been related to relief from bottom stress from storms. The winter of 1997 was stormy with lower OSI values while the winter of 1998 was calm and had correspondingly high levels of biogenic activity with increasing OSI values.

In the post-diversion period, the OSI exhibited no significant trends even in 2005, which was the stormiest year on record (Butman *et al.* In prep.). However, the increase in pioneering Stage I fauna in 2005 and 2006 would be consistent with increased stress to the benthos, with the two likely sources in 2005 being outfall operation and severe storm activity. Examination of sediment TOC and *Clostridium perfringens* spores for 2005 (both potential indicators of an outfall effect), found that neither increased when normalized to percent fines (Chapter 3, this report), which leaves storm activity as a possible source of stress in 2005 (Butman *et al.* In prep.). Evidence of a coarsening in sediment grain-size (reduction in fines) and TOC (lower %) following the 2005 storms was also found at seven stations (Chapter 3, this report). These grain-size and TOC patterns continued into 2006.

4.2 Methods

4.2.1 Image Analysis

The digital SPI images were analyzed by using Adobe Photoshop®. Data from each image were sequentially saved to a spreadsheet file for later analysis. Details of how these parameters were estimated can be found in Diaz and Schaffner (1988) and Rhoads and Germano (1986). Table 4-2 summarizes the parameters measured. Video of surface sediments in front of the prism were recorded onto digital videotape and still frames were extracted using Final Cut Pro® software. Still frame images were sharpened and the histograms equalized with Adobe Photoshop®.

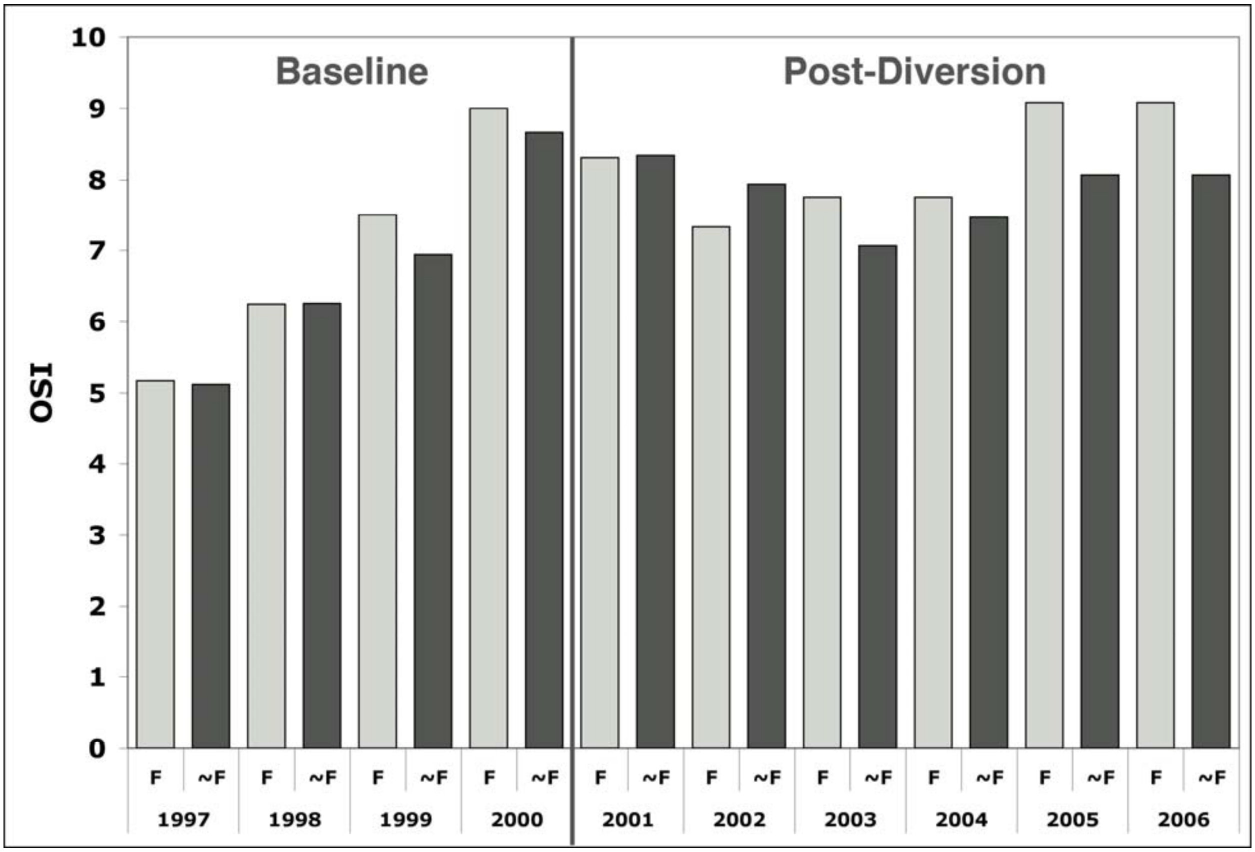


Figure 4-4. Average Organism Sediment Index (OSI) summarized by year and topographic feature for stations with measured values in all years. The relatively flat topographic area within which the outfall is located is F (see Figure 4-1), other areas around the outfall are ~F.

Table 4-2. Parameters measured from Sediment Profile Images.

Parameter	Units	Method	Description
Sediment Grain Size	Modal phi interval	V	An estimate of sediment types present. Determined from comparison of image to images of known grain size
Prism Penetration	cm	CA	A geotechnical estimate of sediment compaction. Average of maximum and minimum distance from sediment surface to bottom of prism window
Sediment Surface Relief	cm	CA	An estimate of small-scale bed roughness. Maximum depth of penetration minus minimum
Apparent Reduction-oxidation Potential Discontinuity Depth (from color change in sediment)	cm	CA	Estimate of depth to which sediments appear to be oxidized. Area of aerobic sediment divided by width of digitized image
Thickness of Sediment Layers	cm	CA	Measure thickness above original sediment surface
Methane/Nitrogen Gas Voids	Number	V	Count
Epifaunal Occurrence	Number	V	Count, identify
Tube Density	Number /cm^2	V	Count
Tube Type Burrow Structures Pelletal Layer Bacterial Mats	 — cm —	 V V V	 Identify Measure thickness, area Determine presence and color
Infaunal Occurrence	Number	V	Count, identify
Feeding Voids	Number	V	Count, measure thickness, area
Apparent Successional Stage	—	V,CA	Estimated based on all of the above parameters
Organism Sediment Index	—	CA	Derived from RPD, successional stage, gas voids (Rhoads and Germano 1986)

V: Visual measurement or estimate
CA: Computer analysis

4.2.2 Statistical Analysis

Given the nonrandom selection of nearfield station locations, fixed-effect longitudinal designs were used to analyze patterns in the data. Generalized estimating equations (GEE) were applied with a model structure using the normal distribution and identity link with cross-station correlations assumed to be equal (Zeger *et al.* 1988). Analysis of variance (ANOVA) and analysis of covariance were also used to test for differences between and within areas for quantitative parameters. Normality was checked with the Shapiro-Wilk test and homogeneity of variance with Bartlett's test. If variance was not homogeneous, Welch analysis of variance, which allows standard deviations to be unequal, was used in testing for mean differences (Zar 1999). Tukey's LSD test was used for multiple mean comparisons. All statistical tests were conducted using SAS® (SAS Institute, Inc.). Cluster analysis was conducted with normalized Euclidean distance with complete linkage sorting using PRIMER 6 (PRIMER-E Ltd.).

4.3 Results and Discussion

4.3.1 Summary of 2006 SPI Data

Physical Processes and Sediments—Sediment grain size in 2006 continued to be heterogeneous and ranged from pebble to fine-sand-silt-clay (Figures 4-5 and 4-6). When compared to 2004 and 2005, sediments in 2006 appeared to have remained coarser. In 2004, eight stations had maximum grain sizes coarse or coarser than gravel. This increased to 11 stations in 2005 and 13 in 2006 (Table 4-3). The years when sediments appeared finer were 1999, 2000, 2003, and 2004. While part of the year-to-year variation in grain-size within some stations could be attributed to small-scale patchiness of sediments within the 30-m radius station target, the storminess of 2005 appeared to be a major factor in the coarsening of nearfield sediments. Sediment grain-size analysis also confirmed a coarsening of sediments in 2005 and 2006 (Chapter 3). Prism penetration, which is correlated with grain-size, was similar in 2006 to 2005 (paired t-test, $p = 0.424$) with lowest penetration occurring at sand to pebble stations and the highest at mixed muddy stations. Penetration was shallowest (0.0 cm) at Station NF13, which was pebble and cobble, and deepest (14.5 cm) at Station NF21, which had fine-sand-silt-clay (Figure 4-5 and Table 4-3). Relative to the baseline years, sediment grain sizes in 2006 were most similar to samples from 1995 through 2000. For baseline year 1992, sediments coarser than gravel were not recorded from the SPI images. This was likely related to the image analysis methods, which did not report pebble or cobble grains. A reanalysis of 1995 and 1997 images did find pebble and cobble grains at eight stations where they were not reported by previous analyses (Table 4-4). Images from 1992 were not available for reanalysis. Sediment grain-size analysis in 2006 found that the percentage of sand and gravel had increased at seven stations (NF10, NF13, NF14, NF15, NF17, NF20, and NF21) compared with previous years (Chapter 3). All of these stations except NF20 were located in the same topographic feature as the outfall. For these seven stations, the SPI-estimated modal grain-size coarsened for NF14, NF15, and NF20 (Table 4-4). A similar pattern of increased coarse grains was observed at stations FF10, FF13, NF07, NF19, and NF23. The coarsening of sediments in 2006 was likely related to bottom disturbance from 2005 storms, which were associated with the second highest bottom stress winter on record (Butman *et al.* In Prep.). Evidence of bottom current stress in the form of grain-size layering was observed at stations NF02, NF04, NF05, NF16, and NF19 (Table 4-4). In all cases of layering, it appeared that coarser sediments overlaid finer sediments, which could be related to storm-induced winnowing of fines from surface sediments.

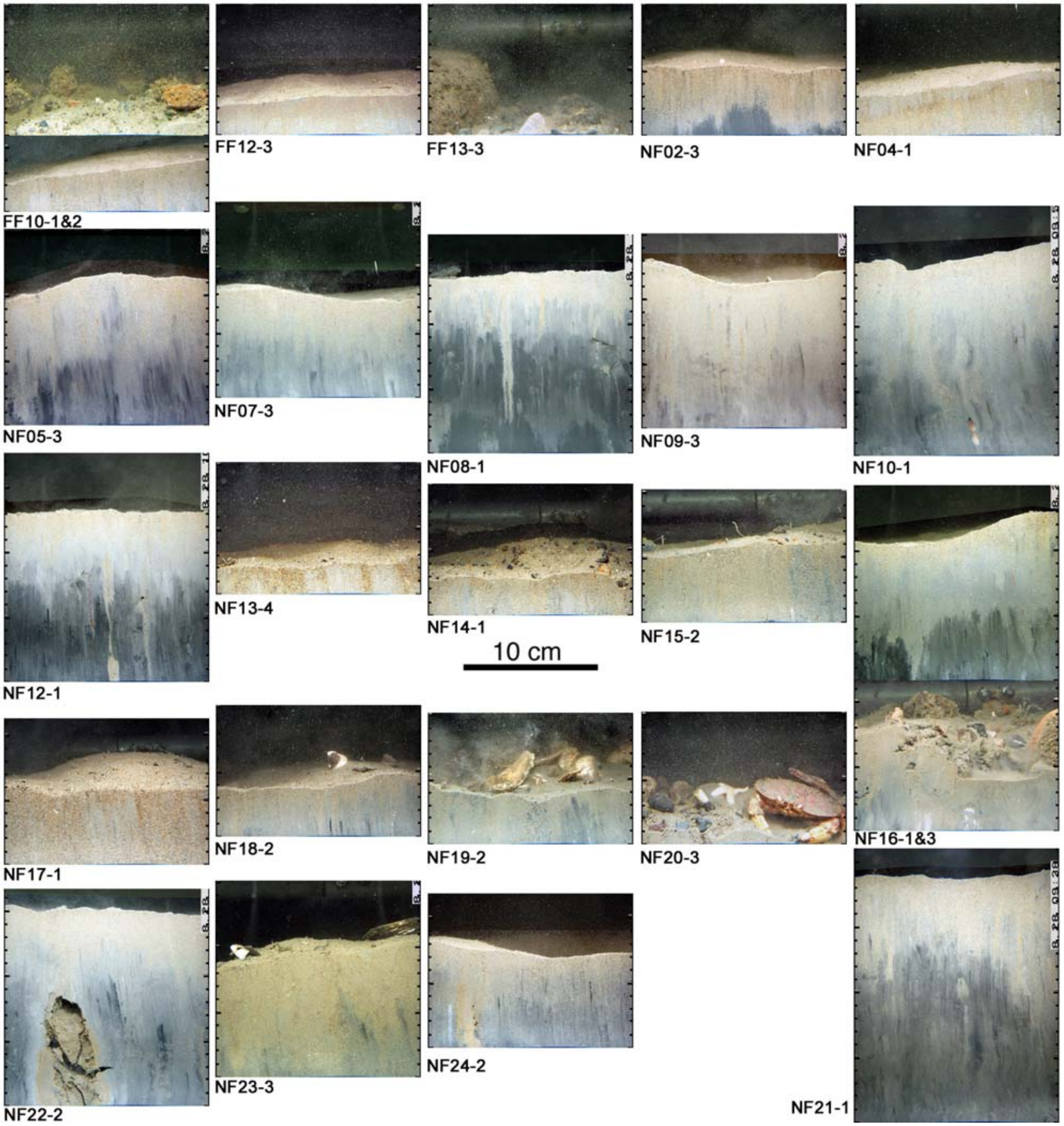


Figure 4-5. Example SPI for 2006 nearfield stations. Number following station is replicate image number. Image color was enhanced to emphasize the difference between oxic and anaerobic sediments.

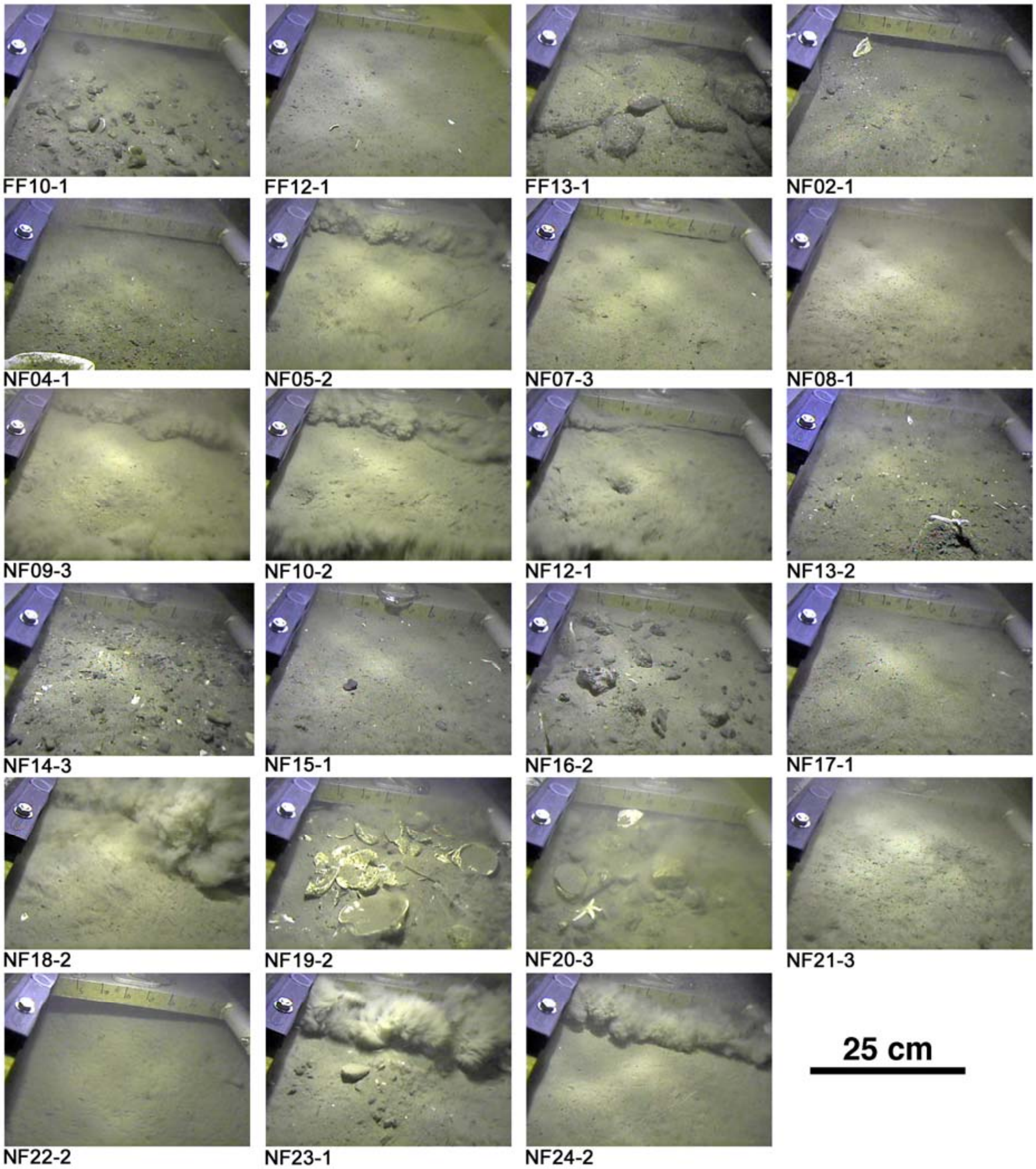


Figure 4-6. Example sediment surfaces for 2006 nearfield stations extracted from videotape. Number following station is replicate image number. The contrast was enhanced and edges sharpened in all images.

Table 4-3. Summary of SPI parameters for nearfield stations, August 2006. Data from all replicates were averaged for quantitative parameters and the median was used for categorical parameters.

STA	PEN[1] (cm)	SR[2] (cm)	RPD[3] (cm)	Modal Grain Size	Max Grain Size	Surface Process	Amphi. Tubes	Worm Tubes	INF[4]	BUR[5]	Oxic Voids	SS[6]	OSI[7]
FF10	1.4	1.3	>1.4**	FS to FSGRPB	PB	PHY	NONE	MANY	0.0	0.0	0.0	I	IND
FF12	2.6	1.2	>2.6	FS	GR	PHY	NONE	SOME	0.0	1.0	0.0	I-II	IND
FF13	0.0	IND*		CLPB to CBPB	CB	PHY	NONE	MANY	IND	IND	IND	I	IND
NF02	4.4	1.1	3.7	FS/FSSI to FS	PB	PHY	NONE	FEW	0.3	0.7	0.0	I	6.7
NF04	3.6	1.4	>3.6	FS/FSMS to FSMS	PB	PHY	NONE	SOME	0.0	0.3	0.0	I-II	8.0
NF05	8.2	1.3	4.5	FS/FSSI to FSSI	FS	BIO/PHY	SOME	MANY	3.7	5.0	0.7	II-III	9.3
NF07	10.9	2.0	3.4	FSSICL	FS	BIO/PHY	NONE	SOME	5.3	3.3	0.7	I-II	7.7
NF08	13.2	1.1	2.6	FSSICL	FS	BIO/PHY	FEW	MANY	4.0	2.3	2.0	II-III	8.0
NF09	9.2	1.1	4.2	FSSICL	FS	BIO/PHY	FEW	SOME	5.7	3.0	0.0	II-III	9.7
NF10	12.9	1.8	4.1	FSSICL	FS	BIO/PHY	FEW	FEW	4.0	3.3	0.0	II-III	9.3
NF12	13.9	1.8	3.1	FSSICL	FS	PHY	NONE	SOME	3.7	4.0	2.0	II-III	8.7
NF13	1.8	0.8	>1.8	FSMSGR	PB	PHY	NONE	SOME	0.0	0.0	0.0	I	IND
NF14	2.5	1.0	>2.5	FSSIGRPB	PB	PHY	NONE	SOME	0.3	0.0	0.0	I	IND
NF15	3.8	1.1	5.3	FSSIGR	PB	PHY	NONE	FEW	0.7	0.0	0.0	I	7.0
NF16	6.9	2.9	2.6	FSSI/SICL to FSSIGRPB	PB	PHY	NONE	SOME	1.0	0.3	0.0	I	5.3
NF17	3.7	0.8	>3.7	FSMS	MS	PHY	NONE	SOME	0.0	0.0	0.0	I-II	8.0
NF18	4.6	1.3	2.2	FSSI to FSSIGR	PB	PHY	NONE	SOME	1.7	0.3	0.3	I-II	6.7
NF19	3.7	1.1	1.9	FS/FSSI to FS	PB	PHY	NONE	FEW	1.7	1.0	0.0	I	4.5
NF20	1.1	1.3	>1.1	FSSIGR	PB	PHY	NONE	SOME	0.0	0.0	0.0	I	IND
NF21	14.5	2.1	2.7	FSSICL	FS	BIO/PHY	NONE	SOME	3.0	3.7	1.3	II-III	8.0
NF22	11.0	1.4	2.7	FSSICL	FS	BIO/PHY	NONE	SOME	3.0	2.0	0.0	II-III	8.0
NF23	6.6	1.5	4.6	FSMSGR	PB	PHY	NONE	SOME	0.0	0.0	0.0	I-II	8.0
NF24	7.8	1.9	2.7	FSSICL	GR	BIO/PHY	NONE	SOME	3.7	3.3	0.7	I-II	6.7

IND = Indeterminate ** > = Actual values are deeper than prism penetration.

Table 4-4. Range of sediment grain size at nearfield SPI stations for all sampled years.

	Baseline						Post-Diversion					
Station	1992	1995	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006
FF10	VFS	.	PB to VFS	VFS	CB to SIFS	PB to GR	CB to FS	PB to FSSICL	VFS	FSSICL	PB to FSSI	FS to FSGRPB
FF12	.	.	VFS	FS	FS	VFS	VFS	VFS	VFS	VFS	VFS	FSGR
FF13	.	.	SIFS	SIFS	CB to FSSI	CB to SI	FSSI	CB to FSGR	CB to FSSI	FSSI	CB to PB	CLPB to CBPB
NF02	VFS	PB to CS	SIFS	PB to GR	CB to FSSI	CB to MSCS	FSSI	FSSI	FSMS/FSSI	FSSICL	SIFS	FS/FSSI to FSPB
NF04	FS	FS	PB to VFS	FS	GR to FS	FS	PB to FSMS	PB to FS	FS	FS	FSMS	FS/FSMS to FSMSPB
NF05	FS	VFS	VFS	VFS	FS/SICL	FS/SICL	FSSICL	FSSICL	FSSICL	FSSICL	FS/FSSI	FS/FSSI to FSSI
NF07	VFS	VFS	VFS	VFS	SIFS	SIFS/CL	FSSICL	FSSICL	FSSICL	FSSICL	PB to FSSICL	FSSICL
NF08	VFS	SIFS	VFS	VFS	SIFS	SIFS	SIFS	FSSICL	SIFS	FSSICL	FSSICL	FSSICL
NF09	VFS	VFS	VFS	VFS	FSSI	FSSI	FSSICL	FSSI	FSSICL	FSSICL	FSSICL	FSSICL
NF10	VFS	VFS	VFS	VFS	FSSICL	FSSICL	FSSICL	FSSICL	FSSICL	FSSICL	FSSICL	FSSICL
NF12	VFS	SI	SIFS	SIFS	FSSICL	FSSICL	FSSICL	FSSI	FSSICL	FSSICL	FSSICL	FSSICL
NF13	FS	PB to VFS	PB to FS	PB to SIFS	FSMS	PB to FSMS	GR to FSMS	PB to FSMS	PB to FSMS	FSMSGRPB	FSMSGR	FSMSGRPB
NF14	FS	PB to VFS	PB to VFS	PB to VFS	PB to SIFS	PB to FSSICL	PB to FSSI	PB to FSSI	PB to FSSIGR	FSMSSIGRPB	PB to FSMSSI	FSSIGRPB
NF15	FS	PB to VFS	PB to VFS	GR to FS	PB to FSSI	PB to FSSI	PB to FSSI	GR to VFS	PB to FSSIGR	FSMSSIGRPB	PB to FSMSSI	FSSIGRPB
NF16	VFS	SIFS	VFS	SIFS	FSSICL	PB to FSSI	CB to FSSICL	FSSICL	CBPB	PB to FSSICL	PB to SICL	FSSI/SICL to FSSIGRPB
NF17	FS	CS to FS	FS	FS	GR to FSMS	PB to FSMS	FSMS	FSMS	FSMS	FSMS	FSMS	FSMS
NF18	VFS	PB to VFS	GR to VFS	GR to VFS	PB to SIFS	FSSICL	PB to FSSICL	PB to FSSICL	PB to FSSIGR	FSSIGRPB to FSMS	PB to FSSI	FSSI to FSSIGRPB
NF19	.	PB to VFS	GR to VFS	FSSICL	FSSICL	CB to FSSICL	GR to FSSI	VFS	CB to FSSI	FSSIGRPB	PB to FSSI	FS/FSSI to FSPB
NF20	VFS	PB to VFS	CB to FSMS	GR to SICL	PB to SIFS	PB to SIFS	PB to FSSI	FSSI	CB to FSSIGR	FSSIGRPB	PB to FSSI	FSSIGRPB
NF21	.	SIFS	VFS	SIFS	SIFS	SIFS	SIFS	FSSICL	FSSICL	FSSICL	FSSICL	FSSICL
NF22	.	SIFS	SIFS	SIFS	SIFS	SIFS	FSSICL	FSSICL	FSSICL	FSSICL	FSSICL	FSSICL
NF23	.	CS to VFS	FS	FS	PB to FSSICL	GR to FSMS	PB to FSMS	GR to FSMS	PB to FSMS	FSMSGRPB	PB to FSMS	FSMSGRPB
NF24	.	SI	SIFS	FSSICL	PB to FSSICL	FSSICL	FSSICL	FSSICL	FSSICL	FSSICL	FSSICL	FSSICLGR

CB = Cobble GR = Gravel PB = Pebble CS = Coarse-sand CL = Clay MS = Medium-sand FS = Fine-sand VFS = Very-fine-sand SI = Silt / = Layered

Apparent color RPD Depth—At seven porous, coarse-sediment stations (FF10, FF12, NF04, NF13, NF14, NF17, and NF20) the apparent color RPD layer depths were deeper than the prism penetration for all replicates. For these stations, prism penetration was then assumed to be a conservative minimum estimate of the RPD layer depth and was included in the calculation of the average RPD layer depth for 2006. At stations NF02, NF15, NF19, and NF23, one or two of the three replicate images had RPD layers that were deeper than the prism penetration and at station FF13 all three replicate images had indeterminate RPD layers due to pebble and cobble sediments. The general pattern in RPD layer depths in 2006 was similar to both the baseline and previous post-diversion years (Figure 4-3). In 2006, the average apparent color RPD layer depth ranged from >1.1 cm (NF20) to 5.3 cm (NF15), with a grand mean of 3.0 cm (SD = 1.09 cm). A Welch ANOVA, which tests for equality of mean while allowing the standard deviations to be unequal (a problem when sample sizes are unequal, 123 for baseline years vs. 22 for 2006), found that there was a significant increase in the depth of the apparent color RPD layer depth between baseline years and 2006 (F = 8.65, p = 0.007). The fact that in 2006 the RPD was deeper than baseline would indicate that the RPD threshold was not exceeded. The difference between 2006 and the baseline was a deepening of the RPD by an average of 0.7 cm or 32%. When the six baseline years were compared to the six discharge years using a repeated measures generalized estimating equation, the discharge years had significantly deeper RPD layers (baseline to discharge years multiplier 0.202, SE = 0.097, p = 0.038). If the same analysis is restricted to the nine stations with only measured RPD layers (Figure 4-3) for all 12 years of data, the post-diversion years have even deeper RPD layers (baseline to discharge years multiplier 0.510, SE = 0.106, p = <0.001).

Biogenic Activity—Biogenic structures and organism activity observed in SPI for 2006 was about the same as for 2005. Relative to 2004, both 2005 and 2006 SPI appeared to have less biogenic activity. For example, while tubes were observed at all 23 stations, their overall density was lower in 2005 and 2006. In 2004, ten stations had many tubes (>24 tubes/image); there were five and four stations with many tubes in 2005 and 2006, respectively. Most stations had moderate densities (from 18 to 24 tubes per image) of small (<1 mm diameter) polychaete tubes, likely spionids, which are the most abundant small tube-building infauna at nearfield stations (Chapter 5). Only stations NF05, NF08, NF09, and NF10 had larger amphipod-like tubes. Mobile epifauna were not common: small shrimp were seen at stations FF10 and NF04, *Cancer* spp. crab were seen at stations NF04 and NF20. The lower levels of biogenic structures and epifauna are consistent with the dominance of physical processes in structuring surface sediments with surfaces in 2006 appearing similar to 2005. In 2006, 8 of the 23 stations appeared structured by a combination of biological and physical processes (*e.g.*, NF09). At 15 stations (e.g., FF13), physical processes dominated. No station was classified as having a biologically structured sediment surface in 2006 (Table 4-3). Relative to 2005, when tubes covered 20% of stations with cobble- and pebble-size sediments, 58% of cobble and pebble sediments in 2006 were covered with tubes.

The number of subsurface biogenic structures, primarily burrows and oxic voids, and free-burrowing infaunal worms were not significantly different between 2006 and 2005, but mean structures per image all trended down. The number of worms in 2006, 1.9 (SE = 0.66) worms per image, was significantly lower than the last three years of the baseline period, the only years with worms per image data, (Welch ANOVA, F = 12.13, p = <0.001). The last three years of the baseline period averaged 3.9 (SE = 0.40) worms per image. The decline in tubes and infaunal worms in images was corroborated by the infaunal data where the number of species and abundance declined from 2005 to 2006 (See Chapter 5).

Successional Stage and Organism Sediment Index—The distribution of estimated successional stages of the infaunal communities in 2006 was about evenly split between pioneering (Stage I) at 40% and a combination of pioneering and intermediate (Stage I to II) at 30%, and a combination of intermediate and equilibrium (Stage II to III) at 30% of stations (Figure 4-2). Stations with successional Stage I designation had little indication of biogenic activity other than small worm tubes on the sediment surface and tended to have coarser-grained sediments (Table 4-3). Stage II and III successional designations were made based on the degree of biogenic sediment reworking and presence of larger fauna. Relative to 2005, the pioneering Stage I classification increased in 2006 for the third time post-baseline, the other times being 2002 and 2005 (Figure 4-2). Over the 15-year period of sampling the nearfield, the largest shift in successional stage occurred during the baseline period between 1997 and 1998 when the number of stations with Stage I classification declined and stations with Stage II to III increased (Figure 4-2). Prior to 1998, the Stage I classification accounted for over half of all stations. From 1998 to 2006 Stage II and III classifications dominated. Biogenic structures associated with activities of successional Stage II and III fauna were the most common evidence of biological processes in 2006 and were similar to those found during the baseline period. Included were what appeared to be *Haploops* spp. tubes (NF05), biogenic whips or sticks of *Dyopedos* spp. (FF12), and biogenic mounds (NF09). Subsurface biogenic structures associated with infaunal organisms included active oxic burrows (NF05) and water-filled oxic voids (NF21). A ceriantheid anemone was observed at station NF10. Overall, trends in estimated successional stage for the nearfield corresponded closely to those within Boston Harbor (Maciolek *et al.* 2006). This correspondence may reflect some broad regional response to a combination of nutrient reduction, shifting location of loading points, and climatic events.

In 2006, the mean Organism Sediment Index (OSI) was 7.6 (SE = 0.33) for the 17 stations with calculated values, which was statistically higher than the baseline grand mean of 6.4 (SE = 0.15) (ANOVA, F = 5.7, p = 0.018) and the highest yearly grand average OSI (Figure 4-4). Rhoads and Germano (1986) developed the OSI for assessing benthic conditions of inshore estuarine and coastal embayments in the northeast and found that OSI values <6 were associated with benthic communities under some form of stress, either from organic loading or physical processes, while higher values of the OSI were associated with well-developed communities. Based on this interpretation of the OSI, on average the nearfield SPI stations were not stressed. However, caution must be applied when the OSI is used in a different environment as a means of assessing benthic conditions. Diaz *et al.* (2003) found that for Chesapeake Bay OSI values of <3 were associated with stressed benthic communities based on comparison with the benthic index of biotic integrity (BIBI, Weisberg et al. 1997). In 2006, two stations had OSI values <6 (NF16 and NF19). At these stations the stressor appeared to be physical processes with no sign of stress from organic loading (Table 4-3). At another six stations, which were also physically dominated, the OSI could not be calculated because of shallow prism penetration. The lowest station-averaged OSI value was 4.5 at station NF19, which had coarse heterogeneous sediments with little evidence of biological activity. In 2005, NF19 also had the lowest average OSI value (3.0). The highest average OSI in 2006 was 9.7 at station NF09, which had finer sediments and a well-developed infaunal community.

4.3.2 Comparison of Pre-and Post-Diversion Results

If the outfall were considered a point source of stress to the nearfield, then local outfall effects would be related to local topography and currents, which would influence erosion/deposition events and transport of materials from the outfall, and with distance from the outfall. To test this hypothesis we constructed a series of GEE models with stations as a fixed repeated measure, baseline/post-diversion and topography (flat area where outfall was located vs. other areas, see Figure 4-1) as binary factors, and distance measured as a straight line from a station to the nearest diffuser on the outfall as a covariate. Parameters from SPI, infaunal community, and sediments for all years and stations were the dependent variables. Overall, the analyses failed to identify many significant differences. At the community structure level, none of the infaunal parameters was different between baseline and post-diversion periods, or between topographic features, or distance from outfall (Table 4-1). For sediment parameters, *Clostridium perfringens* spores and TOC, both normalized to percent fines, decreased with distance from the outfall; however, there were no significant relationships with baseline/post-diversion or topographic features, likely due to high between year variation. For SPI parameters, infauna per image, oxic and anaerobic voids per image all declined post-diversion, while RPD layer depth increased post-diversion (Table 4-1).

While sediments at many stations in 2006 continued to be heterogeneous, with a mixture of grain sizes ranging from sandy-silts-clays to pebbles (Table 4-3), there was no significant change in the sedimentary environment relative to baseline vs. post-diversion years. Recent conditions for 2005 and 2006 point to the possible influence of storms as a major structuring factor for nearfield benthic habitats. In 2005, sediment grain-size analysis did indicate that sediments at seven nearfield stations were coarser relative to 2004, possibly related to bottom stress from winter storms that were the strongest on record for the Boston area (Chapter 3, Butman *et al*. In Prep.). Overall, modal grain-size estimated from SPI in 2005 for all 23 stations (mean 4.1, SE 0.4 Phi) tended to be coarser than 2004 (mean 4.4, SE 0.3 Phi), with 2006 (mean 3.8, SE 0.4 Phi) being almost as coarse as the sediment in 1992 (mean 3.6, SE 0.1 Phi), which was the second most stormy year on record (Butman *et al.* In prep). Thus, it appears that particularly stormy years can influence surficial sediments at broad regional scale within the nearfield. Sediment grain-size heterogeneity is a characteristic of most nearfield stations and is related to regional geomorphology (Butman *et al.* 2004). The predominance of coarse-grained sediments also reflected the importance of physical processes in structuring benthic habitats. In 2005 and 2006, it appeared that physical processes predominated over biological processes in structuring surface sediments with biogenic structures on the sediment surface and organism activity within the sediment appeared to be lower relative to 2004 and less than the last three years of the baseline period, which marked the high point for biogenic activity and coincided with a period of low winter storm activity.

Based on SPI, there did not appear to be much change between the baseline and post-diversion periods in the sediment color or fabric at a station, which would indicate there has not been an accumulation of organic matter in surface sediments of the nearfield stations since the start of outfall operation. If TOC of sediments was increasing, the color of anaerobic sediments would shift from lighter gray to darker gray (Fenchel 1969). Sediment flux measurements and TOC trends support the SPI conclusions that organic material for the post-diversion years have remained low indicating there has been little change in sediment quality since start of outfall operation (Chapter 3 and Tucker *et al*. In Prep.).

The OSI, an index of benthic habitat conditions, trended upward from 2004 with a grand average of 7.4 (SE 0.4) in 2005 and 7.6 (SE 0.3) in 2006 (Figure 4-4). This increase in OSI appears counter to the increase in physical stress the bottom received over the winter of 2004–2005 (Butman *et al*. In Prep.), but it was surficial sediments with small surface- and near-surface-dwelling infauna, mostly pioneering successional Stage I fauna, which were disrupted by higher bottom stress but were able to recolonize after the disturbance. Deeper dwelling fauna responsible for much of the subsurface biogenic activity did decline but were less affected. This, combined with deeper RPD layer depths, led to higher OSI values even with the increased predominance of physical processes. This positive response of the OSI to increased physical stress in coastal habitats points to the problems of using an index based on a muddy estuarine paradigm to assessing habitat conditions in open coastal systems. In contrast, the increasing trend in OSI that started in 1998 was in response to increased importance of biological processes in structuring surface sediments throughout the nearfield. For example, in 1999 nine stations and in 2001 four stations had dense mats of what appeared to be polychaete tubes (>50,000 tubes per m^2), but tube mats have not been observed since 2002. Also, the medium-size twisted tube that was widespread at nearfield stations in 2001 did not occur in 2006. While biogenic activity at the sediment surface appeared to be reduced in 2006 relative to the last portion of the baseline period, the level of subsurface biogenic activity appeared similar.

4.3.3 Spatial and Temporal Patterns

Within the nearfield, variation through time appeared to be related to both regional trends and small-scale, on the order of 10s of m, spatial variation (Maciolek *et al.* 2006). For example, based on the modal grain-size estimated from SPI for 1997 to 2006, cluster analysis (normalized Euclidean distance with complete linkage sorting) divided the 23 stations into two groups based on temporal trends in grain size (Figure 4-7 and Chapter 3, this report). Data from 1992 and 1995 were not included in the analysis because not all 23 stations were sampled (Table 4-5). Sediment grain-size data were also not included since both grab and SPI data produced similar results in previous year's analyses (Maciolek *et al.* 2006). Group A was six coarser stations with Group B containing the other 17 stations that tended to be finer grained (Figure 4-7). From 1999 to 2006, median Phi was significantly lower for Group A stations (Table 4-5). Differences in modal grain-size between Groups A and B tended to increase from 2003 to 2006, primarily because Group A coarsened relative to Group B. Modal grain-size for Group B stations exhibited no pattern and little change over this period. The largest difference was in 2006 when Groups A and B were 2.9 Phi apart in modal grain-size. It appeared that Group A coarsened between 2004 and 2005 but Group B remained essentially the same. Cluster analysis of years also indicated that 2005 and 2006 were separated from other years (Figure 4-7). Spatially, there was no pattern to Groups A and B as both groups were spread across the entire nearfield (Table 4-5 and Figure 4-1). The coarsening of grain-size in 2006 for Group A is consistent with the higher bottom stress in 2005 from winter storms (Butman *et al*. In Prep.). Possible hypotheses as to why Group B stations did not coarsen in 2006 are that bottom stress was not uniform over the nearfield and Group B stations were not subjected to higher bottom stress, or there was no source of coarser sediments close to the Group B stations. Most of the Group B stations were consistently fine-grained sediments from 1995 to 2006 (Tables 4-4 and 4-5). Percent fines (silt+clay) followed a similar pattern as modal Phi, with 1999 and 2000 having Group A and B the same, which may have been a function of a three-year calm weather period that started in 1998 (Butman *et al*. In Prep.). The only sedimentary parameter related to the outfall spatially was *Clostridium perfringens* spores normalized to percent fines, which increased at Group A stations the first two years after outfall operation (2001 and 2002). In subsequent years the groups were not significantly different. Percent TOC normalized to percent fines was not significantly different between groups for any year, which indicates outfall operation is not affecting organic carbon distribution over the nearfield.

Infaunal community structure parameters, when averaged by Groups A and B, tended not to be significantly different from year to year (Table 4-5). The exceptions were declining trends in total species and log-series *alpha* (LSA) for 2005 and 2006 when Group A was lower than Group B. Measures of infaunal activity, such as bioturbation, from SPI (infauna, burrows, and oxic voids per image) were all lower for Group A stations relative to Group B, which was primarily a function of sediment grain-size being coarse in Group A. The exception was infauna/image during the calm weather year of 1998 when both groups were not significantly different (Table 4-5). Estimated successional stage was also similar between groups for 1998 due to a regional advancement from Stage I dominance to Stage II and III dominance from 1997 conditions. 1997 was a stormy weather year, which may have favored pioneering Stage I, keeping successional stage estimates lower. Similarly, 2005 was a stormy year and marked the start of declining successional stage estimates, but OSI did not decline as RPD layer depths increased, likely related to physical processes associated with stronger bottom currents. If OSI is considered a relative measure of benthic habitat conditions, then Group A stations were more stressed than Group B stations from 2000 to 2004. Prior to 2000, OSI was similar between groups in 1997 and 1999. In 1998, the OSIs were higher for Group A stations, likely in response to calm weather conditions. In 2005 and 2006, OSIs for both groups had increased and were not significantly different. The depth of the apparent color RPD layer, primarily an integrator of biological activity, varied between groups and years. In 1997 and 1998, the RPD layers were deeper at Group A stations and then declined relative to Group B stations from 1999 to 2003. In 2006, Group A stations again had deeper RPD layers.

Table 4-5 . Temporal comparison of grab parameters using GEE models. Station Groups A and B were determined from cluster analysis of modal SPI grain-size.

Group A: FF12, FF13, NF04, NF13, NF17, and NF23

Group B: FF10, NF02, NF05, NF07, NF08, NF09, NF10, NF12, NF16, NF21, NF22, NF24, NF15, NF14, NF18, NF19, NF20

		Estimated Modal Grain Size (phi)							**Total Abundance**					
	Year	**Group A**		**Group B**	**Estimate Multiplier**	**SE**	**p**		**Group A**		**Group B**	**Estimate Multiplier**	**SE**	**p**
Baseline	1992*	3.0		3.8					1086		2316			
	1995*	2.6		3.9					1459		2146			
	1997	3.7	=	4.1	-0.48	0.34	0.153		2774	=	2617	156.4	579.49	0.787
	1998	3.7	=	4.2	-0.51	0.53	0.335		2045	=	2634	-589.8	368.46	0.109
	1999	3.5	<	5.0	-1.50	0.47	0.001		2451	=	2931	-480.0	294.88	0.104
	2000	3.3	<	4.5	-1.28	0.55	0.021		2400	=	2603	-203.0	380.31	0.594
Post-Diversion	2001	3.1	<	5.0	-1.95	0.38	<0.001		1998	=	2112	-113.8	412.70	0.783
	2002	2.9	<	5.0	-2.11	0.26	<0.001		2816	=	3585	-768.6	687.23	0.263
	2003	3.2	<	4.6	-1.48	0.55	0.007		2296	<	3501	-1204.2	400.80	0.003
	2004	3.0	<	4.9	-1.88	0.47	<0.001		2310	=	1987	323.5	587.76	0.582
	2005	2.2	<	4.8	-2.66	0.67	<0.001		1729	=	1867	-138.0	526.94	0.793
	2006	1.7	<	4.6	-2.92	0.72	<0.001		1475	=	1439	35.7	300.85	0.906
		Percent Fines (silt + clay)							**Total Species**					
	Year	**Group A**		**Group B**	**Estimate Multiplier**	**SE**	**p**		**Group A**		**Group B**	**Estimate Multiplier**	**SE**	**p**
Baseline	1992*	3		45					54		65			
	1995*	2		44					58		68			
	1997	16	<	36	-20.02	10.16	0.049		69	=	79	-9.42	7.99	0.238
	1998	10	<	29	-19.41	6.60	0.003		69	=	79	-10.21	6.57	0.120
	1999	16	=	33	-17.75	9.51	0.062		67	=	76	-8.20	4.32	0.058
	2000	19	=	34	-13.98	11.17	0.211		61	<	73	-11.96	4.67	0.010
Post-Diversion	2001	12	<	36	-23.82	7.56	0.002		63	=	68	-4.75	4.98	0.340
	2002	16	<	40	-24.34	7.97	0.002		73	=	79	-5.74	6.16	0.352
	2003	15	<	36	-21.68	7.77	0.005		76	=	84	-7.46	7.43	0.316
	2004	17	<	47	-29.87	12.80	0.020		70	=	79	-9.30	11.20	0.406
	2005	11	<	40	-28.50	11.90	0.017		55	<	64	-10.00	3.80	0.008
	2006	15	<	39	-24.80	12.11	0.041		56	<	66	-9.87	3.32	0.003

*	Years not included in GEE models as all stations were not sampled
**	Parameter not measured that year
***	No measured RPDs for Group A
****	1 = Pioneering, 2 = Intermediate, 3 = Equilibrium

Table 4-5 continued.

		***Clostridium perfringens* spores/ Percent Fines**							**Shannon Diversity H′**					
	Year	**Group A**		**Group B**	**Estimate Multiplier**	**SE**	**p**		**Group A**		**Group B**	**Estimate Multiplier**	**SE**	**p**
Baseline	1992*	278		56					4.0		3.7			
	1995*	58		121					4.0		3.9			
	1997	159	=	120	39.34	55.14	0.476		3.4	<	4.0	-0.59	0.25	0.019
	1998	69	=	78	-8.94	10.43	0.391		3.7	=	3.8	-0.10	0.29	0.731
	1999	106	=	60	46.33	28.48	0.104		3.7	=	3.5	0.22	0.29	0.439
	2000	43	=	38	5.60	11.20	0.617		3.8	=	3.7	0.21	0.26	0.412
Post-Div.	2001	199	>	91	108.4	52.02	0.037		3.9	=	4.0	-0.09	0.26	0.719
	2002	173	>	99	74.56	36.14	0.039		4.0	=	3.6	0.35	0.29	0.219
	2003	129	=	72	56.25	46.70	0.228		3.9	=	3.7	0.26	0.21	0.224
	2004	127	=	53	73.33	42.85	0.087		4.0	=	4.3	-0.31	0.29	0.288
	2005	126	=	96	30.63	62.02	0.621		3.6	=	3.6	-0.04	0.22	0.864
	2006	58	=	46	10.23	20.47	0.617		3.6	=	3.9	-0.25	0.18	0.171
		Percent TOC / Percent Fines							**Log Series *Alpha***					
	Year	**Group A**		**Group B**	**Estimate Multiplier**	**SE**	**p**		**Group A**		**Group B**	**Estimate Multiplier**	**SE**	**p**
Baseline	1992*	0.20		0.04					12.9		12.8			
	1995*	0.05		0.02					12.8		13.9			
	1997	0.03	=	0.03	0.00	0.00	0.774		13.5	=	15.8	-2.24	1.55	0.147
	1998	0.03	=	0.03	0.00	0.01	0.498		14.5	=	15.8	-1.31	1.65	0.426
	1999	0.06	=	0.03	0.03	0.03	0.251		13.4	=	14.6	-1.26	1.07	0.239
	2000	0.03	=	0.03	-0.01	0.01	0.312		12.2	=	14.6	-2.33	1.30	0.073
Post-Div	2001	0.05	=	0.04	0.01	0.02	0.725		13.3	=	14.2	-0.90	1.46	0.536
	2002	0.03	=	0.04	-0.01	0.01	0.624		14.8	=	14.9	-0.08	1.67	0.961
	2003	0.03	=	0.02	0.00	0.01	0.395		15.2	=	15.7	-0.49	1.78	0.782
	2004	0.03	=	0.02	0.01	0.01	0.470		14.0	=	16.8	-2.76	2.00	0.168
	2005	0.02	=	0.02	0.00	0.01	0.838		11.4	<	13.2	-1.76	0.62	0.005
	2006	0.04	=	0.02	0.02	0.01	0.128		11.9	<	14.6	-2.73	0.55	<0.001
		OSI							**Infauna per Image**					
	Year	**Group A**		**Group B**	**Estimate Multiplier**	**SE**	**p**		**Group A**		**Group B**	**Estimate Multiplier**	**SE**	**p**
	1992*	6.0		6.9					.	**	.			
	1995*	6.9		5.8					.	**	.			
	1997	4.2	=	5.0	-0.81	0.54	0.135		.	**	.			
Baseline	1998	7.4	>	6.1	1.30	0.39	0.008		1.8	=	3.8	-1.98	1.14	0.082
	1999	7.2	=	7.0	0.24	0.45	0.598		2.0	<	5.9	-3.88	1.41	0.006
	2000	6.1	<	7.6	-1.56	0.48	0.001		0.8	<	4.8	-3.94	1.09	<0.001
	2001	4.9	<	7.2	-2.25	0.41	<0.001		1.0	<	4.4	-3.41	1.01	0.007
	2002	4.9	<	6.8	-1.92	0.67	0.004		0.2	<	3.8	-3.54	0.52	<0.001
Post-Div	2003	4.2	<	6.3	-2.11	0.70	0.003		0.0	<	3.5	-3.49	0.61	<0.001
	2004	5.9	<	6.9	-0.94	0.42	0.026		1.6	<	6.0	-4.44	1.45	0.002
	2005	6.3	=	7.5	-1.28	0.68	0.061		0.3	<	2.7	-2.34	0.54	<0.001
	2006	8.0	=	7.5	0.46	0.39	0.239		0.0	<	2.5	-2.46	0.44	<0.001

Table 4-5 continued.

		RPD (cm)							Burrows per Image					
	Year	**Group A**		**Group B**	**Estimate Multiplier**	**SE**	**p**		**Group A**		**Group B**	**Estimate Multiplier:**	**SE**	**p**
Baseline	1992*	2.2		2.7					.	**	.			
	1995*	3.3		2.4					.	**	.			
	1997	2.1	>	1.7	0.44	0.15	0.004		.	**	.			
	1998	2.2	>	1.5	0.68	0.13	<0.001		0.5	<	1.6	-1.09	0.51	0.033
	1999	1.6	<	2.1	-0.53	0.13	<0.001		1.4	<	5.0	-3.63	1.19	0.002
	2000	2.0	<	2.8	-0.75	0.17	<0.001		1.1	<	3.9	-2.84	0.83	0.006
Post-Div	2001	1.7	<	2.8	-1.04	0.23	<0.001		1.3	<	5.1	-3.80	1.06	<0.001
	2002	.	***	2.5					0.0	<	2.4	-2.36	0.32	<0.001
	2003	1.4	<	2.2	-0.78	0.10	<0.001		0.1	<	5.8	-5.62	0.97	<0.001
	2004	2.2	=	2.4	-0.24	0.13	0.080		1.4	<	4.1	-2.70	0.72	<0.001
	2005	2.1	=	2.6	-0.50	0.26	0.054		0.3	<	2.8	-2.48	0.51	<0.001
	2006	4.6	>	3.3	1.34	0.25	<0.001		0.3	<	1.9	-1.63	0.44	<0.001
		Estimated Successional Stage****							Oxic Voids per Image					
	Year	**Group A**		**Group B**	**Estimate Multiplier**	**SE**	**p**		**Group A**		**Group B**	**Estimate Multiplier:**	**SE**	**p**
Baseline	1992*	1.0		1.3					.	**	.			
	1995*	1.1		1.4					.	**	.			
	1997	1.2	=	1.3	-0.17	0.12	0.174		.	**	.			
	1998	2.2	=	2.4	-0.21	0.13	0.101		0.1	<	0.9	-0.78	0.24	0.001
	1999	2.0	<	2.4	-0.38	0.15	0.013		0.0	<	1.3	-1.32	0.33	<0.001
	2000	1.5	<	2.2	-0.74	0.15	<0.001		0.1	<	1.3	-1.28	0.31	<0.001
Post-Div	2001	1.5	<	2.1	-0.60	0.13	<0.001		0.2	<	0.8	-0.66	0.25	0.009
	2002	1.3	<	2.0	-0.65	0.17	0.002		0.0	<	0.9	-0.85	0.20	<0.001
	2003	1.3	<	2.0	-0.70	0.18	<0.001		0.0	<	0.9	-0.93	0.25	<0.001
	2004	1.4	<	2.0	-0.58	0.16	<0.001		0.1	<	1.0	-0.93	0.27	0.006
	2005	1.3	<	1.8	-0.55	0.17	0.001		0.0	<	0.7	-0.69	0.14	<0.001
	2006	1.3	=	1.7	-0.37	0.19	0.053		0.0	<	0.5	-0.45	0.16	0.006
		Prism Penetration (cm)												
	Year	**Group A**		**Group B**	**Estimate Multiplier**	**SE**	**p**							
	1992*	2.2		2.7										
	1995*	3.8		8.7										
	1997	2.8	<	5.7	-2.94	1.16	0.011							
Baseline	1998	4.5	=	7.5	-2.99	1.83	0.103							
	1999	3.4	<	10.1	-6.63	1.56	<0.001							
	2000	3.3	<	9.0	-5.71	1.33	<0.001							
Post-Div	2001	3.0	<	7.1	-4.05	1.29	0.002							
	2002	2.0	<	8.4	-6.40	1.09	<0.001							
	2003	1.4	<	6.0	-4.65	0.97	<0.001							
	2004	3.5	<	8.9	-5.38	1.55	0.005							
	2005	2.3	<	8.7	-6.33	1.00	<0.001							
	2006	3.1	<	7.6	-4.60	1.35	0.006							

*Years not included in GEE models as all stations were not sampled
**Parameter not measured that year
***No measured RPDs for Group A
****1 = Pioneering, 2 = Intermediate, 3 = Equilibrium

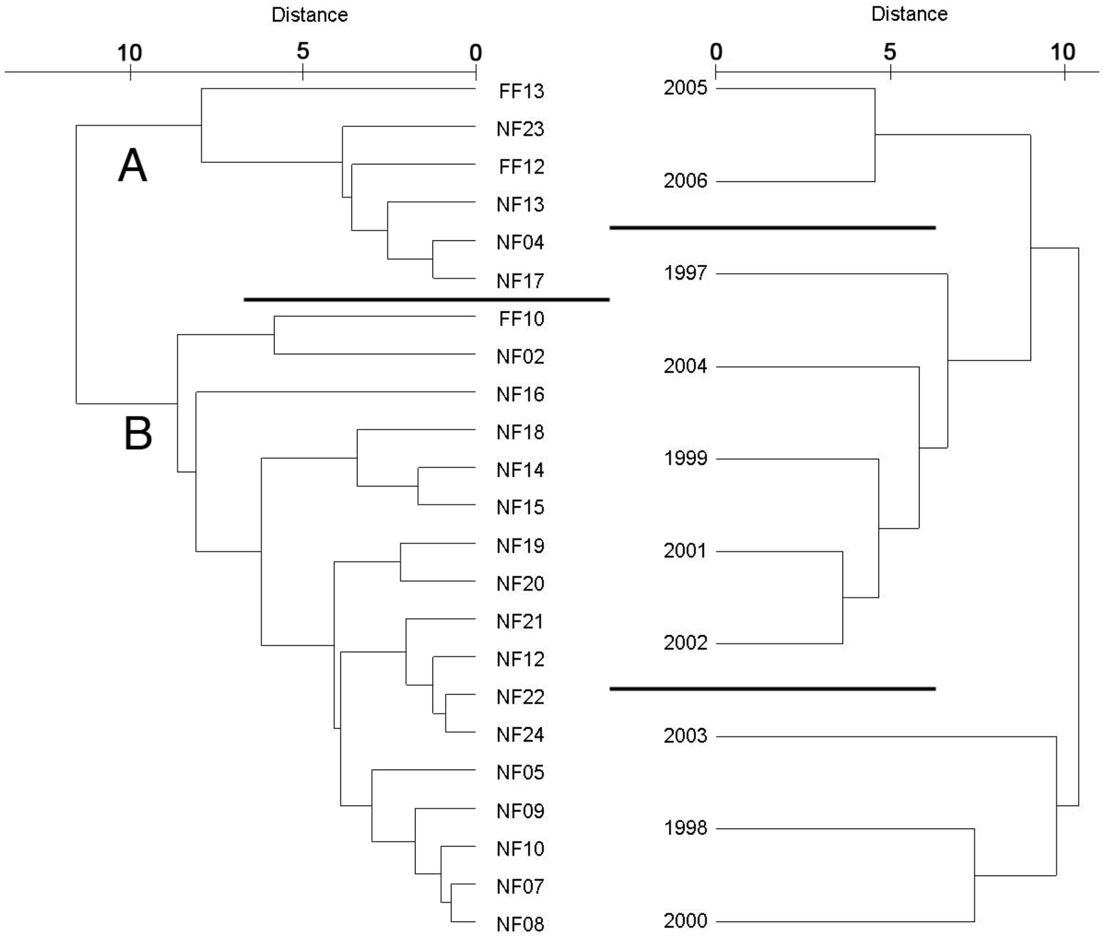


Figure 4-7. Cluster analysis grouping of stations and years for SPI estimated modal sediment grain-size (Phi). Based on normalized Euclidean distance with complete linkage sorting.

4.4 Monitoring Question

- *Have the sediments become more or less anoxic; that is, has the thickness of the sediment oxic layer decreased or increased?*

For assessing outfall effects, the MWRA (1997) set a 50% reduction in the apparent color RPD layer depth over the study area as a critical trigger level. Similarly, a 50% increase in apparent color RPD over the baseline would be noteworthy. The average apparent color RPD for 2006 of 3.0 cm (SD = 1.09 cm) was significantly different from the baseline RPD of 2.3 cm ($F = 8.65$, $p = 0.007$). The fact that in 2006 the RPD was deeper than baseline would indicate that the RPD threshold was not exceeded. The difference between 2006 and the baseline was a deepening of the RPD by an average of 0.7 cm or 32%. The average RPD for 2006 was at the high end of the range of annual RPDs, with 1998 being the shallowest year at 1.6 cm and 1995 the deepest year, also at 3.0 cm (Figure 4-8).

When the six baseline years were compared to the six discharge years using a repeated measures generalized estimating equation (GEE), the discharge years had significantly deeper RPD layers (baseline to discharge years multiplier 0.202, SE = 0.097, $p = 0.038$). If the same analysis is restricted to the nine stations with measured RPD layers (Figure 4-3) for all 12 years of data, the post-diversion years have even deeper RPD layers (baseline to discharge years multiplier 0.510, SE = 0.106, $p = <0.001$).

Based on the color and texture of sediments in the 2006 SPI images, it does not appear that the amount of deposited organic matter has changed relative to the operation of the outfall, post-diversion, or the baseline for the nearfield SPI stations. TOC was also not different between baseline and post-diversion years (Chapter 3). The percentage of TOC in sediments in 2006 tended to be at the low end of the range of all values from 1992 to 2005 for the 12 nearfield stations sampled.

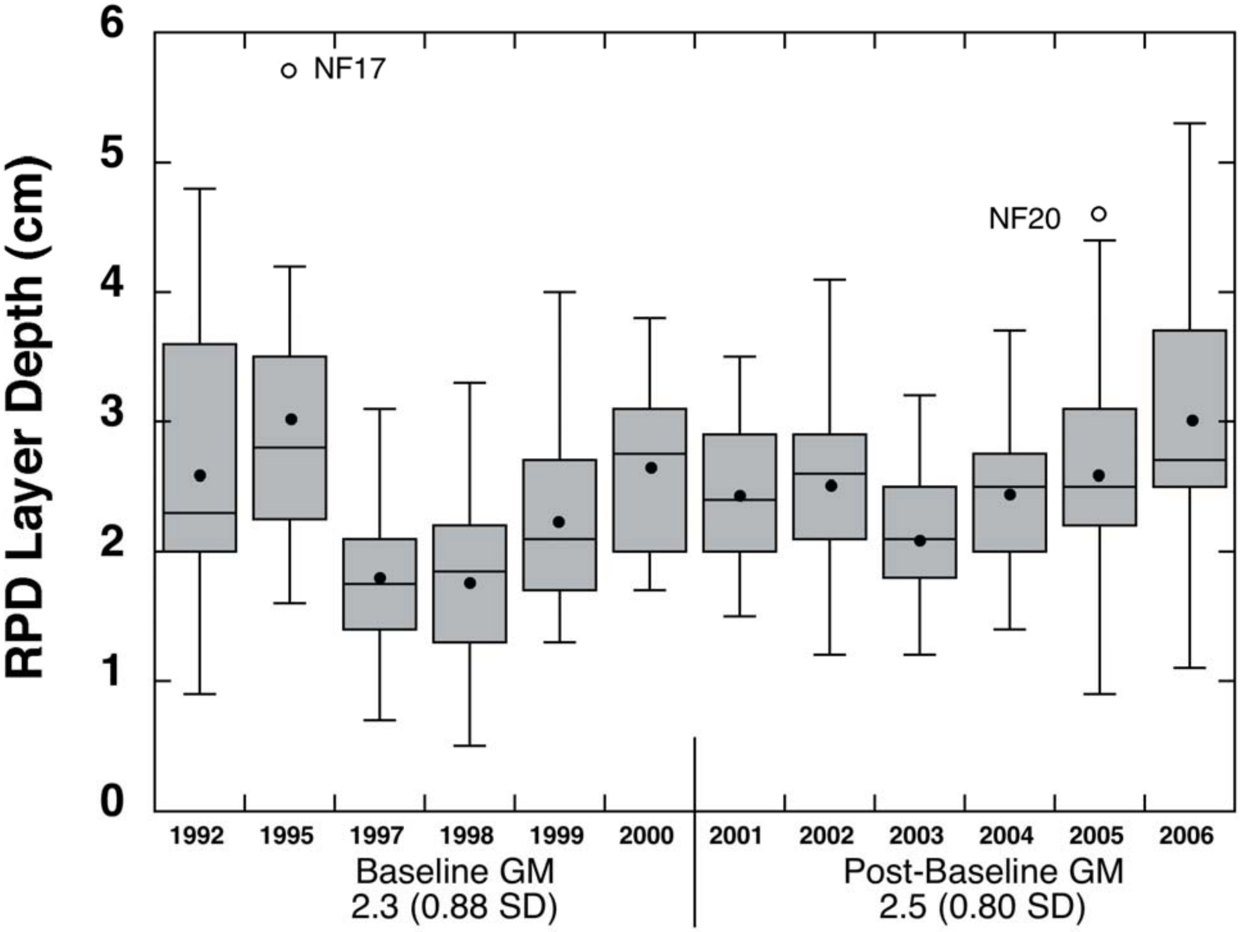


Figure 4-8. Apparent color RPD layer depth (cm) summarized by year for all data from nearfield stations. Box is interquartile range (IR), bar is median, circle is mean, and whiskers are data range. Outliers are >(2*IR).

5. 2006 SOFT-BOTTOM BENTHIC INFAUNAL COMMUNITIES

by Nancy J. Maciolek and *Woollcott K. Smith*

5.1 Status of the Bay

5.1.1 Monitoring Program

The MWRA has studied the soft-bottom benthos of Massachusetts Bay for several years as part of the program to locate an outfall system nine miles off Deer Island. Stations have been sampled annually since August 1992. The area near the diffuser array, where potential impacts might occur, is primarily hard-bottom with few areas of soft sediments, resulting in the necessity of positioning benthic stations according to sediment type, rather than randomly. This constraint has resulted in the majority of the 23 nearfield stations being positioned to the north and west of the diffuser array (see Figure 2-1). Six of these stations (NF12, NF17, NF24, FF10, FF12, FF13) are sampled in triplicate, and single samples are collected from the remaining 17 stations. Eight farfield stations, also sampled in triplicate, represent an area far enough from the outfall that they are not expected to be impacted by the discharge. These farfield stations are located in a wide geographical area, from near Cape Ann in the north to Cape Cod Bay in the south. Two of the stations (FF04 and FF05) are located within the Stellwagen Basin National Marine Sanctuary, and two stations (FF06 and FF07) are within Cape Cod Bay.

Only minor repositioning of stations has occurred since the inception of the program (*i.e.*, station FF01 was replaced with FF01A). Three stations (FF10, FF12, and FF13) originally considered as farfield stations were reclassified as nearfield beginning in 1996, although the station designations were not changed. Other changes in the sampling program, which occurred primarily during the early years (1992–1994), are discussed in the annual reports to the MWRA (*e.g.*, Blake *et al.* 1998). In 2003, the MWRA reviewed and revised the monitoring program, and with the concurrence of the EPA, has rescaled the sampling effort. Beginning in 2004, only half the stations were sampled for benthos and sediment parameters TOC and grain size, *i.e.*, four of the eight farfield and 13 of the 23 nearfield stations. In 2006, the subset of stations sampled was the same as that sampled in 2004 (see Chapter 1 Introduction and Chapter 2 Field, this report).

5.1.2 Benthic Communities

During the baseline period (1992–2000), multivariate analyses of the infauna data suggested that sediment grain size was the dominant factor in structuring the benthic communities. The nearfield stations fall into one of two major sediment regimes: fine sediments characterized by the polychaete annelids *Prionospio steenstrupi*, *Spio limicola*, *Mediomastus californiensis*, and *Aricidea catherinae*; and sandy sediments (primarily NF13, NF17, and NF23) characterized by the syllid polychaetes *Exogone hebes* and *E. verugera* and the amphipods *Crassicorophium crassicorne* and *Unciola* spp. In addition to the influence of habitat heterogeneity, the nearfield area, in water depths of 27–35 m, is often affected by strong winter storms (*e.g.*, Bothner 2001), which cause episodes of sediment resuspension that potentially impact the benthic communities (Hilbig and Blake 2000, Kropp *et al.* 2002).

The fauna that characterizes the farfield differs from that seen in the nearfield. The farfield stations span a greater depth range (33–89 m) and are geographically widespread, with sediment types that are generally finer than those seen in the nearfield. Polychaete worms (*e.g., Euchone incolor, Aricidea quadrilobata,* and *Levinsenia gracilis*) are the predominant organisms at most of the stations, although *P. steenstrupi* is common at some of the stations. A different species of polychaete, *Cossura longocirrata*, is dominant at station FF06 in Cape Cod Bay, along with *Euchone incolor*, which typically indicates the presence of the deep-burrowing holothurian *Molpadia oolitica* (Rhoads and Young 1971).

Samples collected in 2001–2005, after the outfall went online, have not indicated any discernable impact of the discharge on the infauna (Kropp *et al.* 2002, Maciolek *et al.* 2003, 2004, 2005, 2006). The few statistical differences detected in the benthic community parameters, such as increased numbers of certain species and increased dominance by certain species at one or two of the nearfield stations, were considered to be natural fluctuations in the populations and not related to the outfall discharge.

5.2 Methods

5.2.1 Laboratory Analyses

Sediment grab samples were rinsed with filtered seawater over 300-µm-mesh screens and transferred to 70–80% ethanol for sorting and storage. To facilitate the sorting process, all samples were stained in a saturated, alcoholic solution of Rose Bengal at least overnight, but no longer than 48 h. After rinsing with clean alcohol, all organisms, including anterior fragments, were removed and sorted to major taxonomic categories such as polychaetes, arthropods, and mollusks. Organisms were then identified to the lowest practical taxonomic category, usually species. Voucher specimens of each species were kept as part of the MWRA reference collection.

5.2.2 Data Analyses

Preliminary Data Treatment—Appendix C1 contains detailed information on how various taxa were treated prior to statistical analysis. For example, some taxa were merged before the analyses were performed so that the data are consistent throughout the several years of the program. Another 173 taxa are juvenile or categories that represent more than one species, and are therefore not included in calculations of diversity. These modifications were generally similar to those performed in previous years.

Calculations of abundance included all infaunal taxa occurring in each sample, whether identified to species level or not, but did not include epifaunal or colonial organisms. Calculations based on species (number of species, dominance, diversity, evenness, similarity, and principle components analysis) included only those taxa identified to species level, or those treated as such. A list of all taxa identified during the Outfall Monitoring Program (1992–2006) is contained in Appendix C2.

Statistical Analysis—Initial inspection of the benthic data included production of summaries of species densities by sample, tables of species dominance, and tabulation of numbers of species and numbers of individuals per sample. Data were inspected for any obvious faunal shifts or species changes between stations. Following these preliminary inspections of the data, a series of community parameters was calculated along with multivariate statistics to assess community patterns and structure. Changes in infaunal community structure that are suspected to be due to the outfall can be assessed by comparing community structure differences between the nearfield and farfield through time, and evaluating changes in community structure before and after the outfall went online in September 2000.

All models described and analyzed in this report start with the following basic log-linear model for mean abundance or concentration, μ_{ij}, at station *i* in year *j* with sediment property, x_{ij}.

$$\log\left(\mu_{ij}\right) = \mu + \alpha_{si} + \alpha_{yj} + \beta_1 x_{ij},$$

where α_{si} denotes the fixed effect associated with station *i* and α_{yj} denotes the fixed effect associated with station year *j*. In most cases we have used percent fine grains as the covariate variable that adjusts for sediment type.

The indicator variable $I_D(y)$ denotes the diversion event,

$$I_D(y) = \begin{cases} 1 & if \;\; y \geq 2001 \\ 0 & if \;\; y < 2001 \end{cases}$$

and the indicator variable $I_N(station)$ denotes the near field station,

$$I_5(\text{station}) = \begin{cases} 1 & \text{if station is less than 5 km from outfall.} \\ 0 & \text{otherwise.} \end{cases}$$

and

$$I_{2.5}(\text{station}) = \begin{cases} 1 & \text{if station is less than 2.5 km from outfall.} \\ 0 & \text{otherwise.} \end{cases}$$

A linear model that includes the diversion-by-nearfield factor can be written as

$$\begin{aligned} \log\left(\mu_{ij}\right) = \mu + \alpha_{si} + \alpha_{yj} + \beta_1 x_{ij} + \alpha_{5D} I_5(station_i) I_D(y_j) \\ + \alpha_{2.5D} I_{2.5}(station_i) I_D(y_j) \end{aligned} \qquad (0.1)$$

where α_{5D} and $\alpha_{2.5D}$ are the fixed effect interaction terms associated with the zones after the diversion event. The goal is to estimate "relative differences between these zones that are associated with the divergence event,"

$$\text{Relative change associated within 5 km after 2000} = e^{\alpha_{5D}}$$

$$\text{Relative change associated within 2.5 km after 2000} = e^{\alpha_{2.5D}}$$

Note that for stations within 2.5 km of the diffuser these effects are nested and multiplicative. For these stations the change relative to the to stations greater than 5 km from the diffuser is $e^{\alpha_{5D}} e^{\alpha_{2.5D}}$.

This analysis estimates the relative change and the degree of statistical uncertainty associated with the relative change.

When response variable of interest, Y_{ij}, can be modeled as a continuous positive variable, the most applicable and straightforward model is the lognormal model, that is, $\log\left(Y_{ij}\right)$ is approximately normally distributed with mean $\log\left(\mu_{ij}\right)$ given by equation (0.1) with a standard deviation of σ. Under the lognormal model we have that

$$E[Y_{ij} \mid \mu_{ij}, \sigma] = \mu_{ij} \exp\left(\sigma^2 / 2\right) \text{ and } Var(Y_{ij}) = \mu_{ij}^{\,2}\left(\exp\left(\sigma^2\right) - 1\right).$$

Note that under this model the variance is proportional to the square of the expected response. Also, μ_{ij} denotes the geometric mean and $\mu_{ij} \exp\left(\sigma^2 / 2\right)$ denotes the arithmetic mean.

The above model needs to be modified when the dependent variable is a count of a relatively rare indicator species. When some counts are zero or near zero, the distribution of the discrete response variable can be modeled as negative binomial distribution with mean μ_{ij} given by equation (0.1) and the dispersion parameter $1/\theta$.

$$\Pr(Y_{ij} = k \mid \mu_{ij}, \theta) = \frac{\Gamma\left(k + \theta\right)\mu_{ij}^{k}\,\theta^{\theta}}{\Gamma\left(\theta\right)k!(\theta + \mu_{ij})^{\theta + k}} \quad .$$

Under the negative binomial model we have that

$$E\left[Y_{ij} \mid \mu_{ij}, \theta\right] = \mu_{ij} \text{ and } \mathrm{Var}\left[Y_{ij} \mid \mu_{ij}, \theta\right] = \mu_{ij} + \frac{\mu_{ij}^{2}}{\theta} \quad . \qquad (0.2)$$

Note that under the negative binomial model the variance is proportional to the mean squared plus an additional term, μ_{ij}, which accounts for the Poisson variation in the counts.

A maximum likelihood method implemented in the Splus library, MASS, was used to estimate the model parameters for this model and to test the null hypothesis $H_0 : \alpha_{10D} = 0$. Similar negative binomial regression procedures are available in SAS, STATA and other statistical software systems. Smith (1989) discusses the use of the ANOVA-like similarity analysis.

Multivariate similarity and clustering programs used for this report are included in COMPAH96, originally written by Dr. Donald Boesch and now available from Dr. Eugene Gallagher at the University of Massachusetts, Boston (http://www.es.umb.edu/edgwebp.htm). Patterns in benthic communities were analyzed by similarity analysis using CNESS (chord-normalized expected species shared), which was developed by Gallagher (Trueblood *et al.* 1994) and is related to Grassle and Smith's (1976) NESS (normalized expected species shared). CNESS and NESS can be made more or less sensitive to rare species in the community; these algorithms were developed primarily for use with deep-sea data, in which no single species usually accounts for more than 4–10% of the individuals. CNESS is calculated from the expected species shared (ESS) between two random draws of *m* individuals from two samples. For this project, the optimal value of *m* was determined to be 15. For comparison, the Bray-Curtis similarity measure was also used based on a fourth-root transformation of the data (performed in order to diminish the impact of numerically dominant species). Both similarity matrices were clustered using group average sorting and dendrograms were plotted. Results of these analyses were inspected for patterns among and between the different seasons.

PRIMER v.5 (Clarke and Gorley 2001) was used to calculate several diversity indices, including Shannon's H′ (base 2), Pielou’s evenness value J′, Sanders-Hurlbert rarefaction, and Fisher’s log-series *alpha*. Magurran (1988) classifies diversity indices into three categories: (1) species richness indices (*e.g.*, rarefaction); (2) species abundance indices (*e*.g., log-series *alpha*), and (3) indices based on the proportional abundances of species (*e.g*., Shannon index). The Shannon index, which is based on information theory, has been popular with marine ecologists for many years, but this index assumes that individuals are randomly sampled from an infinitely large population and that all species are present in the sample (Pielou 1975, Magurran 1988): neither assumption correctly describes the environmental samples collected in most marine benthic programs. Fisher's log-series model of species abundance (Fisher *et al.* 1943) has been widely used, particularly by entomologists and botanists (Magurran 1988). Taylor's (1978) studies of the properties of this index found that it was the best index for discriminating among subtly different sites, and May (1975) demonstrated that Sanders-Hurlbert rarefaction curves are often identical to those produced under the assumption that the distribution of individuals among species follows a log-series distribution. Hubble (2001) considers *alpha* the fundamental biodiversity parameter and promoted the use of this index for studies of diversity in all environments.

Principal Components Analysis of Hypergeometric Probabilities (PCA-H) was also applied to the benthic data. PCA-H is an ordination method for visualizing CNESS distances among samples (see Trueblood *et al.* 1994 for details). The PCA-H method produces a metric scaling of the samples in multi-dimensional space, as well as two types of plots based on Gabriel (1971). The Euclidean distance biplot, presented in this report, provides a two-dimensional projection of the major sources of CNESS variation. The species that contribute to the CNESS variation can be determined using matrix methods adapted from Greenacre's correspondence analysis (Greenacre 1984). These species are plotted as vectors in the Euclidean distance biplot. PCA-H was performed using MATLAB as an operating platform and additional programs written by Dr. E.D. Gallagher.

5.3 Results and Discussion

5.3.1 Species Composition of 2006 Samples

Species Composition—A list of all species collected as part of the Outfall Monitoring Program is included in Appendix C2. One species, the polychaete *Nothria conchylega* (Sars, 1835), was newly reported from the 2006 samples, which comprised 237 valid species. Several species were given new designations, based on reevaluation or publications in 2006 (Table 5-1).

Table 5-1. Comparison of old and new designations for species reported from the Massachusetts Bay samples.

Old Name	New Name	Reference
Polychaeta		
Caulleriella sp B	*Caulleriella venefica*	Doner and Blake 2006
Chaetozone sp. Mass Bay	*Chaetozone anasimus*	Doner and Blake 2006
Chaetozone sp. BH	*Chaetozone hystricus*	Doner and Blake 2006
Pionosyllis sp. A	*Eusyllis* sp. A	reevaluated by NJ Maciolek
Polygordius sp. A	*Polygordius jouinae*	Ramey *et al.* 2006
Oligochaeta		
Enchytraeidae sp. 1	*Marionina welchi* Lasserre, 1971	reevaluated by R. Winchell
Tubificidae sp. 2	*Limnodriloides medioporus* Cook, 1969	reevaluated by R. Winchell

The number of valid taxa in the Massachusetts Bay database, which includes both nearfield and farfield samples, now stands at 448 species. Over the course of the program, 402 species have been found at the nearfield stations and 350 species at the farfield stations.

5.3.2 Benthic Community Analysis for 2006: Nearfield

Several benthic community parameters, including the number of organisms and species in each sample, and the calculated measures of diversity (Shannon H′) and evenness (Pielou's J′), and Fisher's log-series *alpha,* were calculated for each sample. All nearfield samples collected prior to the outfall becoming operational in September 2000 were used to determine a baseline average value for each parameter. Baseline values were not recalculated after the stations were divided into subsets to be sampled on a rotating basis because the subsets, which were chosen randomly, are considered to be reflective of the original range of values (MWRA 2003).

Baseline values and the mean value for each parameter for each year from beginning in 1992 are plotted below, with the means for the two subsets of stations represented by different symbols. Results by sample are given in Appendix C3, Table C3-1, and community parameters for individual stations are plotted in the figures in Appendix C3.The means for all parameters except abundance were slightly higher than those recorded in 2005; however, they were lower than recorded for the same subset of stations in 2004.

***Density*—**The highest mean infaunal density per nearfield sample was recorded in 2002 (3,476 organisms per sample), and was only slightly lower in 2003 (3,138 organisms per sample). Since then, mean abundance has declined every year (Figure 5-1). The 2006 mean was 1,349.1 ± 498.1 SD organisms per sample, well below the baseline mean of 2,242 organisms. It was also the second lowest recorded in the program, with only 1993 being slightly lower (Figure 5-1). Maciolek *et al.* (2003) considered the high variability at some stations, which contrasted with the stability of other stations over time, and suggested that several processes, biological as well as physical, were operating in this system. Annual fluctuations in the population densities of several species and the occasional scouring of the bottom by storms both contribute to the overall invertebrate densities recorded from the benthic grab samples.

Inspection of the abundance data for individual nearfield stations (Appendix C3, Table C3-1, Figure C3-1) revealed that total densities had declined at eight of the 13 nearfield stations (FF10, FF13, N05, N07, NF08, NF09, NF12, and NF16) and were the same or slightly higher at the remaining five stations (NF17, NF18, NF19, NF22, and NF23). *(Note: Values for NF12 and NF17 are compared with values for 2005, since those stations are sampled every year.)*

At the eight stations where densities had decreased, the decline ranged from 18.0 percent at NF05 to 59.7 percent at NF08. The lowest abundances were found at NF08 (677 organisms per sample) and NF17 (848 organisms per sample), and the highest at NF18 and NF19 (1,907 and 2,425 organisms per sample, respectively).

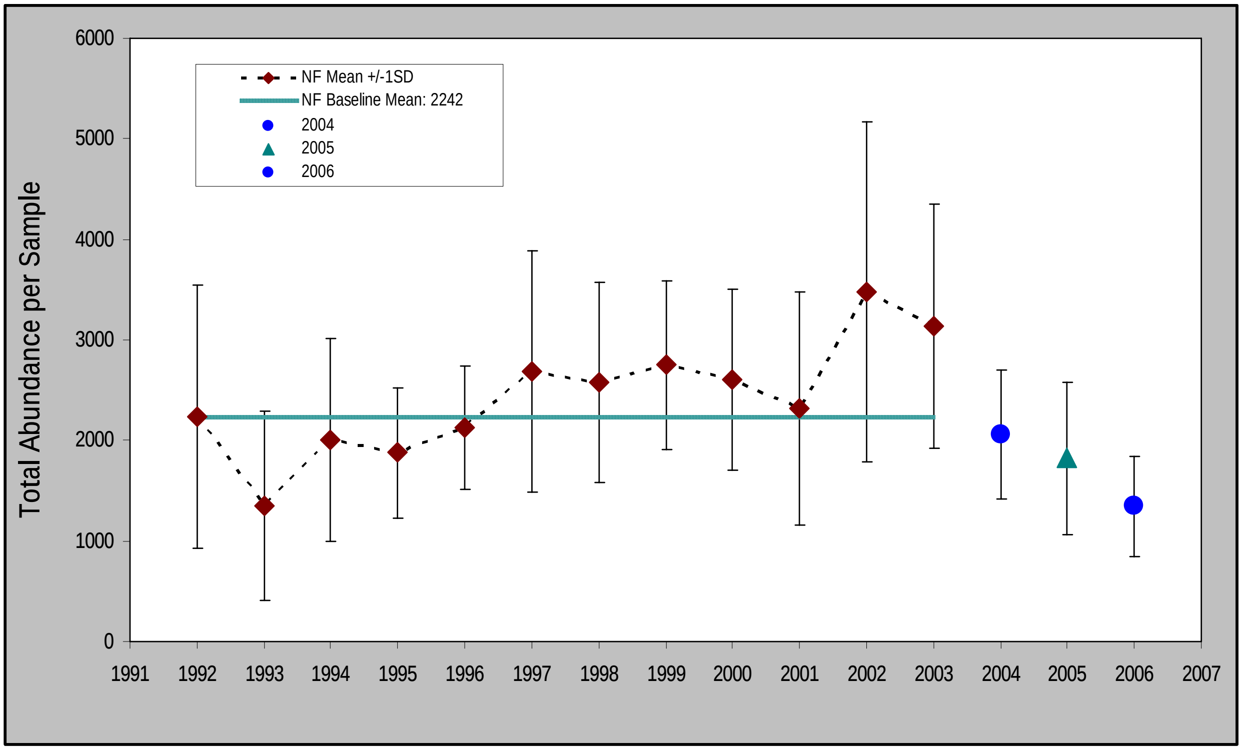


Figure 5-1. Mean abundance per sample for nearfield stations. The means for the two subsets of stations, one sampled in 2004 and 2006, and the other in 2005, are indicated by different symbols.

Species Richness—In 2006, 187 species occurred in the 21 nearfield samples, with a mean of 61.9 species per sample (Figure 5-2A); this result is virtually identical to species richness in 2005, when a mean of 61.1 species per sample was recorded for the alternate set of nearfield stations (Maciolek *et al.* 2006). The average number of species per sample increased from 2001 through 2004, when it was well above the baseline average of 65, but decreased at all stations (except FF12) in 2005. In 2006, species richness was the same (NF22) or increased slightly (by one to six species per sample) at NF12, NF17, and NF18. At the remaining stations, species richness values were 65.6 to 89.9 % of the 2004 values (the last time these stations were sampled). The largest decreases were at NF23 (a 34.4% decrease from 93 to 61 species) and NF07 (a 29.1% decrease from 103 to 73 species) (Appendix C3, Figure C3-2).

Diversity and Evenness—In 2006, all three measures indicated a small, insignificant increase in diversity compared with 2005 results (Figure 5-2B–D), but a decline compared with the 2004 values for this subset of stations.

As in 2005, the means of both Shannon diversity (H′ = 3.78) and Pielou's evenness (J′ =0.64) were comparable to the baseline means (H′ = 3.68; J′ = 0.62) (Figure 5-2B,C; Appendix C3, Figures C3-3 and C3-4). Shannon diversity values at individual stations declined at all stations except NF17, where it increased from 3.38 in 2005 to 3.70 in 2006. Until this year, H′ had declined at NF17 every year since reaching a high of 4.29 in 2002 (Appendix C3, Figure C3-3). The largest decline in H′ was at NF19, where the value dropped 25.5 percent from 4.26 in 2004 to 3.17 in 2006.

Mean evenness in 2006 was 0.64, a small increase from the mean (0.61) recorded in 2005, and a small decrease from the mean (0.67) measured for the same station set in 2004. Most individual stations had values similar to those measured the last time each station was sampled. The largest changes were seen at NF19 (a 23 percent decrease from 0.67 in 2004 to 0.52 in 2006) and NF17 (a 6 percent increase from 0.62 in 2004 to 0.65 in 2006) (Appendix C3, Figure C3-4).

The diversity measure log-series *alpha* was higher in 2006 (13.75) than in 2005 (12.6), but lower than that recorded for the same station set in 2004, when the program high of 16.2 was reached (Figure 5-2D, Appendix C3, Figure C3-5). When individual stations were considered (Appendix C3, Figure C3-5), *alpha* was higher at two stations, NF12 and NF17, in 2006 compared with the previous sampling year. *Alpha* increased 23.2 percent, from 12.79 in 2005 to 15.77 at NF12, and 7.7 percent, from 11.29 to 12.16, at NF17. While *alpha* approached the highest levels recorded at NF12 (16.24 in 1998), diversity at NF17 was still below the highest value of 15.66 recorded in 2002. The largest declines were at NF23 (30.2 percent, from 17.96 to 12.53), NF07 (25.9 percent from 21.06 to 15.60), and NF05 (25.3 percent from 19.89 to 14.85). Compared to the Shannon index, which is based on information theory and makes assumptions that are not met by the present samples (see Methods section 5.2.2 above), log-series *alpha*, which is based on species numbers and abundances, appears to provide a better discrimination among subtly different sites and thus is more reliable in reflecting the actual environmental trend.

Dominant Species—Dominant species at each nearfield station are listed in Appendix C4, along with the percent contribution of each to the total community, based on total individuals in the sample and those that were identified to species. In the latter case, the percentage is usually just a few tenths of a point less than when calculated for total individuals. The dominant species at the nearfield stations have been consistent over the past several years, although changes in their absolute numbers, and numerical rank in the samples, have changed from year to year.

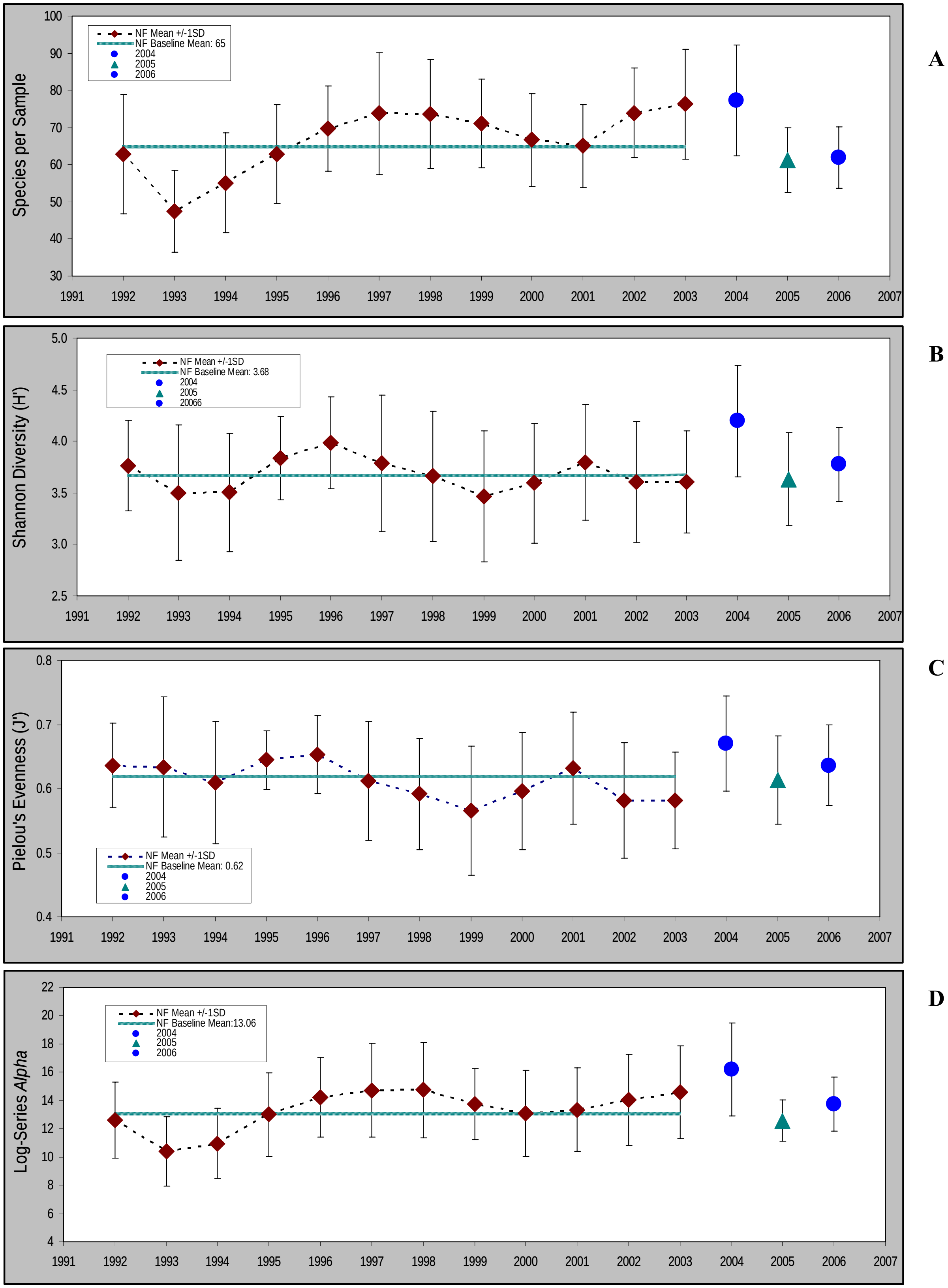


Figure 5-2. (A) Number of species per sample, (B) Shannon diversity, (C) evenness, and (D) log-series alpha at nearfield stations from 1992–2006.

The spionid polychaete *Prionospio steenstrupi* has been the numerical dominant in Massachusetts Bay for the past several years, and is a numerical dominant in all sediment types, which range from 5 to 70 % fines (see Chapter 3), found at the nearfield stations. In spite of reduced densities beginning in 2004, *P. steenstrupi* remained the numerical dominant at six of the 13 nearfield stations sampled that year (Maciolek *et al.* 2005) and was the numerical dominant at nine of the 12 nearfield stations sampled in 2005 (Maciolek *et al.* 2006). In 2006, *P. steenstrupi* accounted for 27 percent of all infaunal organisms collected and was the numerical dominant at eight of the 11 nearfield stations, where it accounted for 15–53 percent of the organisms in a sample. It was also second to *Spio limicola* at one additional station (NF05). At the sandy station NF17, where another spionid, *Spiophanes bombyx,* was the numerical dominant, *P. steenstrupi* was the fourth most abundant species. The pattern of increase and decline in numbers of *P. steenstrupi* (Figure 5-4) varied among individual stations, with an increase seen at some (*e.g.*, NF19) and a decline at others (*e.g.*, NF12) in 2006 compared with earlier years.

Other polychaete species, including *Levinsenia gracilis*, *Mediomastus californiensis*, and *Ninoe nigripes*, were also among the numerical dominants at many nearfield stations. These three species usually co-occur with *P. steenstrupi* as numerical dominants at the majority of nearfield stations; one or both are found within the top five dominant at all stations except those with the coarsest sediments. *N. nigripes* has become increasingly more abundant over the past several years, whereas *L. gracilis* and *M. californiensis* have maintained their numerical rank in the nearfield communities for the past several years.

A different suite of species is found at the coarse-grained stations NF17 and NF23. At these stations, where percent fines are only 2–8% of the sediments, the bivalves *Ensis directus* and *Cerastoderma pinnulatum*, the ascidian *Molgula manhattensis*, amphipods such as *Crassicorophium crassicorne*, and the sand dollar *Echinarachnius parma* are the dominant species (Appendix C4). These sandy communities have also been consistent throughout the course of the monitoring program.

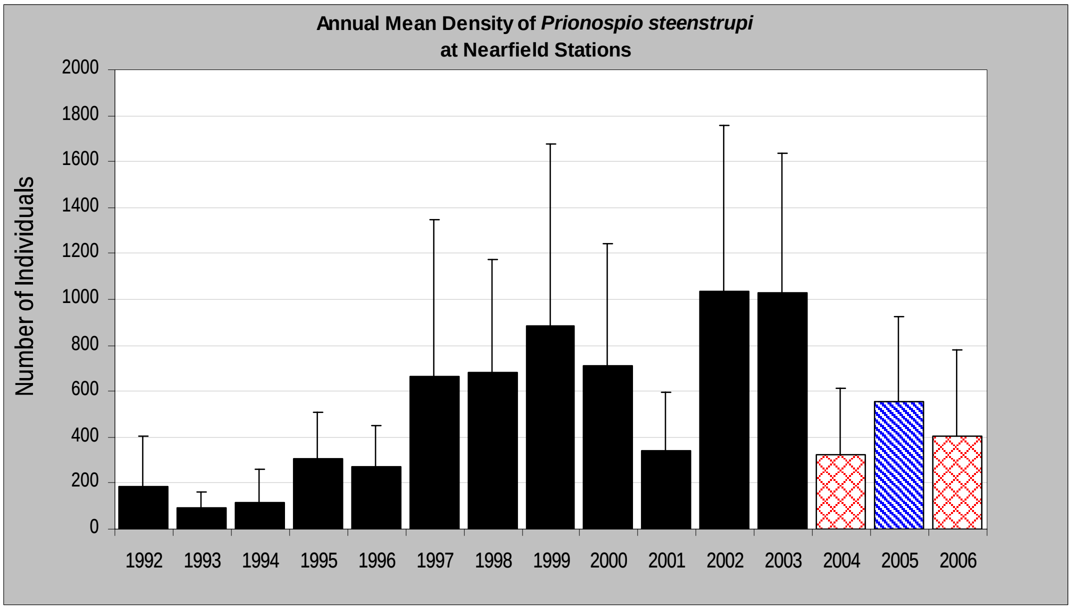


Figure 5-3. Annual mean density of P*rionospio steenstrupi* at nearfield stations. Two subsets of stations were sampled, one in 2005 and the other in 2004/2006.

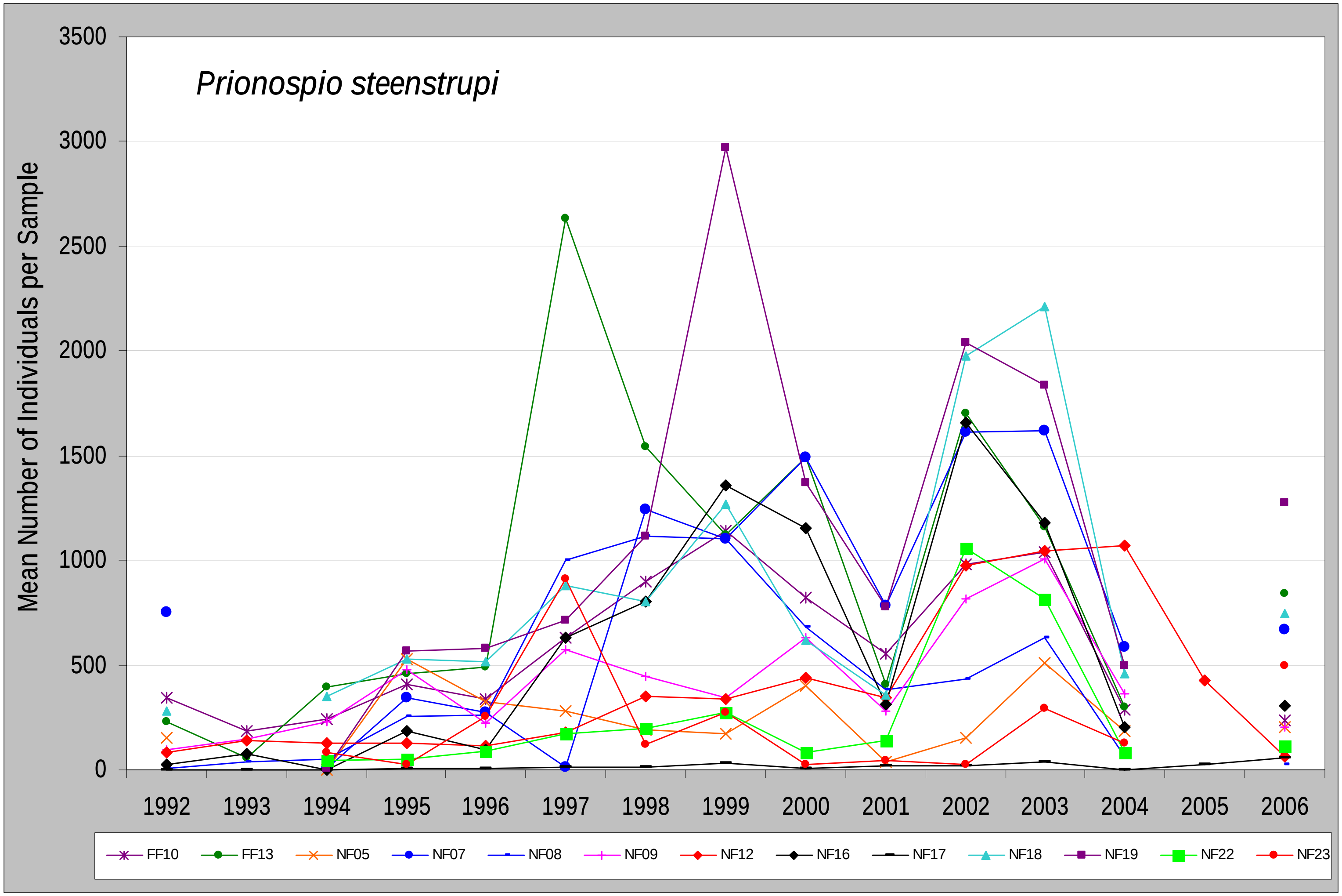


Figure 5-4. Yearly abundance (or mean abundance) of *Prionospio steenstrupi* at nearfield stations sampled in 2006.

5.3.3 Benthic Community Analysis for 2006: Farfield

Benthic community parameters, including the number of organisms and species in each sample, and the calculated measures of diversity (Shannon H′) and evenness (Pielou's J′) and Fisher's log-series *alpha*, are examined annually. All farfield samples collected prior to the outfall becoming operational in September 2000 were used to determine a baseline average value for each parameter. Baseline values and the mean value for each parameter for each year from 1992–2006 are plotted below, with the means for samples after 2003 indicated with a different symbol for each subset of stations. Results by sample are given in Appendix C3, Table C3-1, and community parameters for individual stations are plotted in the figures in Appendix C3.

The farfield stations are located within a large geographic area, and consequently occupy a variety of habitats (Figure 2-2, Table 2-1), making it difficult to generalize over the area. FF04 and FF05 are in relatively deep water (90 and 65 m, respectively, in the Stellwagen Basin National Marine Sanctuary, while FF09 is in about 50 m of water, intermediate between the nearfield stations and the Stellwagen Basin stations. FF07 is in Cape Cod Bay in about 39 m (see Table 2-1).

Density—Mean density at the farfield stations declined dramatically in 2006, when a mean of 978.6 ±614.9 organisms per sample was recorded; this value is 42 and 37 percent of the densities recorded in 2005 and 2004, respectively (Figure 5-5A). Abundance declined at all four farfield stations compared with abundances recorded in 2005 and in 2004, when these stations were last sampled (Figure 5-5B). The change was most pronounced at FF07 in Cape Cod Bay, and least at FF09.

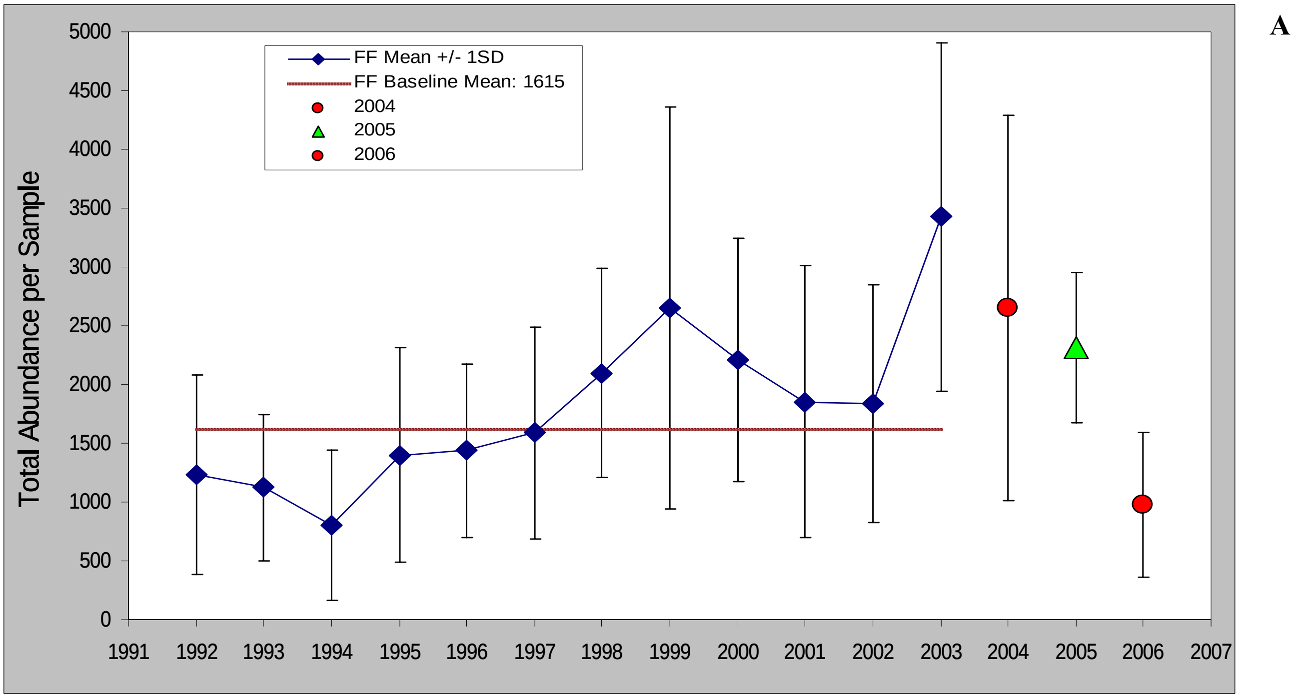
The change in abundance at each farfield station was due to different factors at each location, although the spionid polychaetes *Prionospio steenstrupi* and *Spio limicola* influenced three of the four stations:

- At FF04, mean densities in 2003 and 2004 were around 1280–1400 organisms per sample, but declined in 2006 to 476.7 organisms per sample, due to the significant reduction in the numbers of *S. limicola*.

- At FF05, mean density in 2006 was only 15 percent of the mean density recorded in 2004. The population crash of *Spio limicola* and, to a much lesser extent that of *Aricidea quadrilobata* resulted in the lowest density since 1994 at this station, which had the largest decline in abundance of the four farfield stations.

- At FF07, the Cape Cod Bay station, the high abundances recorded in 2003 and 2004 were due primarily to both *Euchone incolor,* a surface feeder associated with the fecal mounds produced by the deep-dwelling holothurian *Molpadia oolitica* (Rhoads and Young 1971), and *Cossura longocirrata,* a subsurface deposit feeder. Density at FF07 declined to roughly 30 percent of the 2004 values (1486.7 organisms per sample in 2006 vs. 5001.7 in 2004), reflecting the decline in numbers of *E. incolor* and *C. longocirrata*.

- At FF09, which had the smallest decline in mean density of the four farfield stations, a small decline in the abundance of *Prionospio steenstrupi* was offset by small increases in the abundances of *Spio limicola* and *Levinsenia gracilis*.



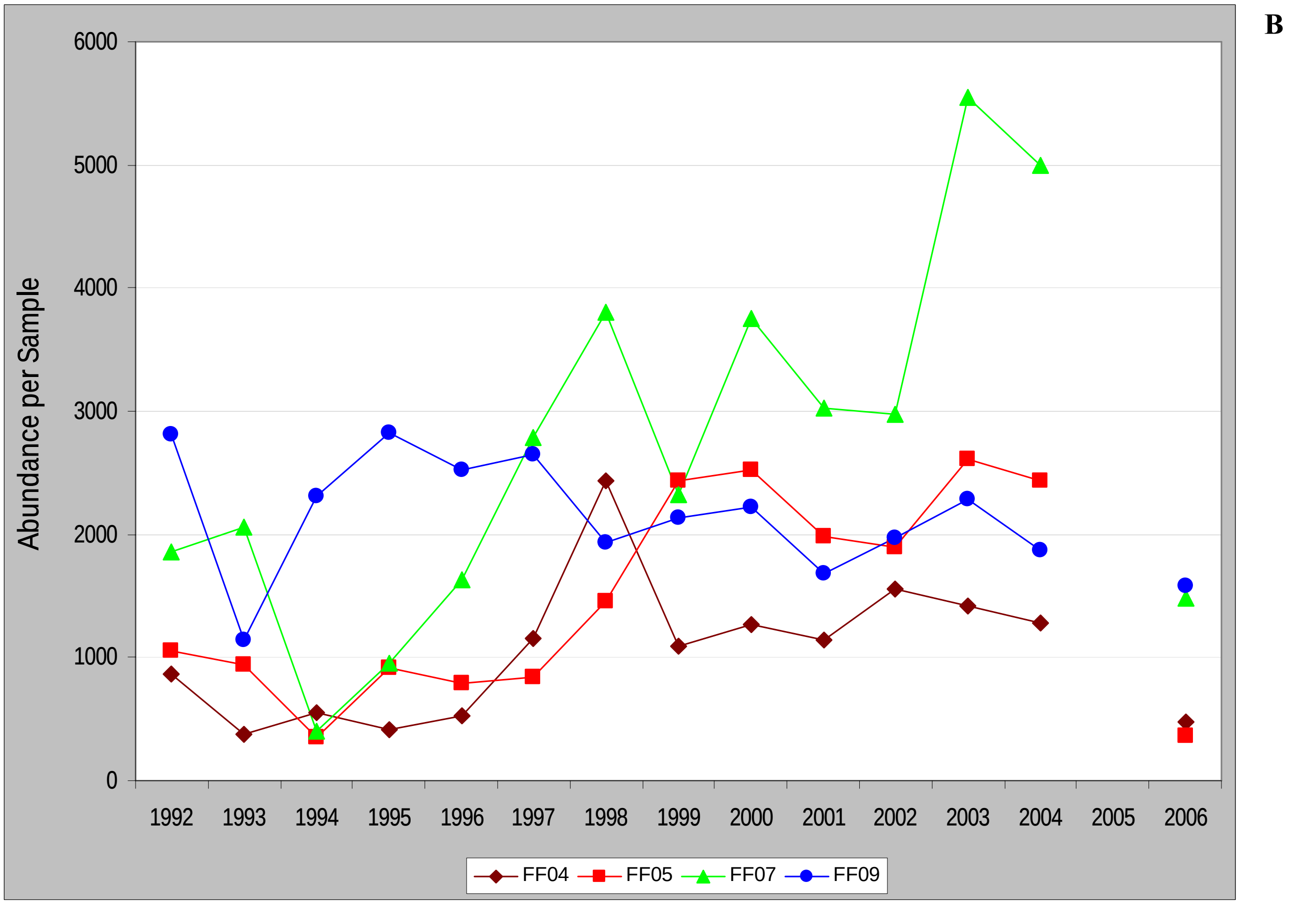


Figure 5-5. (A) Mean abundance per sample for farfield stations. Different subsets of four stations each were sampled in 2004/2006 and 2005. (B) Annual mean abundance at each farfield station.

Species Richness—In 2006, 242 species were identified from the 12 farfield samples taken at four locations, with an average of 62.9±24.7 species per sample and a range from 46.7 species at FF04 to 101.7 species at FF09. In 2004, the average for these four stations was 79.8 species per sample (range 57.7–104.3) (Maciolek *et al*. 2004). The mean number of species per sample declined primarily at three of the four farfield stations, FF04, F05, and FF07 (Figure 5-6A, Appendix C3, Figure C3-2), and brought the overall mean down to only slightly above the baseline value of 61 species.

***Diversity and Evenness*—**The changes in these parameters in 2006 were very small, especially when compared with the values obtained in 2004 for this station set. Compared with values obtained for 2005, abundance, species, and log-series *alpha* declined, while Shannon diversity and evenness increased.

In 2006, mean Shannon diversity (H′) at the farfield stations was 4.31 (compared with the baseline mean of 3.74, (Figure 5-6B). Three of the four stations increased compared with H′ values recorded in 2004 (Figure 5-6B, Appendix C3, Figure C3-3): FF04 decreased from 4.53 to 4.02; whereas FF05 increased from 3.86 to 4.74, FF07 increased from 2.91 to 3.62, and FF09 increased slightly from 4.77 to 4.83.

Pielou's evenness (J′) (mean = 0.73) was the highest mean recorded for these four stations (Figure 5-6C). When stations were examined individually and evenness values compared with those obtained when the stations were last sampled in 2004 (Figure 5-6B, Appendix C3: Figure C3-4), evenness was seen to have increased especially at FF05 (from 0.59 to 0.83) and FF07 (from 0.50 to 0.65). Similar values had been obtained at both stations early in the program (1994–1996, Figure C3-4), although not in recent years. A small decline was seen at FF04 (from 0.76 to 0.73) and a trivial increase at FF09 (from 0.71 to 0.72). These values are all well above baseline.

Mean log-series *alpha* increased from 14.49 in 2005 to 16.28 in 2006, remaining well above the baseline mean of 13.4 (Figure 5-6D). These four stations had a mean *alpha* value of 16.75 when last sampled in 2004. *Alpha* declined slightly at two (FF04, FF05) of the four farfield stations, and increased slightly at two stations (FF07, FF09) compared with values obtained in 2004 (Figure 5-6D).

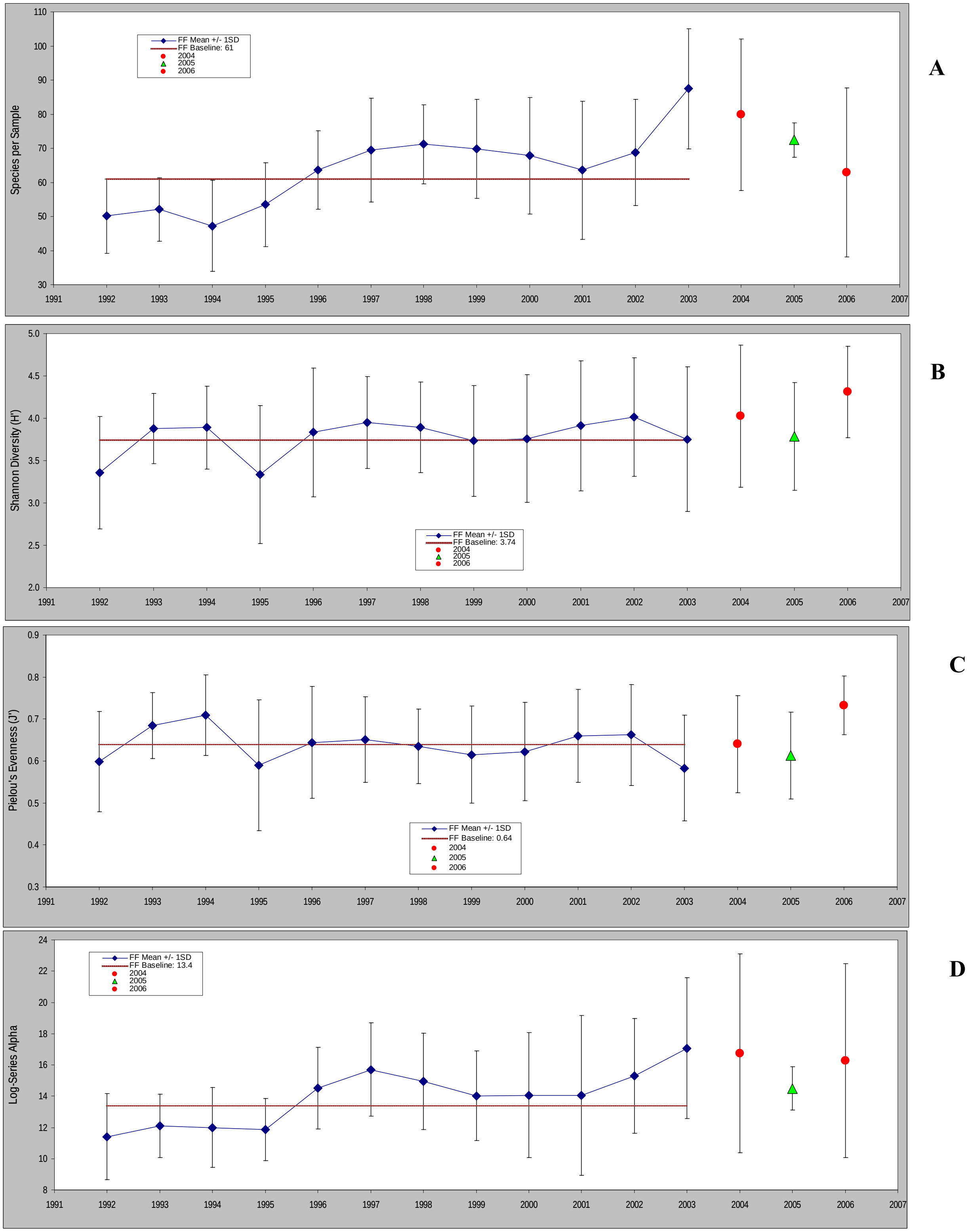


Figure 5-6. Annual mean parameters for farfield benthic infaunal stations. (A) Mean number of species per sample, (B) Mean Shannon diversity, (C) Mean evenness, and (D) Mean log-series *alpha* at farfield stations from 1992–2006. The means for the two subsets of stations sampled in 2004 and 2006, and 2005, respectively, are indicated by different symbols.

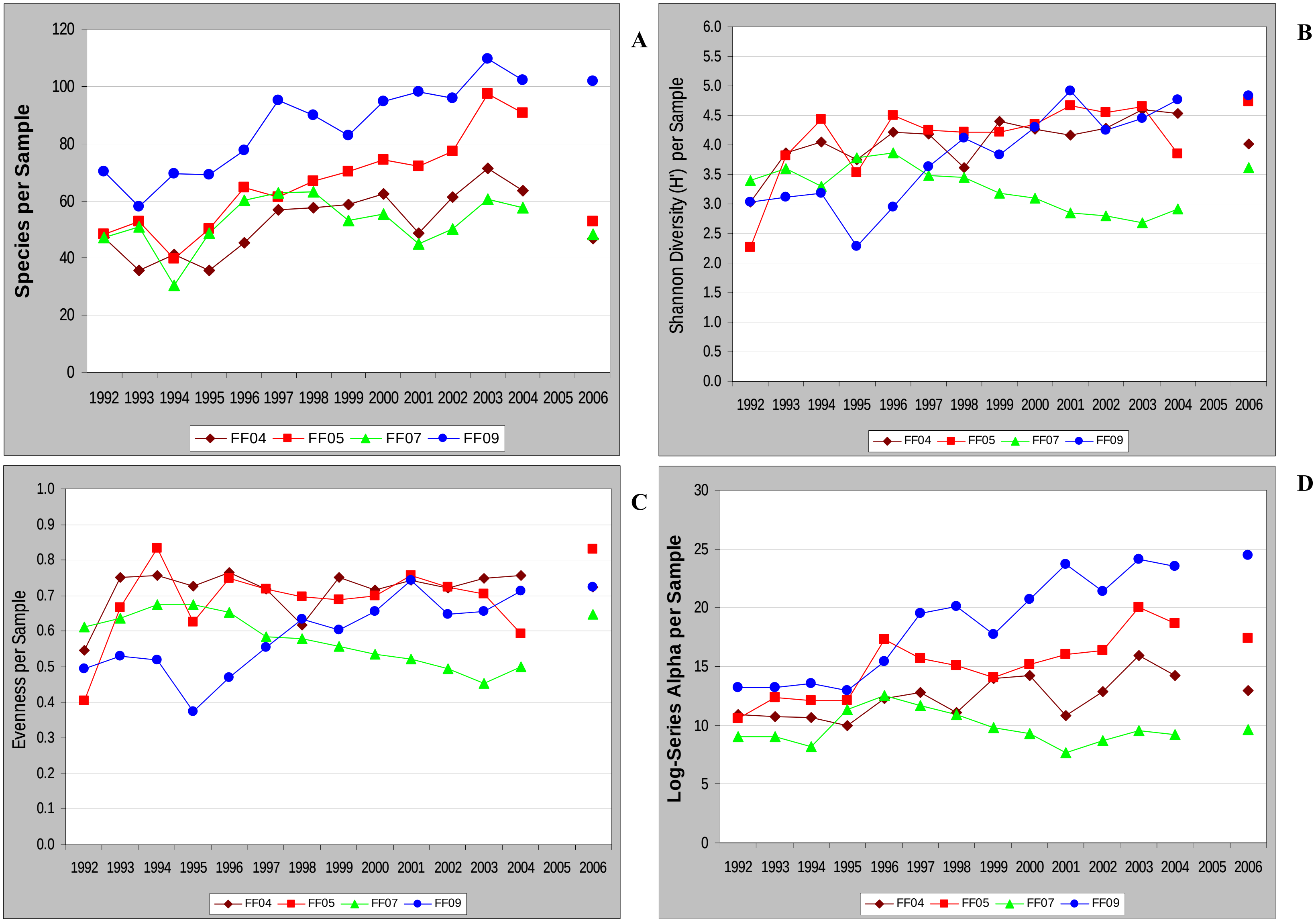


Figure 5-7. Annual parameters for individual farfield benthic infaunal stations sampled in 2006. (A) Mean number of species per sample, (B) Mean Shannon diversity, (C) Mean evenness, and (D) Mean log-series *alpha*.

Dominant Species—Dominant species at each farfield station are listed in Appendix C4, along with the percent contribution of each to the total community based on both total individuals in the sample and those that were identified to species. In the latter case, the percentage is usually just a few tenths of a point less than when calculated for total individuals. The population fluctuations of six of the dominant species are shown in Figure 5-8. FF04 and FF05 had many top ten numerical dominants in common, albeit in different rank order.

- At FF04, the spionid *Prionospio steenstrupi* was the numerical dominant, accounting for nearly 23 percent of the individuals collected at this station. Although dominant at many of the nearfield stations over the past few years, *P. steenstrupi* has not previously been within the top five numerical dominants at this station. Other previously important species, such as *Cossura longocirrata* and *Spio limicola*, continued to be important components of the fauna, whereas others, such as *Chaetozone anasimus* (formerly called *Chaetozone setosa* mb) and *Aricidea quadrilobata*, dropped in rank to eighth and twelfth place, respectively.

- At FF05, *Levinsenia gracilis*, *Ninoe nigripes*, and *Mediomastus californiensis* were the numerical dominants, replacing those that were most numerous in 2003 and 2004 (S. *limicola*, *P. steenstrupi*, and *A. quadrilobata*).

- At FF07, the top three numerical dominants were *C. longocirrata*, *Euchone incolor*, and *Aricidea catherinae*, as in 2002 through 2004. Although the abundances of these species had declined substantially in 2006 compared with earlier years, they continued to be the most numerous in the samples.

- At FF09, *P. steenstrupi*, and *Levinsenia gracilis* continued to be numerical dominants, while *Anobothrus gracilis* declined in numbers and was replaced by *Nucula delphinodonta* and *Spio limicola*.

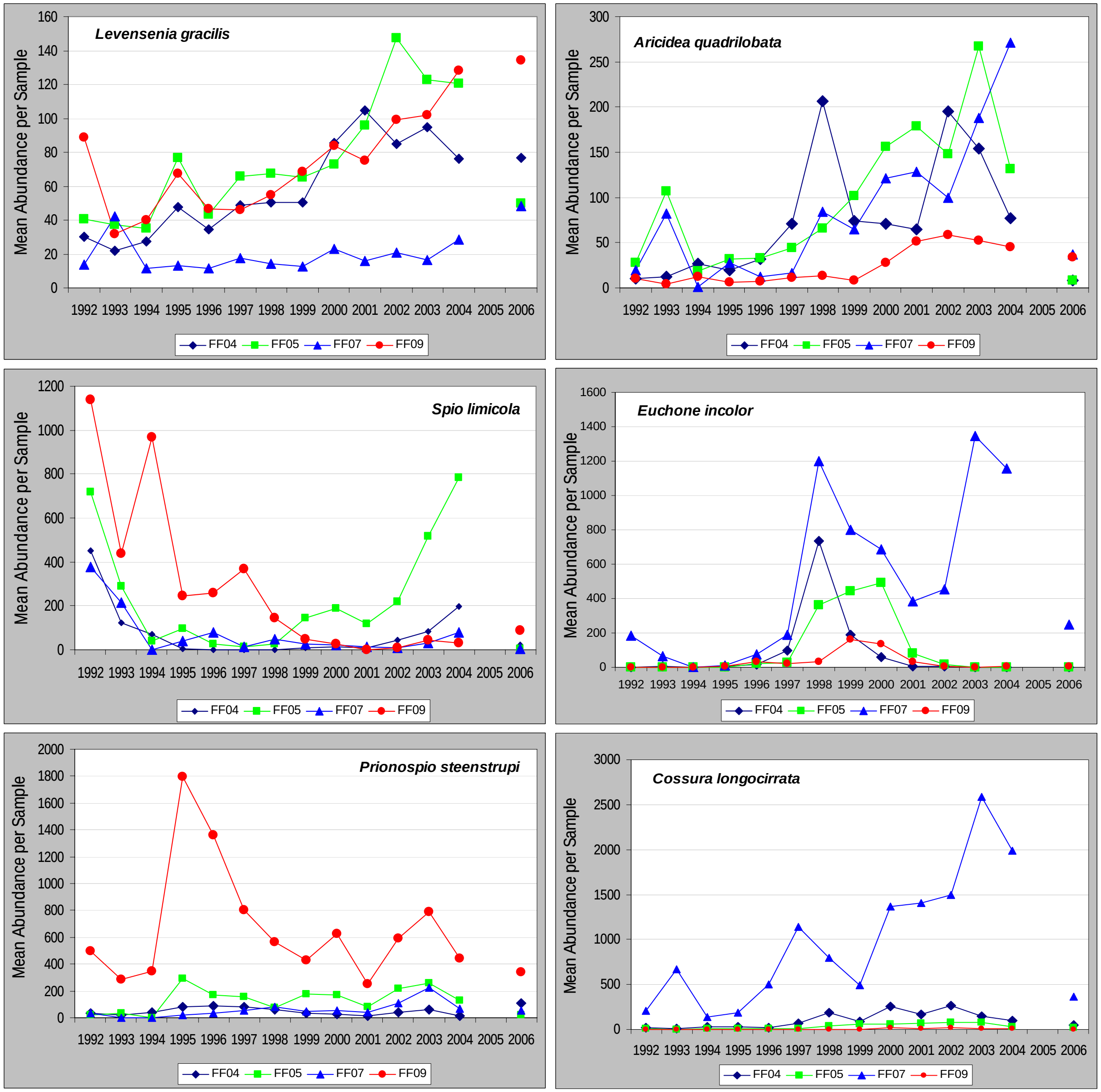


Figure 5-8. Mean density per 0.04-m^2 sample of species common at the farfield stations.

5.3.4 Multivariate Analysis of 2006 Samples

***Similarity Analysis*—**The CNESS (*m* =15) similarities of the 33 samples taken in 2006 were clustered using group average sorting (Figure 5-9). The samples form five major groups or clusters, at roughly the 0.80 level (highest dissimilarity in CNESS is 1.41). The five groups comprise (1) farfield stations FF04 and FF05, which are close to or in Stellwagen Basin, (2) FF09, to the west and inshore of Stellwagen, (3) all nearfield stations except NF17 and NF23, (4) Cape Cod Bay station FF07, and (5) sandy stations NF17 and NF23. Where replicates were taken at a station, those replicates are always more similar to samples from within the station than to samples from another station.

With CNESS, samples from stations NF17 and NF 23 (group 5) have a very low level of similarity to the remaining stations. These stations are characterized by coarser-grained sediments than are found at the other stations, and are characterized by a different suite of species than is found at the fine-grained stations. The dichotomy between farfield stations FF04, FF05, FF07, FF09 (groups 1, 2, and 4) and the large group (3) of nearfield samples reflects the higher densities of *Cossura longocirrata*, *Euchone incolor*, and *Anobothrus gracilis* at these stations.

The Bray-Curtis analysis of these data (after a fourth-root transformation to decrease the influence of species with high abundances) resulted in a similar overall pattern (Figure 5-10). Specific similarities among the nearfield stations differ to a small degree between the two analyses, but replicates from single stations cluster together, as in previous years (Maciolek *et al.* 2004, 2005, 2006); the only exception this year was that one replicate from FF10 was more similar to samples from NF07 and NF09 than to the other two replicates from that station. In both analyses, the groups comprising the sandy stations NF17 and NF23 had the lowest similarity to the remainder of the samples.

One difference in similarities among stations between 2004 and 2006 is that in 2004 (with both CNESS and Bray-Curtis) FF09 was most similar to samples from the deeper stations FF04 and FF05, whereas in 2006, the CNESS analysis indicated that FF09 formed an independent group equal in similarity to groups 1 (FF04 and FF05) and 3 (silty nearfield samples). The Bray-Curtis analysis for 2006 suggested that the cluster of three replicates from FF09 was more similar to samples from the silty nearfield stations than to the remaining farfield stations (FF04, FF05, and FF07), a pattern seen in many earlier analyses. In the mid- to late 1990s when nearfield and farfield stations were included in the same analyses, FF09 was more similar to some of the nearfield stations than to FF04 and FF05 (Hilbig *et al.* 1997, Blake *et al.* 1998a,b). For example, Blake *et al.* (1998b, p. 67, Figure 39) described a “large nearshore mud assemblage” that included FF01A, FF09, and several nearfield stations, including NF08 and NF22. FF04 and FF05, deeper stations to the east, usually clustered separately from FF09. Some changes to this clustering pattern were seen in the early 2000s, with FF09 showing more affinity to FF04 and FF05 based on the CNESS algorithm (but retaining a high similarity to FF01A and to the nearfield stations with the Bray-Curtis algorithm (*e.g.*, Maciolek *et al.* 2004, Figures 5-9 and 5-10). Such shifts likely reflect both small changes in sediment type and dominant infauna: in 2006, abundances of the dominant *Prionospio steenstrupi*, as well as *Levinsenia gracilis*, *Spio limicola* and *Mediomastus californiensis* were higher at FF09 than at FF04 or FF05, and more similar to densities of those species at the nearfield stations.

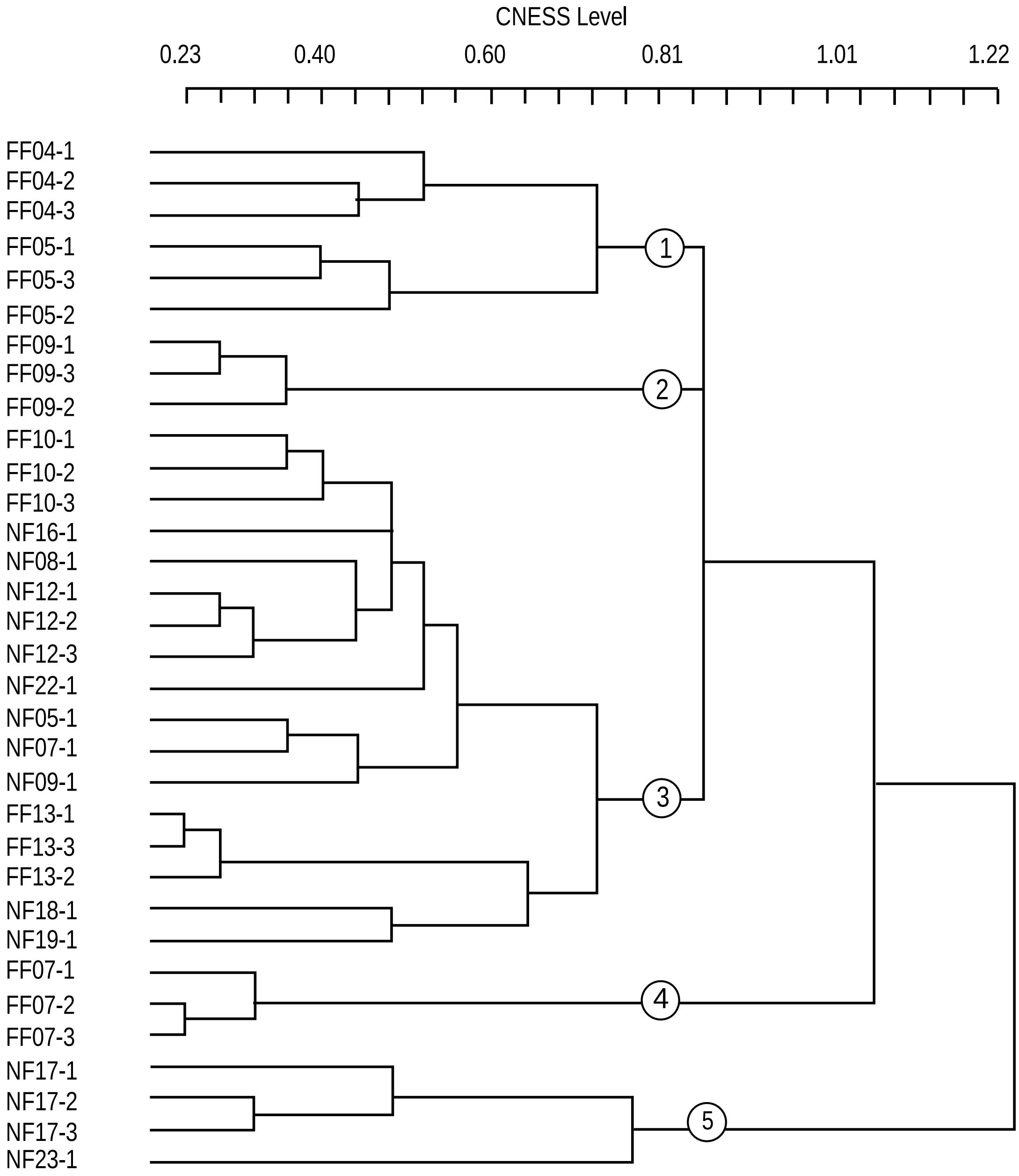


Figure 5-9. Relationship of 2006 samples based on CNESS similarity (*m*=15) and group average clustering.

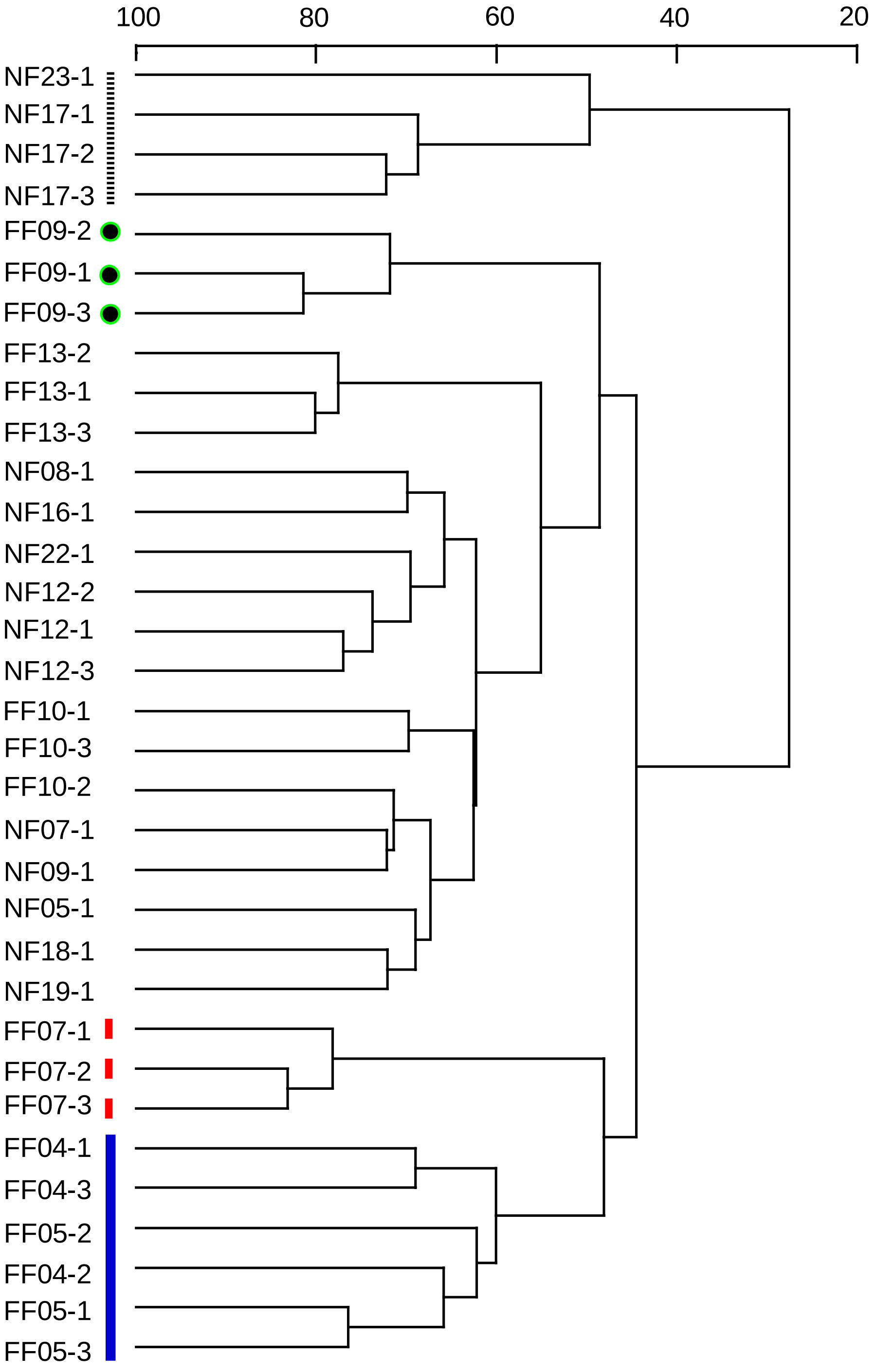


Figure 5-10. Relationship of 2006 samples based on Bray-Curtis similarity after fourth-root transformation of the data and group average clustering. Samples corresponding to CNESS groups are identified by solid blue line (group 1), green circle (group 2), no line (group 3), dashed red line (group 4), and barred black line (group 5).

PCA-H analysis**—**The PCA-H analysis based on the CNESS similarities separated the cluster groups discussed above along several multidimensional axes, with axis 1 and axis 2 together accounting for 51% of the total variation (Figure 5-11A). These two axes most likely represent a combined sediment grain size vs. depth (or region) gradient; however, these factors are not clearly assignable to either axis, although axis 1 appears to represent a separation according to sediment type. The CNESS clusters are distinct in this two-dimensional presentation, with the Cape Cod Bay station FF07 (group 4) well separated from the other farfield stations (FF04 and FF05, cluster group 1) and FF09 in cluster group 3. The nearfield stations in cluster group 3 separate along axis 2 from the farfield stations, and from other nearfield stations along axis 1. With CNESS (m=15), 37 of the 237 species recorded in 2006 accounted for 89% of the variation in the community structure, and contributed at least 1% to the PCA-H axes (Table 5-2).

The species accounting for at least 2% of the CNESS variation, and therefore the ones responsible for the separation of the samples, are indicated for Axes 1 and 2 in the Gabriel Euclidean distance biplot (Figure 5-11B) and are detailed for Axes 1–3 in Table 5-3. The majority of nearfield stations, as well as FF09, are structured by the surface-deposit- (and sometimes filter-) feeders *Prionospio steenstrupi* and *Spio limicola*, and the subsurface deposit feeders *Mediomastus californiensis*, *Levinsenia gracilis*, *Monticellina baptisteae*, and the bivalve *Thracia conradi*. The sandy nearfield stations (NF17 and NF23) are characterized by the spionid polychaete *Spiophanes bombyx*, the syllid polychaete *Exogone hebes* (an omnivore), another omnivore polychete *Ninoe nigripes*, the ascidian *Molgula manhattensis*, and the bivalves *Cerastoderma pinnulatum* and *Ensis directus*. *Cossura longocirrata* is the important species at farfield station FF07, and the remaining two farfield stations, FF04 and FF05, are also influenced by *C. longocirrata* as well as *Levinsenia gracilis* and *Ninoe nigripes*.

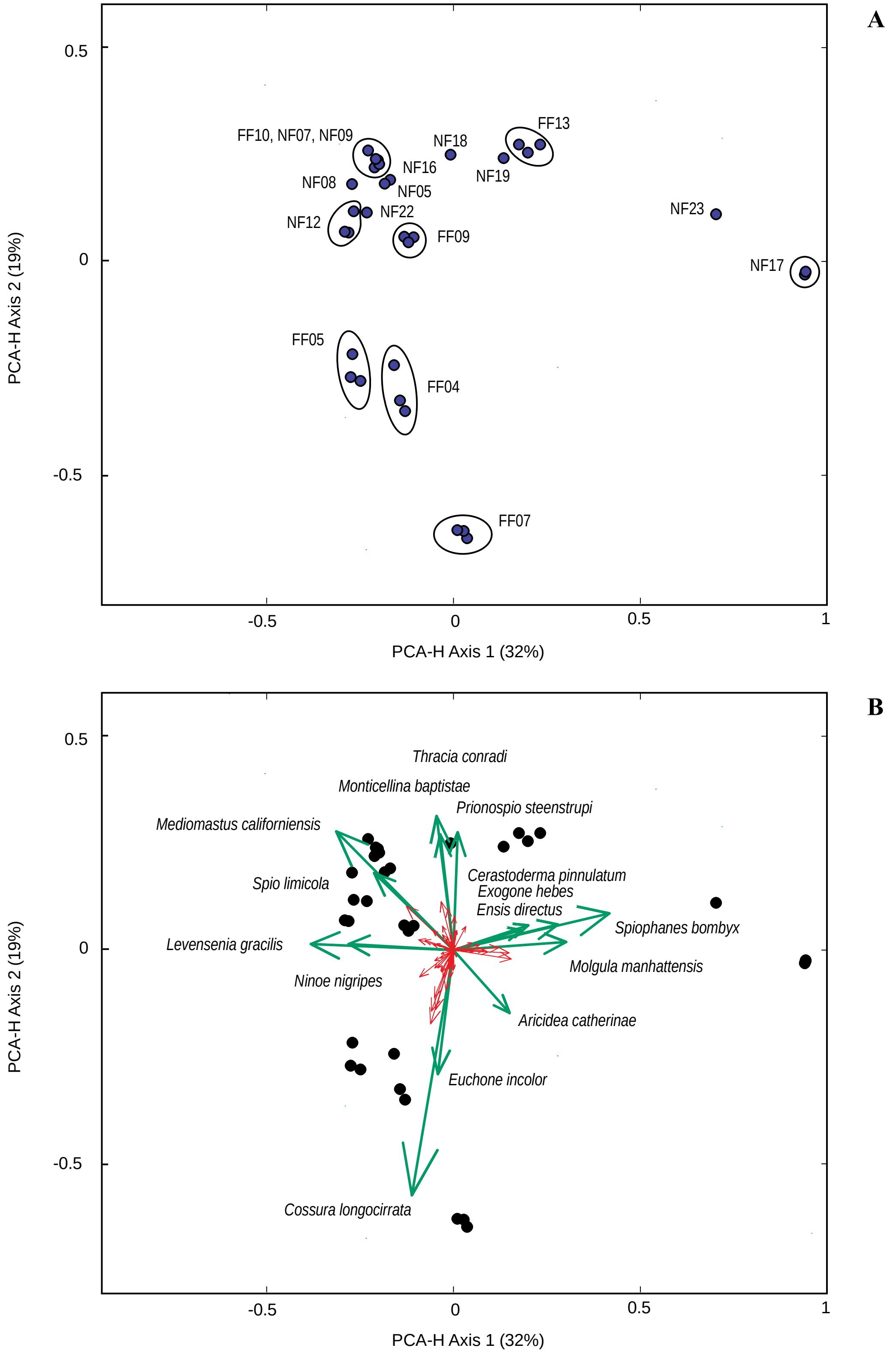


Figure 5-11. Metric scaling on PCA-H axes 1 and 2 of the 2006 benthic infaunal samples (A) and the Euclidean distance biplot showing the species responsible for at least 2% of the variation (B).

Table 5-2. Contribution of the 37 species in the 2006 Massachusetts and Cape Cod Bay samples identified by PCA-H analysis as important in structuring the infaunal communities, and their loadings on each of the seven PCA-H axes.

PCA-H Rank	Species	Contr.	Total Contr.	Ax.1	Ax.2	Ax.3	Ax.4	Ax.5	Ax.6	Ax.7
1	*Cossura longocirrata*	7	7	1	33	0	2	4	1	1
2	*Spiophanes bombyx*	6	13	17	1	0	4	0	3	0
3	*Mediomastus californiensis*	6	19	10	8	5	2	0	6	0
4	*Levinsenia gracilis*	6	25	15	0	3	5	2	0	5
5	*Aricidea catherinae*	5	30	2	2	15	9	6	0	5
6	*Spio limicola*	5	35	5	3	5	5	3	20	1
7	*Ninoe nigripes*	4	39	8	0	5	5	8	1	2
8	*Molgula manhattensis*	4	43	9	0	1	0	5	3	3
9	*Monticellina baptisteae*	4	47	0	7	7	3	3	1	6
10	*Euchone incolor*	4	50	0	8	8	5	2	0	1
11	*Tharyx acutus*	4	54	0	10	5	0	1	2	11
12	*Prionospio steenstrupi*	3	57	0	8	1	2	26	1	0
13	*Limnodriloides medioporus*	3	60	0	2	11	3	1	1	7
14	*Ensis directus*	3	63	8	0	0	2	0	2	0
15	*Nucula delphinodonta*	3	66	2	1	2	13	3	4	3
16	*Exogone hebes*	2	68	4	0	1	1	1	2	2
17	*Trichobranchus roseus*	2	70	1	0	5	1	1	2	3
18	*Anobothrus gracilis*	1	72	0	1	5	0	4	1	1
19	*Syllides longocirrata*	1	73	0	2	2	4	1	0	6
20	*Microclymene* sp.1	1	75	0	0	3	5	0	9	3
21	*Chaetozone hystricosus*	1	76	2	0	1	1	1	0	1
22	*Aphelochaeta marioni*	1	77	1	0	1	1	0	5	0
23	*Cerastoderma pinnulatum*	1	79	3	0	0	0	1	1	1
24	*Crenella decussata*	1	80	0	0	2	8	0	3	1
25	*Aricidea quadrilobata*	1	81	0	3	1	0	0	3	0
26	*Crassicorophium crassicorne*	1	82	2	0	0	1	2	0	0
27	*Leitoscoloplos acutus*	1	83	1	0	0	2	1	1	0
28	Nemertea sp. 12	1	84	0	0	2	1	0	1	1
29	*Pleurogonium rubicundum*	1	84	0	0	0	1	0	5	8
30	*Tubulanus pellucidus*	1	85	0	0	0	2	7	2	1
31	*Chaetozone anasimus*	1	86	0	0	1	0	2	0	0
32	*Monticellina dorsobranchialis*	1	86	0	1	1	0	0	0	0
33	*Arctica islandica*	1	87	0	1	0	0	0	1	1
34	*Aglaophamus circinata*	1	88	1	0	0	0	1	0	0
35	*Scoletoma hebes*	1	88	0	1	1	0	1	1	1
36	*Apistobranchus typicus*	1	89	0	1	1	1	0	0	0
37	*Parougia caeca*	1	89	0	0	0	0	1	1	1

Table 5-3. Contributions to PCA-H axes by species accounting for at least 2% of the CNESS variation among the infaunal samples collected in 2006 as determined by the Gabriel Euclidean distance biplot analysis (see Figure 5-9B).

Important species: Axis 1 vs. 2					
PCA-H Rank	**Species**	**Contr.**	**Total Contr.**	**Axis1**	**Axis2**
1	*Cossura longocirrata*	13	13	1	33
2	*Spiophanes bombyx*	11	24	17	1
3	*Levinsenia gracilis*	9	33	15	0
4	*Mediomastus californiensis*	9	42	10	8
5	*Molgula manhattensis*	6	48	9	0
6	*Ensis directus*	5	53	8	0
7	*Ninoe nigripes*	5	58	8	0
8	*Spio limicola*	4	62	5	3
9	*Thracia conradi*	4	66	0	10
10	*Euchone incolor*	3	69	0	8
11	*Prionospio steenstrupi*	3	72	0	8
12	*Monticellina baptisteae*	3	75	0	7
13	*Exogone hebes*	3	77	4	0
14	*Aricidea catherinae*	2	80	2	2
15	*Cerastoderma pinnulatum*	2	82	3	0
Important species: Axis 1 vs. 3					
PCA-H Rank	**Species**	**Contr.**	**Total Contr.**	**Axis 1**	**Axis 3**
1	*Spiophanes bombyx*	12	12	17	0
2	*Levinsenia gracilis*	11	23	15	3
3	*Mediomastus californiensis*	8	31	10	5
4	*Ninoe nigripes*	7	38	8	5
5	*Aricidea catherinae*	7	44	2	15
6	*Molgula manhattensis*	6	50	9	1
7	*Ensis directus*	5	56	8	0
8	*Spio limicola*	5	60	5	5
9	*Limnodriloides medioporus*	4	64	0	11
10	*Exogone hebes*	3	67	4	1
11	*Euchone incolor*	3	70	0	8
12	*Cerastoderma pinnulatum*	2	72	3	0
13	*Monticellina baptisteae*	2	74	0	7
14	*Trichobranchus roseus*	2	76	1	5
Important species: Axis 2 vs. 3					
PCA-H Rank	**Species**	**Contr.**	**Total Contr.**	**Axis 2**	**Axis 3**
1	*Cossura longocirrata*	18	18	33	0
2	*Euchone incolor*	8	27	8	8
3	*Aricidea catherinae*	8	35	2	15
4	*Thracia conradi*	8	42	10	5
5	*Monticellina baptisteae*	7	50	7	7
6	*Mediomastus californiensis*	6	56	8	5
7	*Limnodriloides medioporus*	6	62	2	11
8	*Prionospio steenstrupi*	5	66	8	1
9	*Spio limicola*	4	70	3	5
10	*Anobothrus gracilis*	3	73	1	5
11	*Trichobranchus roseus*	3	76	0	5
12	*Ninoe nigripes*	2	78	0	5

***Rarefaction analysis*—**By this measure, the farfield station FF09 is seen to have the highest diversity of the sampled stations, followed by FF05 and FF04 (Figure 5-12). The short, steep curves for those two stations suggest that they were undersampled. Although FF09 usually has a fairly high species richness, rarefaction results in other years have placed it lower than stations such as FF10, FF05, and the sandy nearfield stations NF17 and NF24 (e.g., 1995, Hilbig *et al.* 1996). In 2006, the nearfield samples fell between the two extremes, with the sandy stations NF 17 and NF23 having curves lower than the finer-sediment stations such as NF 12 and NF18. The lowest diversity in 2006 was at FF07 in Cape Cod Bay; as in many previous years, this station was dominated by one or two species, thereby reducing the observed diversity.

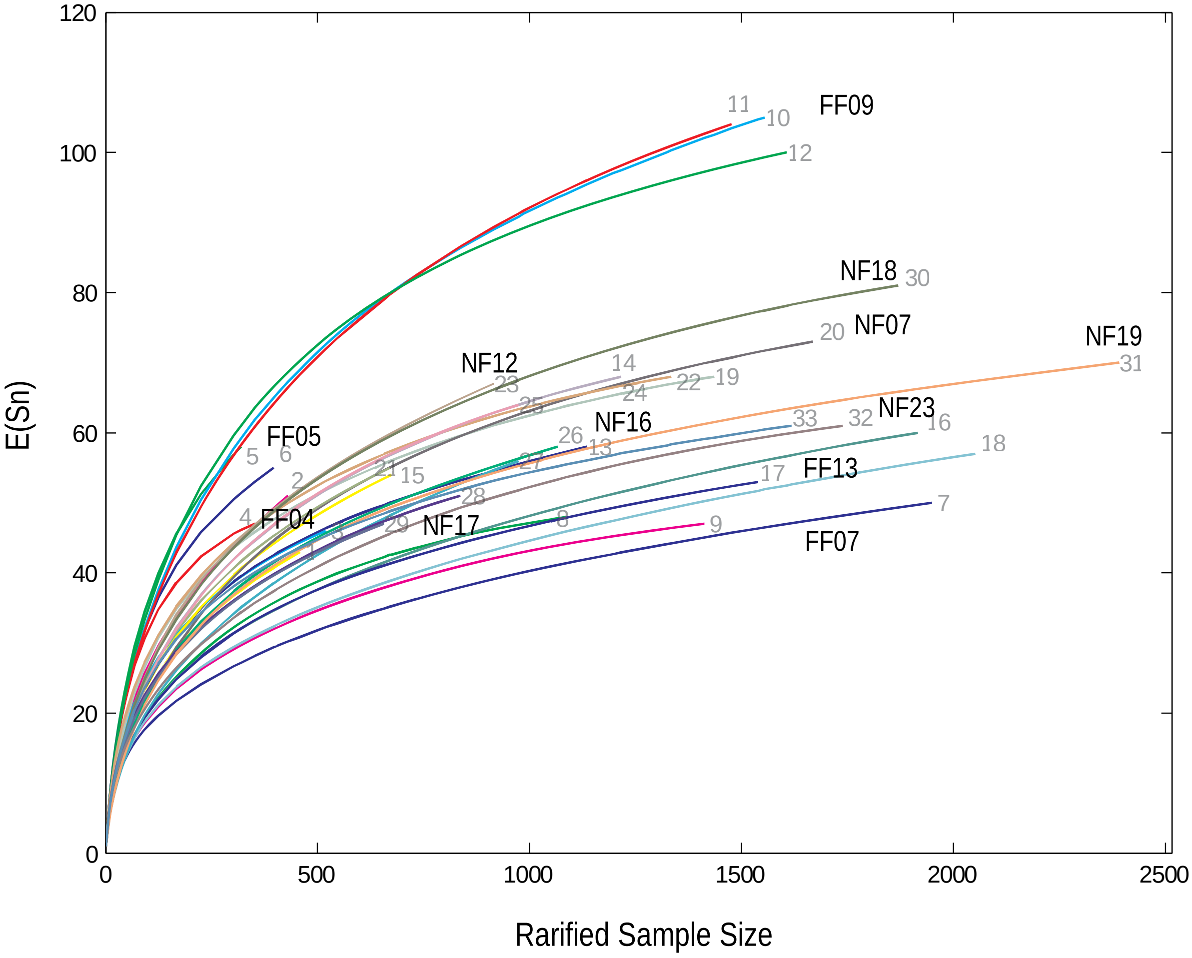


Figure 5-12. Rarefaction curves for samples collected in 2006. The numbers 1-33 refer to the 33 individual samples. Some but not all station numbers are indicated.

5.3.5 Multivariate Analysis of the 1992-2006 Nearfield Samples

As in previous years (Maciolek *et al*. 2004), the farfield stations continued to have low similarity to the nearfield stations; therefore, only the nearfield samples were examined in greater detail for any evidence of an impact from the outfall. Because of limitations in using CNESS, the Bray-Curtis algorithm was used, after a fourth-root transformation of the data.

Bray-Curtis Analysis—A multivariate analysis of all nearfield replicates collected from the 2006 subset of stations between 1992 and 2006 indicated three major groups of samples with less than 20 percent similarity to each other (Figure 5-13). As seen in previous years when CNESS was used (Maciolek *et al*. 2005), the major divisions separate the sandy stations from the finer-grained ones.

The most dissimilar group, Group 1, consisted of ten samples from stations NF 17 (one sample from 2001), NF22 (2000, 2001, 2003, and 2004), and NF23 (five samples from 2000–2004). These samples had less than 10% similarity to the remaining samples.

Group 2 comprised 51 samples, including all but one of the samples from NF17, plus seven from NF23 (1994–1999, and 2006) and one from NF07 (1997). This composition is basically similar to that determined with the CNESS algorithm for samples collected through 2004 (Maciolek *et al.* 2005). The single sample from NF07 in this cluster is from 1997, when abundances at that station were roughly half of that found in other years, and several species usually found at NF07 were absent or scarce, *e.g.*, *P. steenstrupi, M. californiensis, Pholoe minuta, and Phyllodoce mucosa*.

The separation of NF23 samples into two dissimilar groups reflects the marked differences in the species present in the samples. The 2006 sample from NF23 had a very low similarity to those collected in 2000–2004, but was highly similar to samples from 1994–1999. The 2006 sample was distinguished by the absence of Cephalothricidae sp.1 and *Euchone elegans*, both of which had been numerous for several years previous, and high numbers of *Exogone hebes*, *Spiophanes bombyx*, and *Prionospio steenstrupi*, all of which had been absent from the station during the same time frame but numerous in the early years of monitoring. The change in species composition might be due to changes in the sediment texture, however, both cluster groups include NF23 samples with similar ranges of percent sand, or percent sand-plus-gravel, so another more subtle factor is likely accounting for the differences detected by the algorithm. Sediment composition at the other coarse-grained station, NF 17, has been >95% sand each year (see Chapter 3, this report) whereas at NF23, percent sand has ranged from 71% in 1994 (and 2003) to 98% in 1995. In 2006, NF23 had only 63.3% sand, but also had the highest percentage of gravel (31.8%) recorded at this station, making sediments there comparable to other years in terms of coarse texture (Chapter 3, this report).

Cluster Groups 2 and 3, which included 233 samples, had only a 20% similarity with each other. Several subgroups could be differentiated within group 3, including three small subgroups, each with low within-group similarity, plus two larger subgroups comprising 40 and 186 samples, respectively. The first small subgroup, 3a, had a 30% similarity to the remainder of the group 3 samples; it included two samples from 1994 (NF16 and NF05). The second small subgroup, 3b, had a slightly higher but still low within-group similarity of ca. 35%; it comprised two samples from FF13 (1992 and 1995). The third, group 3c, had a 40% within-group similarity to the remaining group 3 samples; it included two samples from NF19 (1992 and 1004), and one from NF07 (1994).

The first major subgroup in cluster group 3, 3d, contained several subgroups. Group d1 included the remaining 40 samples from FF13. These samples were divided into two subclusters comprising samples 1992–1998 and 1999–2006. Sediments at FF13 appear to be patchy, with annual replicates varying widely in percent fines. Some species, such as the polychaetes *Mediomastus californiensis* and *Prionospio steenstrupi*, have been present consistently at FF13, whereas others such as the polychaetes *Dipolydora socialis* and *Eteone longa* were absent or rare in the first several years through 1998 and common in the later years. Other species, such as *Phoronis architecta* and the amphipod *Photis pollex*, were found in high numbers in some years (*e.g*., 1996, 1999, 2000) but not others, most likely corresponding to samples with coarse sediments.

The second major subgroup in cluster group 3, d2, comprised three small subgroupings (d2a, d2b, and d2c) of 19, 1, and 6 samples, respectively, and one major subgroup (d2d) that contained the remaining 160 samples. Group d2a included samples from NF05, NF18, and FF10; group d2b is one sample from NF05, 1995; and group d2c includes samples from NF08 and NF16. The largest group of samples in this analysis is group d2d, which itself contained two major subgroups that were similar at around 52%. One group, d2d-1, included 85 samples from a range of stations, including the majority of NF12 and NF22, plus FF10, NF05, NF07, NF08, NF09, and NF16. This group also included the 2006 samples from eight stations Group d2d-2 comprised 75 samples, primarily FF10 and NF09, but also included the 2006 sample from NF 18 and NF19.

At many stations, samples from the years 1994 through 1999 were dissimilar to those from later years, but the overall within-station similarity levels were such that no before- and after-discharge effects could be identified.

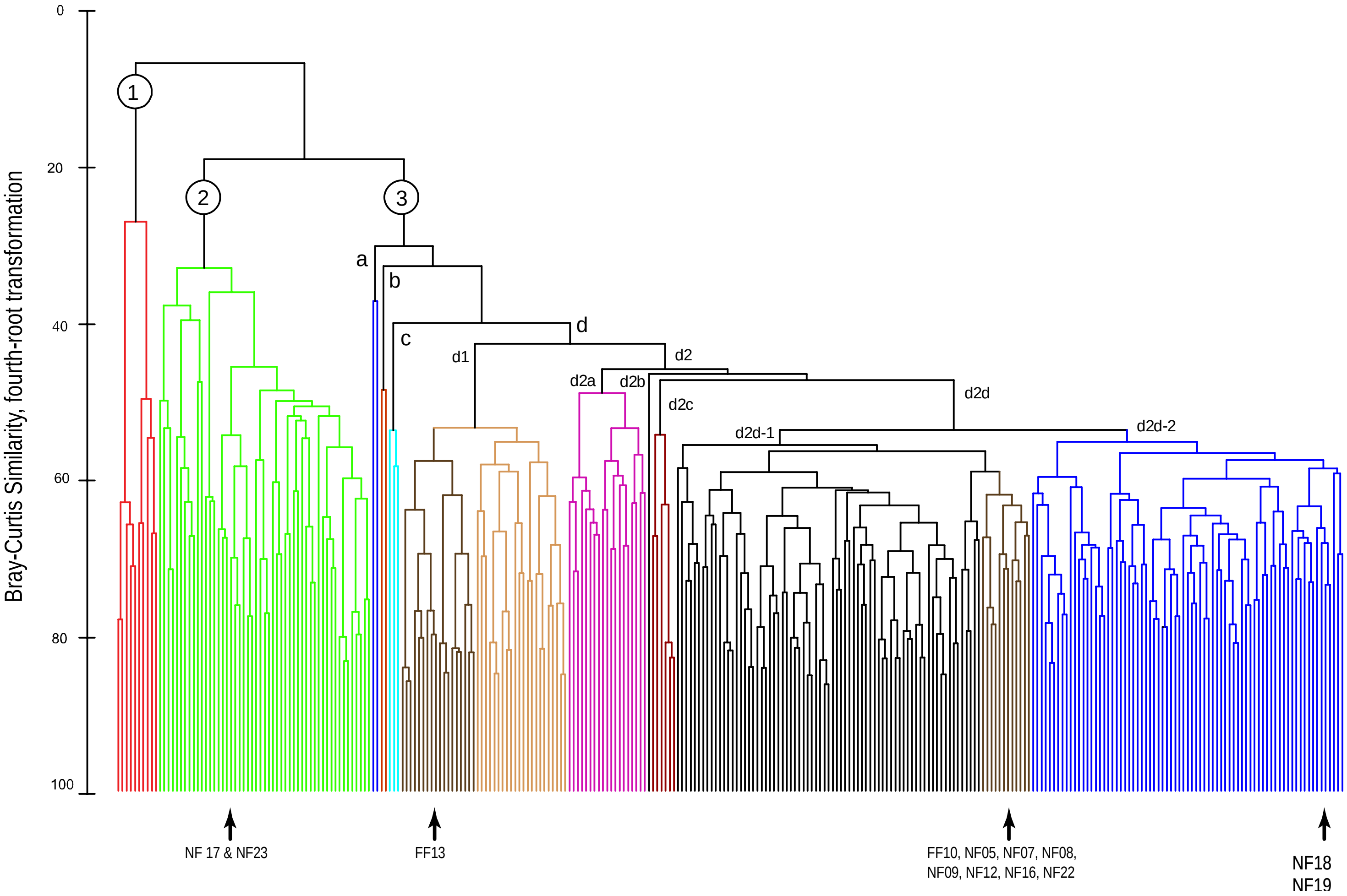


Figure 5-13. Cluster dendrogram of the 2006 subset of nearfield replicates collected 1992–2006, using the Bray-Curtis algorithm based on a fourth-root transformation of the data. Samples collected in 2006 are indicated.

PCAH Analysis—This analysis was based on 294 samples taken at nearfield stations between 1992 and 2006; these samples are all from the subset of stations sampled in 2006.

With CNESS (m=15), 43 of the 408 species recorded in the 294 nearfield samples in 1992–2006 accounted for 84% of the variation in community structure, and contributed at least 1% to the PCA-H axes (Table 5-4). Of these 43 species, 33 were identified as important in a similar analysis of stations sampled in 2005 (Maciolek *et al.* 2006). In turn, the 2005 analysis showed a good correspondence with the PCA-H analysis of the full set of nearfield samples performed in 2003 (Maciolek *et al.* 2004). These results strongly suggest that the two subsets of nearfield stations resemble both the full set and each other in terms of important structuring species. Many of the differences appear to be related to the inclusion of FF10 and FF13 in 2004 and 2006 versus FF12 in 2005.

Axes 1 and 2 of this multidimensional analysis accounted for 37% of the total CNESS variation. As seen in previous years, the sandier station NF17 separated from the remaining samples along Axis 1 (Maciolek *et al.* 2006) (Figure 5-14A). The majority of nearfield samples separated only along axis 2; in particular, FF10, which has a slightly different species composition, separated from the remaining nearfield stations along this axis, similar to the alignment seen for FF12 in 2005. Stations with intermediate positions on this diagram most likely reflect a gradient of species composition and sediment texture. Samples collected in 2006 are indicated by red stars (Figure 5-14A). While the majority are found within the cloud of points associated with the majority of samples, some appear to be somewhat isolated from the other samples from those stations.

The species accounting for at least 2% of the CNESS variation of this dataset are indicated in the Gabriel Euclidean distance biplot (Figure 5-14B) and detailed in Table 5-5. As seen for the 2005 samples, the majority of nearfield stations are structured by the spionid polychaetes *Prionospio steenstrupi* and *Spio limicola,* as well as *Mediomastus californiensis*, *Aricidea catherinae*, *Levinsenia gracilis*, and *Tharyx acutus*. The sandy nearfield stations (NF17, NF23) are influenced by the polychaetes *Exogone hebes*, *Spiophanes bombyx*, *Polygordius jouinae*, and the amphipods *Crassicorophium crassicorne* and *Pseudunciola obliquua*. The influence of particular species also carries a temporal component, with, for example, *Dipolydora socialis* being strongly influential in the early 1990s but not in later years.

Table 5-4. Contribution of the 43 species in the 1992–2006 Massachusetts Bay nearfield samples identified by PCA-H analysis as important in structuring the infaunal communities, and their loadings on each of seven PCA-H axes.

PCA-H Rank	Species	Contr.	Total Contr.	Ax.1	Ax.2	Ax.3	Ax.4	Ax.5	Ax.6	Ax.7
1	*Prionospio steenstrupi*	6	6	11	4	29	0	18	0	5
2	*Spio limicola*	6	13	8	26	0	0	12	0	3
3	*Mediomastus californiensis*	5	18	16	1	0	4	0	2	1
4	*Aricidea catherinae*	5	23	3	13	1	4	25	27	1
5	*Crassicorophium crassicorne*	4	27	11	1	0	8	1	1	0
6	*Tharyx acutus*	4	31	4	5	0	1	10	19	4
7	*Dipolydora socialis*	4	35	0	14	12	6	6	2	0
8	*Spiophanes bombyx*	3	38	6	0	0	7	0	0	9
9	*Levinsenia gracilis*	3	41	3	1	8	9	2	3	2
10	*Ninoe nigripes*	3	44	4	1	2	9	5	0	0
11	*Exogone hebes*	3	46	4	1	6	2	0	1	2
12	*Aphelochaeta marioni*	3	49	2	6	0	0	0	2	1
13	*Nucula delphinodonta*	2	51	2	4	3	0	1	8	2
14	*Polygordius jouinae*	2	53	4	0	0	3	0	0	3
15	*Monticellina baptisteae*	2	55	2	1	4	2	0	8	0
16	*Pseudunciola obliquua*	2	58	3	0	0	5	1	1	0
17	*Euchone incolor*	2	59	1	2	0	1	1	3	0
18	*Cerastoderma pinnulatum*	2	61	2	0	1	2	0	0	0
19	*Molgula manhattensis*	2	62	1	0	0	0	0	0	7
20	*Exogone verugera*	2	64	0	3	5	1	0	1	10
21	*Nephtys cornuta*	1	65	0	4	0	1	0	2	1
22	*Unciola inermis*	1	67	1	0	1	0	0	0	16
23	*Phoronis architecta*	1	68	0	0	1	1	1	1	2
24	*Photis pollex*	1	69	0	2	1	2	0	1	1
25	*Phyllodoce mucosa*	1	70	1	2	1	0	1	2	0
26	*Leitoscoloplos acutus*	1	71	1	0	0	0	1	0	0
27	*Ampharete acutifrons*	1	72	0	0	0	0	0	0	1
28	*Scoletoma hebes*	1	73	0	2	0	0	0	2	1
29	*Ensis directus*	1	74	0	0	0	0	0	0	3
30	*Echinarachnius parma*	1	75	1	0	0	1	0	0	1
31	*Nephtys incisa*	1	76	0	0	0	0	0	0	0
32	*Dipolydora quadrilobata*	1	77	0	1	0	1	1	0	0
33	*Hiatella arctica*	1	77	0	0	1	0	0	0	2
34	*Crenella decussata*	1	78	0	1	0	0	0	1	0
35	*Flabelligera affinis*	1	79	0	0	3	5	1	0	0
36	*Hippomedon serratus*	1	80	0	0	2	3	0	0	1
37	*Limnodriloides medioporus*	1	80	0	0	0	0	1	0	0
38	*Chiridotea tuftsi*	1	81	1	0	0	1	0	0	1
39	*Protomedeia fasciata*	1	82	0	0	1	0	1	0	4
40	*Erythrops erythrophthalma*	1	82	0	0	3	5	0	1	0
41	*Parougia caeca*	1	83	0	0	0	1	1	1	1
42	*Cephalothricidae* sp. 1	1	84	0	0	2	1	0	0	0
43	*Asabellides oculata*	1	84	0	0	0	0	0	1	0

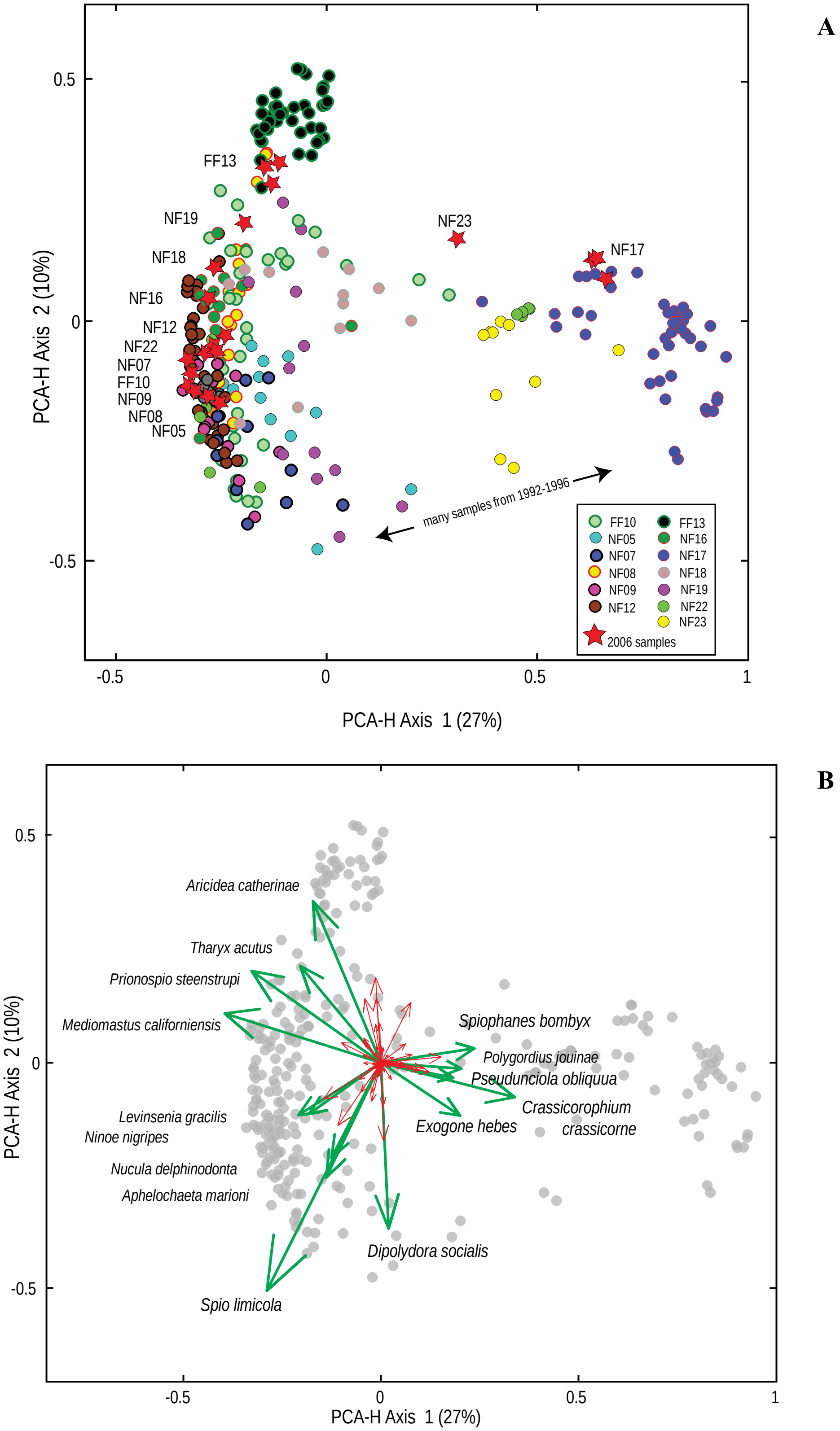


Figure 5-14. Metric scaling on PCA-H axes 1 and 2 of 294 nearfield benthic infaunal samples collected 1992–2006 (A) and the Euclidean distance biplot showing the species responsible for at least 2% of the CNESS (*m*= 15) variation.

Table 5-5. Contributions to PCA-H axes by species accounting for at least 2% of the CNESS variation among the infaunal samples collected from nearfield stations 1992–2006 (see Figure 5-14B for plot of axis 1 vs. axis 2).

Important species: Axis 1 vs. 2

PCA-H Rank	Species	Contr.	Total Contr.	Axis1	Axis2
1	*Spio limicola*	13	13	8	26
2	*Mediomastus californiensis*	12	25	16	1
3	*Prionospio steenstrupi*	9	34	11	4
4	*Crassicorophium crassicorne*	9	42	11	1
5	*Aricidea catherinae*	6	48	3	13
6	*Tharyx acutus*	4	52	4	5
7	*Spiophanes bombyx*	4	56	6	0
8	*Dipolydora socialis*	4	60	0	14
9	*Ninoe nigripes*	4	63	4	1
10	*Exogone hebes*	3	67	4	1
11	*Aphelochaeta marioni*	3	70	2	6
12	*Polygordius jouinae*	3	73	4	0
13	*Levinsenia gracilis*	3	76	3	1
14	*Pseudunciola obliquua*	2	78	3	0
15	*Nucula delphinodonta*	2	81	2	4

Important species: Axis 1 vs. 3

PCA-H Rank	Species	Contr.	Total Contr.	Axis 1	Axis 3
1	*Prionospio steenstrupi*	14	14	11	29
2	*Mediomastus californiensis*	13	27	16	0
3	*Crassicorophium crassicorne*	9	36	11	0
4	*Spio limicola*	7	43	8	0
5	*Spiophanes bombyx*	5	48	6	0
6	*Exogone hebes*	4	52	4	6
7	*Levinsenia gracilis*	4	56	3	8
8	*Ninoe nigripes*	4	60	4	2
9	*Tharyx acutus*	3	64	4	0
10	*Polygordius jouinae*	3	67	4	0
11	*Pseudunciola obliquua*	3	70	3	0
12	*Aricidea catherinae*	3	72	3	1
13	*Monticellina baptisteae*	3	75	2	4
14	*Dipolydora socialis*	2	77	0	12

Important species: Axis 2 vs. 3

PCA-H Rank	Species	Contr.	Total Contr.	Axis 2	Axis 3
1	*Spio limicola*	16	16	26	0
2	*Prionospio steenstrupi*	14	29	4	29
3	*Dipolydora socialis*	13	42	14	12
4	*Aricidea catherinae*	8	51	13	1
5	*Aphelochaeta marioni*	4	55	6	0
6	*Levinsenia gracilis*	4	58	1	8
7	*Nucula delphinodonta*	4	62	4	3
8	*Exogone verugera*	4	66	3	5
9	*Exogone hebes*	3	69	1	6
10	*Tharyx acutus*	3	72	5	0
11	*Nephtys cornuta*	2	74	4	0
12	*Monticellina baptisteae*	2	76	1	4

5.3.6 Statistical Analysis

The basic goal of this analysis was to assess differences in benthic stations after the diversion event in September 2000. Clearly there are differences between stations, years, and sediment types that are not related to the diversion event. A model that accounts for all these sources of variation first can then estimate more efficiently the change associated with the diversion. For this analysis all nearfield stations were divided into three zones: from 10 km to 5 km, from 5 km to 2.5 km, and less than 2.5 km. This stratification divides the stations into roughly equal groups with no stations near the boundaries of the three groups. The stratification partitions the stations in the following way: the 10 km to 5 km stratum includes stations FF10, FF12, FF13, NF02, NF05, and NF08; the 5 km to 2.5 km stratum includes stations NF04, NF07, NF09, NF10, NF16, NF20, NF21 and NF22, and the less than 2.5 km stratum includes stations NF12, NF13, NF14, NF15, NF17, NF18, NF19, NF23 and NF24.

The mean species abundances and other variables, including species richness and total abundance, were plotted separately by zone on a log scale (Figures 5-15–5-17, Appendix C5). The vertical line indicates the date when the effluent was first diverted to the offshore diffuser. The log scale is used for the response variable. On the log scale, zero abundance at a station cannot be plotted; therefore zero values are not shown on these plots and can be thought of as lying just below the plotted area.

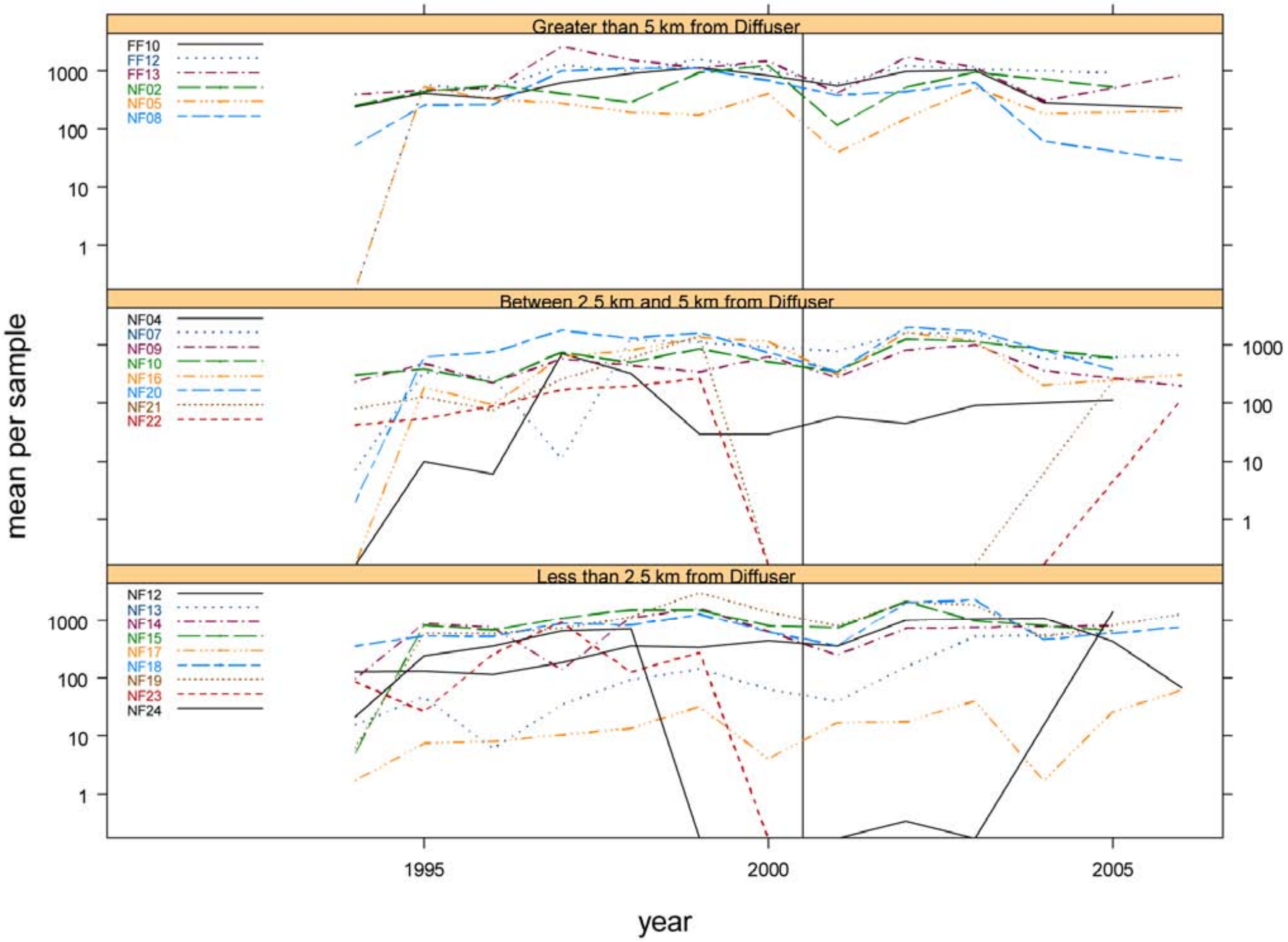


Figure 5-15. Log plot of *Prionospio steenstrupi* at the nearfield stations. Plots of additional species are presented in Appendix C5.

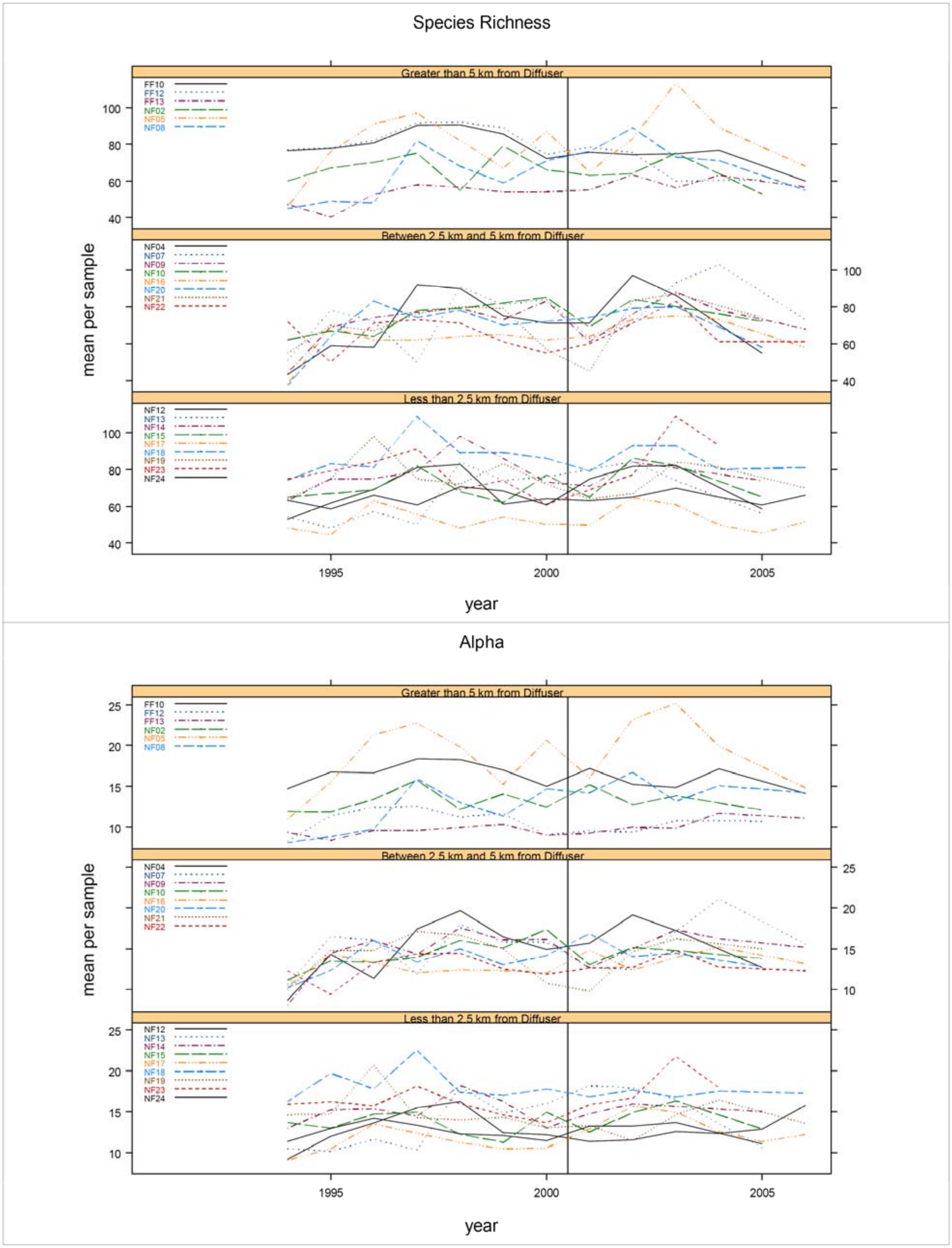


Figure 5-16. Log plots of species richness and log-series *alpha* at the nearfield stations.

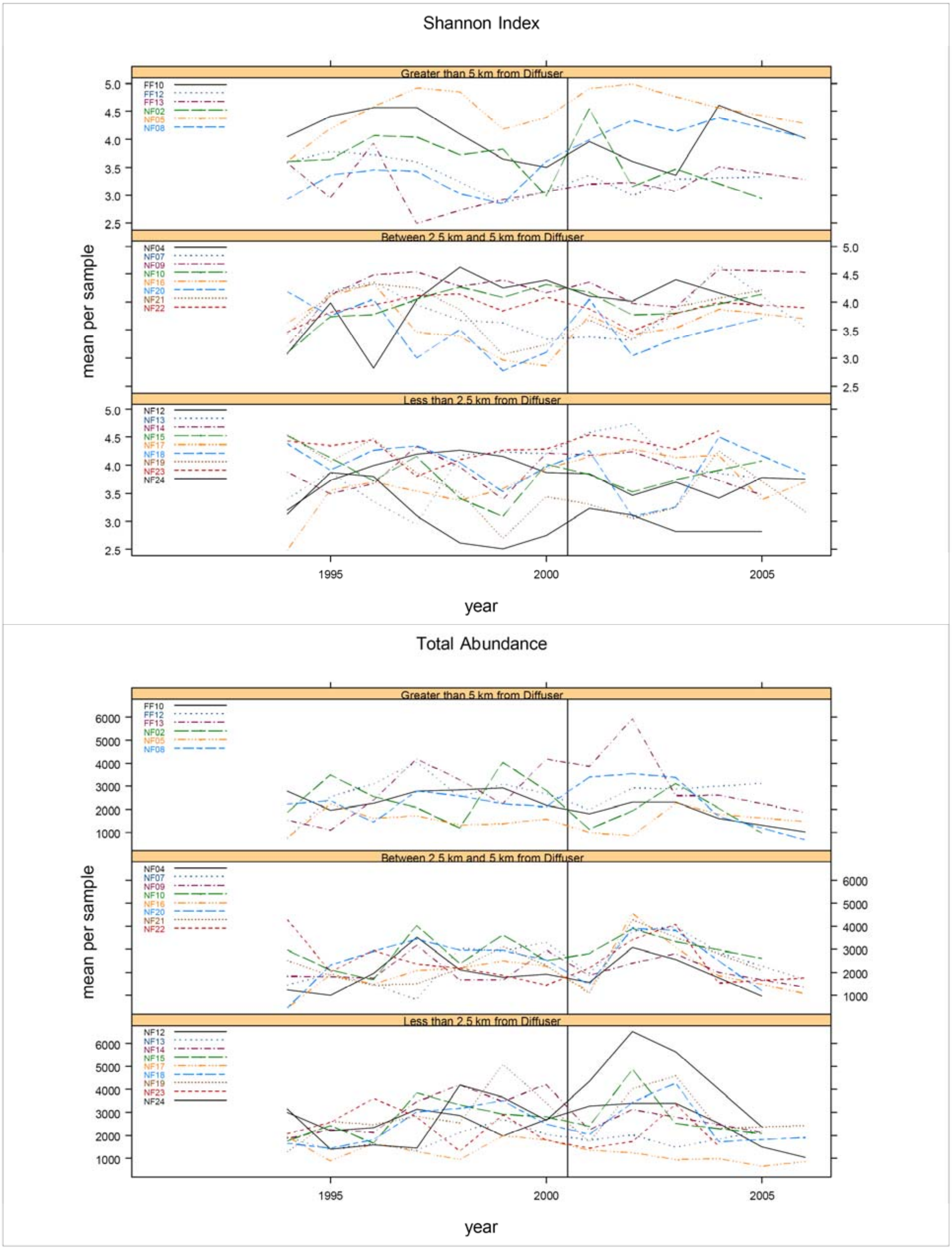


Figure 5-17. Log plots of the Shannon index and total abundance at the nearfield stations.

It is clear from the plots for nearly all species that stations have differing mean abundances and that species abundance varies between years. Indeed, a large proportion of the variation in the data can be explained with this simple log-linear year and station effect model. The question answered by the analysis in the tables below is: *how much of the remaining variation in the data is associated with the diversion?* To model this effect, we included a parameter for the relative increase (decrease) in abundances in stations less than 5 km from the diffuser after September 2000. An additional parameter, change in abundance at stations less than 2.5 km from the diffuser relative to all nearfield stations, was also included. These two relative differences summarize the general changes in the species abundance patterns after the fall of 2000.

A total of 58 species abundances were analyzed using this method (Appendix C5). In this situation, where multiple hypotheses are tested, one needs to adjust for multiple testing. A definition of statistical error that is natural for this kind of question is the false discovery rate (Benjamini and Hochberg 1995). This error rate is defined for each single null hypothesis—say, that single species abundance does not change in the nearfield after the fall 2000 diversion. The false discovery rate is the probability that a single null hypothesis is rejected when in fact that single null hypothesis is true. In many areas of modern biotechnology, where many compounds or species are tested at once, this false discovery rate is the logical error rate to use. For the results presented here, we have implemented the Benjamini and Hochberg procedure at a false discovery rate of $\alpha = 0.05$. In the procedure we compare

$$p-value_i < \frac{i}{m}\alpha,$$

where $p-value_i$ is the i-th smallest $p-value$ and m is the number of comparisons.

One then rejects all null hypotheses below the highest p-value that satisfies the above condition. Bold values in the table indicate which p-values satisfy the above decision rule at the $\alpha = 0.05$ level.

Tables 5-6 and 5-7 report only on the parts of the model estimation that are related to the estimation of the zone-by-diversion sub-model. For the continuous variables reported in Table 5-6, the only important association is an estimated 1.40 relative increase in *Clostridium* in the less-than-2.5-km zone. That is, there was an estimated relative increase in this zone of approximately 40% after the diversion. Approximately 83% of the variance was explained by the complete model, which included year, station, and fine sediment as explanatory variables. However, only 3.9% of the variation was explained by the zone-by-diversion sub-model. Thus, this environmental survey was able to detect a post-outfall 40% relative increase in *Clostridium* at the stations closest to the outfall, even though this increase accounted for only a small percent of the total natural variation in the data. None of the infaunal parameters (total abundance, species richness, log-series *alpha,* and Shannon's H′) were significant.

Table 5-6. Results of the model of six selected continuous variables for the infauna stations.

	Zone-by-Diversion Effect				**Log (Silt) Covariate**		**R-squared**	
	Within 5 km		**Within 2.5 km**					
	multiplier	**P-value**	**multiplier**	**P-value**	**coefficient**	**P-value**	**Complete Model**	**Diversion by Zone Submodel**
Clostridium/fine	1.229	0.009	1.408	**0.000**	0.614	**0.000**	0.831	0.041
Total Organic Carbon	1.023	0.682	1.040	0.420	0.731	**0.000**	0.895	0.001
Species Richness	1.035	0.123	0.986	0.480	-0.012	0.646	0.604	0.004
Log-Series *Alpha*	1.001	0.957	0.998	0.912	0.018	0.507	0.646	0.000
Shannon H′	0.990	0.601	0.992	0.641	-0.003	0.894	0.482	0.002
Total Abundance	1.088	0.138	0.941	0.232	-0.145	0.036	0.491	0.006

The analysis of the individual species abundance data is reported in Table 5-7. Pseudo R^2 denotes the proportion of variation in the count data explained by the model. The natural measure of total variation is the chi-squared rather than the total sum of squares. Very few species exhibited significant effects, either within 2.5 km or within 5 km of the diffuser. In the zone closest to the diffuser, the bivalve *Cerastoderma pinnulatum*, and the polychaetes *Exogone verugera* and *Monticellina dorsobranchialis* showed a significant zone-by-diversion effect. This nested effect compares stations in the 2.5 km strata with stations in the 2.5 to 5 km strata. The within-5-km effect was significant for only the polychaete *Trochochaeta multisetosa*. This effect compares stations in the greater-than-5-km strata with all stations that are less than 5 km from diffuser.

In all significance tests, the false discovery criterion outlined above was used, with a false discovery rate of α=0.05. Since 58 simultaneous tests are conducted for each effect, the p-value needed for a statistically significant effect is relatively small.

It is important to note that the statistical analyses conducted here cannot prove that outfall discharge has impacted the abundance of these taxa. All it can do is identify taxa whose patterns of abundances changed between baseline and discharge monitoring, in a manner consistent with an hypothesized outfall effect. Even in the best designed environmental impact studies this limitation on causal inference exists. This issue is discussed in detail in the reviews of Smith (2002) and Beyers (1998).

It is also important to note that none of the significant zone-by-diversion terms explained more than 2.8 percent of the variability in species abundances in these models, confirming the sensitivity of the analysis and the statistical power afforded by MWRA's monitoring design.

That significant zone-by-diversion effects were observed for only a small subset of nearfield species, and explain only a small percentage of the variability in their abundances, is consistent with the compositional and multivariant analyses presented in section 5.3.5. Those analyses document broad consistency in community composition at nearfield stations through time, with no evidence for a shift in community composition following outfall startup in September 2000.

Table 5-7. Results of the statistical analysis of species abundances at the nearfield infaunal stations.

	Zone by Diversion Effect							Pseudo R-squared	
	Within 5 km		Within 2.5 km		Log(Silt) Covariate			Proportion Chi-squared	
Species	multiplier	P-value	multiplier	P-value	coefficient	P-value	Negative Binomial Theta	Complete Model	Diversion by Zone Submodel
Aglaophamus circinata	0.982	0.2601	0.690	0.1263	-1.214	**0.0001**	0.955	0.728	0.004
Ameroculodes sp. 1	3.379	0.0264	0.455	0.0092	0.022	0.6995	0.645	0.584	0.028
Ampelisca macrocephala	1.752	0.0172	1.109	0.6750	-0.152	0.6702	0.850	0.508	0.012
Amphiporus caecus	1.043	0.4799	1.175	0.3951	0.150	0.6060	1.046	0.386	0.003
Aphelochaeta marioni	0.931	0.6213	0.909	0.6698	-0.133	0.6926	0.600	0.480	0.001
Arctica islandica	1.367	0.1208	0.960	0.8383	0.169	0.5393	0.840	0.431	0.005
Argissa hamatipes	0.900	0.7810	1.135	0.3838	0.235	0.1940	2.488	0.565	0.001
Aricidea catherinae	0.903	0.7077	1.325	0.1442	-0.467	0.0491	0.853	0.457	0.004
Asabellides oculata	1.435	0.3148	0.931	0.8369	-1.015	0.0231	0.497	0.726	0.002
Astarte undata	0.993	0.3680	0.748	0.0723	0.051	0.7000	1.271	0.612	0.005
Capitella capitata complex	0.734	0.4603	1.396	0.0844	0.078	0.8399	0.953	0.465	0.007
Cephalothricidae sp. 1	1.183	0.1878	1.387	0.1398	-0.111	0.7032	0.966	0.801	0.004
Cerastoderma pinnulatum	1.617	0.8790	0.468	**0.0002**	-0.285	0.2341	0.906	0.680	0.016
Ceriantheopsis americanus	0.973	0.9416	1.071	0.6301	0.073	0.7026	2.390	0.436	0.000
Crenella decussata	0.874	0.4175	0.958	0.8134	-1.094	**0.0001**	1.139	0.758	0.001
Dipolydora socialis	0.620	0.0269	0.791	0.3972	-0.584	0.2623	0.434	0.433	0.010
Dyopedos monacanthus	2.412	0.0540	0.611	0.1644	0.050	0.9232	0.402	0.584	0.011
Edotia montosa	0.686	0.0145	1.002	0.9895	0.080	0.5457	1.270	0.571	0.009
Edwardsia elegans	1.852	0.0182	0.760	0.1945	0.095	0.8174	1.256	0.344	0.018
Eteone longa	0.732	0.2045	1.388	0.0137	-0.329	0.0717	2.114	0.659	0.009
Euchone incolor	0.745	0.1104	1.085	0.6466	0.155	0.5405	0.950	0.536	0.004

Table 5-7 (continued).

	Zone by Diversion Effect							**Pseudo R-squared**	
	Within 5 km		**Within 2.5 km**		**Log(Silt) Covariate**			**Proportion Chi-squared**	
Species	**multiplier**	**P-value**	**multiplier**	**P-value**	**coefficient**	**P-value**	**Negative Binomial Theta**	**Complete Model**	**Diversion by Zone Submodel**
Exogone hebes	0.815	0.0601	0.885	0.4105	-0.273	0.2627	1.297	0.706	0.004
Exogone verugera	1.237	0.6076	0.567	**0.0005**	-0.452	0.0653	1.090	0.655	0.014
Galathowenia oculata	1.567	0.0009	1.282	0.1838	0.393	0.1695	1.087	0.664	0.016
Gattyana amondseni	0.892	0.2703	0.813	0.3124	0.233	0.3724	1.590	0.426	0.005
Goniada maculata	1.294	0.1921	0.954	0.8031	0.112	0.8862	2.272	0.510	0.004
Hiatella arctica	1.587	0.4321	0.588	0.0094	-0.625	0.0095	0.828	0.588	0.011
Ilyanassa trivittata	0.852	0.4539	0.965	0.9037	-0.368	0.3506	0.915	0.542	0.001
Leitoscoloplos acutus	0.870	0.5251	1.126	0.4387	0.140	0.4622	1.546	0.642	0.001
Levinsenia gracilis	0.557	0.0037	1.445	0.0159	-0.071	0.9133	1.299	0.653	0.016
Mediomastus californiensis	0.822	0.6299	1.275	0.1213	0.095	0.6897	1.104	0.463	0.004
Metopella angusta	0.830	0.0548	0.800	0.1980	-0.326	0.2242	1.259	0.511	0.009
Micrura spp	1.081	0.3501	1.048	0.6916	0.078	0.6899	2.759	0.528	0.002
Monticellina baptisteae	0.797	0.5700	1.251	0.3141	0.005	0.9864	0.654	0.454	0.002
Monticellina dorsobranchialis	0.595	0.1520	1.819	**0.0002**	0.119	0.7268	1.267	0.562	0.023
Nemertea sp. 12	1.182	0.4028	0.969	0.8591	-0.181	0.4856	1.039	0.592	0.001
Nemertea sp. 2	0.916	0.5379	0.817	0.5505	-0.149	0.8421	0.437	0.316	0.003
Nephtys cornuta	1.118	0.5940	1.054	0.2444	-0.095	0.7357	0.681	0.812	0.000
Nereis grayi	2.590	0.0012	0.534	0.0011	-0.153	0.1943	2.284	0.761	0.022
Ninoe nigripes	0.707	0.0083	0.917	0.5941	-0.406	0.1238	1.043	0.517	0.011
Nucula delphinodonta	0.741	0.1043	1.056	0.7562	-0.487	0.0701	0.999	0.569	0.004
Orchomenella minuta	1.090	0.5147	1.137	0.6860	0.764	0.0440	0.666	0.509	0.001

Table 5-7 (continued).

	Zone by Diversion Effect							**Pseudo R-squared**	
	Within 5 km		**Within 2.5 km**		**Log(Silt) Covariate**			**Proportion Chi-squared**	
Species	**multiplier**	**P-value**	**multiplier**	**P-value**	**coefficient**	**P-value**	**Negative Binomial Theta**	**Complete Model**	**Diversion by Zone Submodel**
Parougia caeca	0.827	0.3781	1.145	0.3619	-0.042	0.8223	1.365	0.460	0.003
Pholoe minuta	0.986	0.0678	0.679	0.0029	0.271	0.0565	1.847	0.546	0.019
Phoronis architecta	0.773	0.3688	1.160	0.4708	-0.618	0.0318	0.776	0.533	0.002
Photis pollex	1.077	0.2844	0.580	0.0047	-0.068	0.7214	1.121	0.675	0.011
Phyllodoce mucosa	0.898	0.0590	0.730	0.0478	-0.370	0.1272	1.171	0.536	0.011
Polygordius jouinae	1.014	0.6627	0.864	0.4174	-0.579	0.0100	1.292	0.756	0.001
Prionospio steenstrupi	1.041	0.2955	1.281	0.1602	-0.097	0.5843	0.870	0.416	0.006
Scoloplos armiger	0.901	0.5867	1.427	0.1230	-0.109	0.7419	0.963	0.418	0.007
Sphaerodoridium sp. A	0.709	0.0215	0.896	0.5524	-0.027	0.7325	2.155	0.592	0.010
Spio filicornis	1.422	0.6357	0.481	0.0052	0.185	0.8403	1.360	0.559	0.020
Spio limicola	0.537	0.0220	1.323	0.2117	-0.331	0.4440	0.606	0.505	0.011
Spiophanes bombyx	1.344	0.0178	1.121	0.4577	-0.052	0.6442	1.512	0.743	0.006
Stenopleustes inermis	0.666	0.0027	0.713	0.1235	-0.084	0.6840	1.027	0.509	0.021
Tharyx acutus	1.030	0.7511	1.064	0.7490	-0.644	0.0187	0.707	0.377	0.000
Thracia conradi	0.533	0.2247	1.959	0.0093	-0.523	0.2490	0.754	0.570	0.017
Trochochaeta multisetosa	0.368	**0.0008**	1.820	0.0134	0.077	0.8179	1.014	0.694	0.027

5.4 Monitoring Questions

- *Has the soft-bottom community changed?*

There have been clear temporal changes in the soft-bottom benthic infaunal community over the time period of the monitoring program, including changes of total infaunal density, species composition and richness, and, to a lesser extent, diversity. Infaunal abundance (per sample) had increased by 2002 by roughly 60% over abundances recorded in the early years of the program. This increase was due primarily to increased abundances of one or a few species, primarily *Prionospio steenstrupi*, which replaced another spionid polychaete, *Spio limicola*, as the dominant at the medium- to fine-grained stations. Species richness also increased, in 2004 reaching the highest mean values recorded in the nearfield area. Some benthic community parameters have appeared to fluctuate in a sine-wave-like pattern, with increases followed by declines. The apex value for abundance seen in 2002 was in fact followed by lower values in 2003–2005, and again by a further decline in 2006. Again, much of this decline was due to the population fluctuation of one species, *P. steenstrupi.* Although the subset of stations sampled in 2006 differed from those sampled in 2005, the decline in mean station parameters appears to be real when compared with the values obtained in 2004 for the same subset of stations. However, based on the statistical analyses performed on the 2006 data, none of these changes are statistically significant nor can they be related to the operation of the outfall.

The larger patterns elucidated over time for the Massachusetts Bay stations have remained stable throughout the program. In similarity tests, the farfield stations have always differed from the nearfield, *e.g.*, the Cape Cod Bay stations comprise a suite of species that gives them a unique signature. Nearfield stations FF10, FF12, and FF13 can be distinguished from the remaining nearfield stations, reflecting the transitional sediment texture at those stations (Chapter 3, this report); similarly, the nearfield sandy stations can be distinguished from nearfield fine-grained stations. These patterns have held whether the entire station set is sampled, or whether the 2004/2006 or 2005 subsets are considered.

- *Are any benthic community changes correlated with changes in levels of toxic contaminants (or sewage tracers) in sediments?*

Detailed investigation of individual stations has not suggested any localized outfall impact, even at stations within 2 km of the outfall (*e.g.*, NF17) where elevated levels of the sewage tracer *Clostridium perfringens* had suggested a modest impact of the discharge in the previous years (Chapter 3, this report).

6. 2006 HARD-BOTTOM BENTHIC HABITATS AND FAUNA

by Barbara Hecker

6.1 Status of the Nearfield Hard-Bottom Environment

Hard-bottom communities inhabiting drumlins in the vicinity of the outfall have been surveyed annually for the last 13 years. These benthic communities have been surveyed utilizing a remotely operated vehicle (ROV) to photograph the seafloor habitats and their inhabitants. The first seven years of surveys (1994 to 2000) provided a baseline database that allowed characterization of the habitats and communities on the drumlins, as well as insight into their spatial and temporal variability (Kropp *et al*. 2002 and others). During the baseline period, the sampling design changed from videotaping a series of transects near the outfall in 1994 (Coats *et al.* 1995), to surveying discrete stations (waypoints) on the drumlins immediately north and south of the outfall, and at several reference sites on drumlins further away (since 1995). The emphasis on data products also has changed from reliance mainly on videotape (1995) to more emphasis on still photographs (1996 to 2006). The video images cover a much broader area and are mainly useful for assessing habitat relief and variability and enumeration of rare, larger mobile fauna, while the still photographs offer much higher resolution for enumeration of most of the fauna.

Images collected during the baseline period indicate that the nearfield hard-bottom habitats are spatially quite variable and the benthic communities inhabiting them are temporally quite stable. The seafloor on the top of drumlins usually consists of a mix of boulders and cobbles, with habitat relief ranging from moderately high to high in areas dominated by larger boulders to moderate to low in areas consisting of a mix of cobbles and occasional boulders. Sediment drape on the top of drumlins varies from light to moderate at most locations and moderately heavy to heavy at a few locations. The seafloor on the flanks of drumlins is frequently variable, and usually consists of a cobble pavement interspersed to varying degrees with patches of sand, gravel, and boulders. Habitat relief on the flanks ranges from low to moderate, depending on how many boulders are present. Sediment drape in the flank areas usually ranges from moderate to heavy. The tops of the drumlins generally tend to be more spatially homogeneous than either the edges of the tops or the flanks of the drumlins, which tend to be more spatially heterogeneous. As a result, small lateral shifts in position near the edges of the drumlin tops or on the flanks frequently result in substantially different habitat characteristics, and hence different communities.

Algae usually dominate benthic communities on the tops of drumlins, while invertebrates (mostly encrusting or attached forms) become increasingly dominant on the flanks of the drumlins. Both encrusting coralline algae and several species of upright algae are quite common throughout the hard-bottom areas near the outfall. Coralline algae usually dominate in areas with light to moderately light sediment drape, while upright algae frequently dominate in areas with moderate sediment drape. Coralline algae is the most abundant and widely distributed taxon encountered in the hard-bottom areas. Its areal coverage and distribution remained quite stable during the entire baseline period. The percent cover of coralline algae appears to be related to the amount of sediment drape, with cover being highest in areas with light drape and lowest in areas with moderately heavy-to-heavy drape. This pattern may reflect susceptibility of the encrusting growth form of coralline algae to smothering by fine particles. In contrast, the abundance and distribution of upright algae appear to be related to habitat relief. These algae are patchily distributed and are only found in appreciable abundances in areas of moderate to high relief. Areas supporting numerous upright algae also tend to have moderate sediment drape, with the holdfasts of the algae appearing to trap sediment.

The benthic communities inhabiting the hard-bottom areas were quite stable during the baseline period, with the structure of the benthic communities remaining relatively unchanged between 1995 and 2000. Occasional year-to-year shifts in cluster designation of specific sites frequently reflected spatial habitat heterogeneity rather than temporal changes in the biotic communities. Upright algae dominated the communities inhabiting the northern reference sites, and several other sites on the top of drumlins on either side of the outfall. In contrast, coralline algae dominated the communities at the two southernmost reference sites, as well as at some drumlin top and flank sites on either side of the outfall. Another southern reference site, located southwest of the outfall, represents a relatively extreme habitat characterized by very large boulders with heavy sediment drape. This area supports few algae, but is inhabited by numerous invertebrates, including a red soft coral *Gersemia rubiformis* which is not found at any of the other sites. Several sites on the flanks of the drumlin located just south of the outfall are relatively depauperate when compared to the other sites. The diffuser heads of the outfall have been colonized by a luxuriant community of frilled sea anemones, *Metridium senile*, sea-peach tunicates, *Halocynthia pyriformis*, and northern sea stars, *Asterias vulgaris*.

The nearfield hard-bottom communities observed during the first five post-discharge surveys were remarkably similar to those observed during the baseline period (Maciolek *et al*. 2004, 2005, 2006a, b). Several modest differences between the pre- and post discharge periods have been noted. The most consistent difference has been a slight increase in sediment drape and a concurrent decrease in percent cover of coralline algae at five stations north of the outfall during the post discharge years. The decrease in percent cover of coralline algae was most pronounced in 2005 and was also observed at an additional six stations. The decreases in coralline algae observed in 2005 were not accompanied by concurrent increases in sediment drape. A trend of decreased abundances of upright algae was also noted during the post-discharge years, and was particularly pronounced in 2003.

The data discussed in this chapter were collected during the sixth post-discharge survey of the hard-bottom communities conducted during late June 2006. This chapter presents the results of the 2006 survey and compares these results to pre-discharge baseline conditions and to the previous post-discharge conditions. All of the waypoints, including an actively discharging diffuser head at the eastern end of the outfall, were successfully surveyed during 2006.

6.2 Methods

An Outland Technology “Outland 1000” remotely operated vehicle (ROV) equipped with video and still cameras was deployed at each station. The ROV was operated at slow speeds close to the seafloor to optimize visual clarity of the images. Video images were collected to provide broad large-scale coverage, while stills photographs (slides) were collected to provide high-resolution images used for semi-quantitative assessment of habitat characteristics and biota.

Both video footage and still photographs were obtained at each of 23 waypoints (Table 6-1, see Figure 2-3). Photographic coverage ranged from 18 to 22 minutes of video footage and 27 to 33 still photographs (35-mm slides) at each waypoint. A total of 7,264 still photographs was taken and used in the following data analysis.

Table 6-1. Photographic coverage at locations surveyed during the 2006 nearfield hard-bottom survey.

Station	Location on drumlin	Depth (m)	Video (min)	Stills (# frames)
T1-1	Flank	28	18	29
T1-2	Top	26	18	30
T1-3	Top	24	19	31
T1-4	Top	25	21	33
T1-5	Flank	29	20	31
T2-1	Flank	28	20	32
T2-2	Flank	33	20	33
T2-3	Flank	28	20	32
T2-4	Flank	31	20	33
T4-2	Flank	27	18	32
T4/6-1	Top	24	22	33
T6-1	Flank	34	20	31
T6-2	Flank	32	20	32
Northern reference				
T7-1	Top	24	18	33
T7-2	Top	24	19	31
T9-1	Top	25	23	32
Southern reference				
T8-1	Top	24	21	32
T8-2	Top	23	20	33
T10-1	Top	24	20	33
T12-1	Top	27	21	27
Farfield reference				
T11-1		35	21	31
Diffusers				
T2-5	Diffuser #2	32	21	29
Diffuser	#44	33	21	31

6.2.1 Visual Analysis

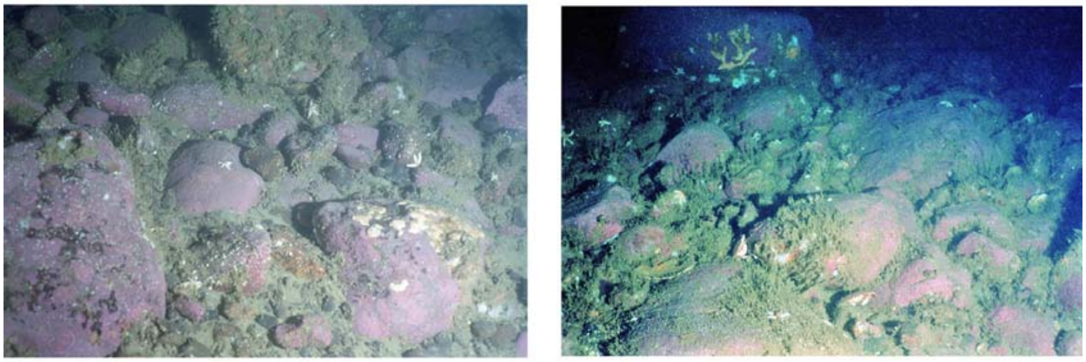
Each 35-mm slide was projected and analyzed for sea-floor characteristics (*i.e.*, substratum type and size class, and amount of sediment drape) and biota. Sediment drape refers to the visible layer of detrital material that drapes many of the rock surfaces in the hard-bottom areas. This material likely consists of a combination of phytodetritus, zooplankton fecal material, fine-grained resuspended sediments, biogenic tubes, and possibly effluent particles. The amount of sediment draped on the rock surfaces was assessed as relative thickness and amount of surface area covered, ranging from clean when the entire rock surface was visible to heavy when none of the rock surface was visible. Examples of several of the sediment drape categories can be seen in Figure 6-1. To facilitate comparisons among stations and years, mean sediment drape values were calculated using the following numerical assignments:

Sediment Drape Category	Numerical value
clean to very light	0
light	1
moderately light	2
moderate	3
moderately heavy	4
heavy	5

Most recognizable taxa were counted and recorded. Several very abundant taxa (for which accurate counts were impossible to obtain) were assessed as percent cover or relative abundance. The abundance of encrusting coralline algae was assessed as rough estimates of percent cover. Several other taxa, a filamentous red alga (identified at *Ptilota serrata*), colonial hydroids, and small barnacles and/or spirorbid polychaetes that were frequently too abundant to count reliably were assessed in terms of relative abundance. The following categories were used to assess abundances of taxa that were not counted on the still photographs:

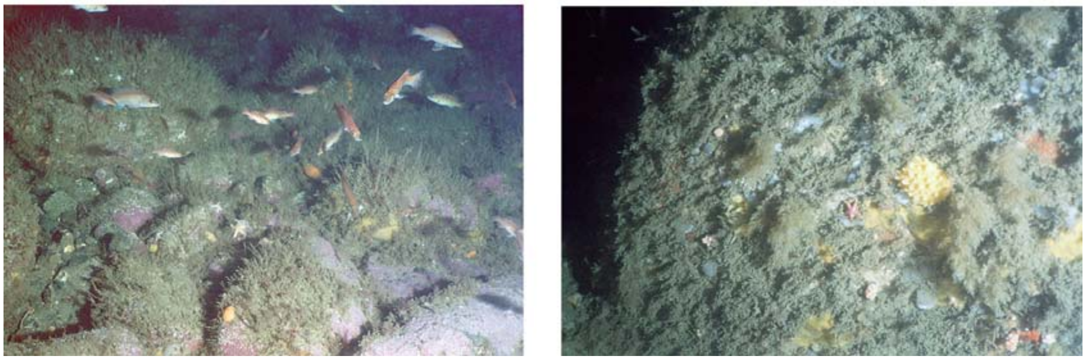
Category	Percent cover	Numerical value assigned for analysis
rare	1-5	1
few	6-10	2
common	11-30	5
	31-50	10
abundant	51-70	15
	71-90	20
	>90	25

Organisms were identified to the lowest practical taxonomic level, about half of them to species, with the aid of pictorial keys of the local flora and fauna (Martinez and Harlow 1994, Weiss 1995) and web searches. Many of the encrusting taxa have not been identified to species. Most of these have been assigned to descriptive categories (*e.g.*, "orange-tan encrusting"); however, each of these descriptive categories possibly includes several species. Additionally, some species might be split between two similar descriptive categories (*e.g.*, "orange encrusting" and "orange lumpy encrusting"), as a result of morphological variability or differences in viewing angles and lighting. Because of high relief in many of the habitats surveyed, all reported abundances are extremely conservative. In many areas, only a portion of available surface area is visible; thus, actual faunal abundances in these areas are undoubtedly much higher than the counts indicate. A summary of the 2006 slide analysis is included in Appendix D1.



light drape (T8-2)

moderately-light drape (T4/6-1)



moderate drape (T7-1)

heavy drape (T10-1)

Figure 6-1. Photographs representative of sediment drape categories. Light drape is the presence of a dusting or small patches of sediment leaving the rock surfaces clearly visible. Moderately light drape is the presence of larger patches of sediment, yet still leaving most of the rock surfaces visible. Moderate drape is the presence of drape on much of the rock surfaces with only small patches showing through. Heavy drape is the entire rock surface covered by a substantial amount of drape.

Changes in taxonomic designations that have occurred during the years of this survey are summarized in Maciolek *et al.* 2006b. Briefly, the category "coralline algae" represent a taxon composed of at least five species of pink crustose algae that can not be differentiated from each other in photographs. Additionally, the red filamentous alga previously designated as *Asparagopsis hamifera*, was subsequently identified as *Ptilota serrata*. Hydroids on or near the diffuser heads previously referred to as *Campanularia* sp. are *Tubularia* sp. A sponge previously referred to as *Halichondria panecia* (crumb of bread sponge), is a species of papillate sponge that belongs to the genus *Polymastia*. This species, *Polymastia* sp. A, is a circular yellow sponge on hard substrate. Another *Polymastia* sponge, *Polymastia* sp. B, is an irregular whitish sponge whose basal cushion is partially buried in sediment. This sponge was previously referred to as a siphon sponge.

The videotapes were viewed to provide additional information about uniformity of the habitat at each of the sites. Notes on habitat relief, substrate size classes, and relative amount of sediment drape were recorded. Rare, large, and clearly identifiable organisms were enumerated. With the exception of the cunner *Tautogolabrus adspersus* (which was frequently very abundant), all fish were enumerated. Counts of abundant motile organisms (namely cunner), cryptic organisms (such as mussels), and all encrusting organisms were not attempted because of the large amount of time accurate counts would require and the general lack of resolution of the video footage. These organisms were assessed in terms of the range of relative abundances mentioned above. A summary of the 2006 video analysis is included in Appendix D2.

6.2.1 Data analysis

Data for all slides taken at each waypoint were pooled. Comparisons among waypoints were facilitated by normalizing species counts to mean number of individuals per slide to account for differences in the number of slides collected at each site. Hydroids, small barnacles, and/or spirorbids were omitted from the data analysis because they consisted of several species, could not be accurately assessed, and it was impossible to tell if they were alive. General taxonomic categories (*i.e.*, fish, sponge, etc.) were included in estimates of total faunal abundances, but were omitted from the community analysis. For community analysis of the 2006 data, only taxa with an abundance of ten or more individuals in the data set were retained. This resulted in 47 of the original 79 taxa being retained for community analysis. Community analysis of the entire data set (years 1996 to 2006) used only taxa that were present with an absolute abundance of at least 50 individuals. Additionally, some taxa were excluded if they had not been consistently identified over the years. This resulted in 52 of the original 118 taxa being used for community analysis of the entire data set.

Community analyses were run using the software package PRIMER v.5 (Clarke and Gorley 2001). Two complementary multivariate pattern recognition techniques, hierarchical classification and non-metric multidimensional scaling (NMDS), were used to examine species similarities among stations obtained from data collected from the still photographs. Both analyses started with pair-wise comparisons of the species composition of stations using the Bray-Curtis similarity coefficient. Prior to analysis the data were square-root transformed to lessen the impact of numerically dominant species. This coefficient was chosen because it relies on the relative proportion that each species contributes to the faunal composition, and as a result is less sensitive to differences in sampling effort among locations than other coefficients. For hierarchical classification, the pairwise station similarities were used to form groupings of stations (clusters) with similar species composition. With this technique, stations with similar species composition cluster closely together, while those with dissimilar species composition cluster further apart. Group-average linkage was used as the clustering algorithm, as this strategy has the advantage of being relatively conservative in clustering intensity, while avoiding excessive chaining. However, the clustering attempts to group stations into discrete clusters and does not adequately depict the finer inter-relationships among stations. NMDS was utilized to further examine inter-relationships among the stations and years. This technique “maps” samples by the rank order of their species dissimilarities, and plots species with similar species composition close together and dissimilar species composition further apart.

Habitat relief was determined only from the video images. A general habitat relief category was assigned for each station following a review of the video images collected at that station. This category was based on a subjective assessment of overall relief of the habitats encountered at that station. Low-relief areas usually consisted of a pavement of cobbles and gravel with few if any smaller boulders. Moderately low-relief areas usually consisted of cobbles with occasional patches of smaller boulders. Moderate-relief areas usually consisted of an equal mix of cobbles and boulders. Moderately high-relief areas consisted of numerous medium to large boulders interrupted by smaller areas of cobbles. High-relief areas usually consisted almost entirely of large boulders with cobbles nestled at their bases. Mean habitat relief was determined by assigning the following values for each relief category, low=1, moderately low=2, moderate=3, moderately high=4, and high=5, and averaging these values over the years.

6.3 Results and Discussion

Habitat characterizations and dominant taxa that were determined separately from video images and still photographs were similar, indicating that the still photographs were representative of the areas surveyed. Differences between the two types of coverage were mainly related to a higher occurrence of some sparsely distributed larger taxa observed in the greater geographic coverage afforded by the videotapes, and the higher occurrence of encrusting and/or smaller taxa afforded by the superior resolution of the still photographs. Additionally, larger mobile organisms that actively avoid the ROV, like the cod *Gadus morhua*, were less likely to be seen in the still photographs.

6.3.1 Distribution of Habitat Types

The seafloor on the tops of the drumlins consisted of a mix of glacial erratics in the boulder and cobble size categories. The seafloor on the drumlin immediately north of the outfall consisted mainly of areas of moderate to moderately high relief characterized by numerous boulders interspersed with cobbles. One area of moderately low relief characterized by cobbles with occasional boulders, and some gravel was encountered on the flank of the drumlin (T1-5). The seafloor on the top of the drumlin located south of the outfall (T4/6-1) had a moderate relief mix of boulders and cobbles. The three flank areas on the southern drumlin consisted of one low relief area of mostly cobbles and gravel (T6-1), and two areas of mixed substrates resulting in moderately low to moderate relief (T6-2 and T4-2, respectively). The seafloor at the three northern reference sites (T7-1, T7-2, and T9-1) consisted primarily of boulders interspersed with cobbles and ranged from moderate to moderately high relief. The seafloor at the southern reference sites ranged from moderately low to high relief. One southern reference site consisted mainly of cobbles with occasional boulders (T8-1) resulting in moderately low relief, while two of the other southern reference sites (T8-2 and T12-1) had more boulders resulting in moderate relief. The remaining southern reference site (T10-1) consisted mainly of large boulders, which resulted in a high relief habitat. The seafloor at the new reference site near Scituate (T11-1) consisted of a cobble pavement overlain with a few large boulders, which resulted in a moderately low relief habitat.

The tops of drumlins had varying amounts of sediment drape, ranging from a light to moderately light drape at T8-2 and T1-4 to a moderately heavy drape at T10-1. Drape at most of the drumlin top areas ranged from moderately light to moderate. In contrast, drape at drumlin flank areas frequently ranged from moderate to moderately heavy. One of the four southern reference sites had moderately light drape (T8-2), two had moderately light to moderate drape (T8-2 and T12-1), while the remaining one had moderately heavy drape (T10-1). In contrast, two of the three northern reference sites had moderate to moderately heavy drape (T7-1 and T7-2), while the remaining site (T9-1) had slightly less drape. Sediment drape was moderate to moderately heavy at most of the flank sites.

Habitat relief and sediment drape frequently were quite variable within many of the sites surveyed. Most moderate to high relief areas also contained numerous small patches of lower relief cobbles and gravel, and some of the low relief areas contained occasional islands of higher relief boulders. Additionally, in areas of moderate to heavy sediment drape, occasional bare rock surfaces neighbored heavily draped ones.

Two diffuser heads were also visited during the 2006 survey, one that was actively discharging effluent (T2-5, Diffuser #2) and one that had not been activated (Diffuser #44). The seafloor in the vicinity of both diffusers consisted of angular rocks in the small boulder size category. This resulted in a high relief island (the diffuser head) surrounded by a moderate relief field of boulders. Sediment drape was moderate at the active diffuser head (T2-5) and moderately heavy at the inactive diffuser head (D#44).

An interesting observation was made this year at T7-2 one of the northern reference stations. A large physically disturbed area was encountered toward the end of the dive at this station (Figure 6-2). Large boulders had been turned over, as evidenced by coralline algae being on the bottom rather than top surfaces, and an extensive area of mussel shell lag was observed. The disturbed area appeared to be caused by some type of mechanical disturbance to the seafloor. The most likely cause of the disturbance would be from the anchoring activity of LNG (Liquefied Natural Gas) tankers. Since 9/11/2001, the year following the diffuser going online, LNG tankers have frequently been seen anchoring in the vicinity of the northern reference stations. During several of the surveys, the field team could not occupy T7-1 or T7-2 until after a tanker vacated the area. Increased anchoring activity at the northern reference locations may be compromising the usefulness of these stations as unaffected reference sites.

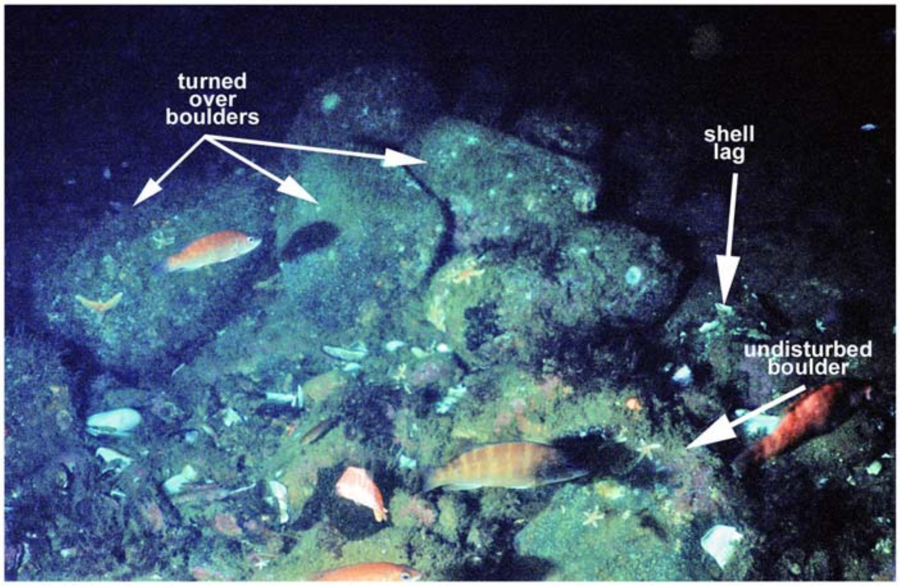


Figure 6-2. Photograph of physical disturbance at northern reference station T7-2 possibly caused by the anchoring of LNG tankers. Boulders with coralline algae on their lower surfaces had been turned over and areas of extensive shell lag were exposed.

6.3.2 Distribution and Abundance of Epibenthic Biota

Eighty taxa were seen during the visual analyses of the 2006 nearfield hard-bottom survey still photographs and videotapes (Table 6-2). All 80 taxa were seen on the still photographs and 52 were seen on the video footage. Taxonomic counts or estimates of abundances from the still photographs included 5,401 algae, 28,302 invertebrates, and 1,625 fish (Table 6-3). Coralline algae was the most abundant algal taxon observed during the survey, with an estimated abundance of 3,364 individuals. Two other algae commonly seen were dulse (*Palmaria palmata*) and a red filamentous alga, *Ptilota serrata*, with abundances of 1,548 and 451 individuals, respectively. The least abundant alga encountered was the shotgun kelp, *Agarum cribosum* (38 individuals).

The five most abundant invertebrates observed on the slides were the frilled anemone *Metridium senile* (3,644 individuals), the northern sea star *Asterias vulgaris* (2,915 juveniles and 2,645 adults), the northern white-crust tunicate *Didemnum albidum* (2,533 individuals), and the brachiopod *Terebratulina septentrionalis* (2,307 individuals). Other abundant invertebrates observed on the still photographs were an unidentified orange/tan sponge (1,824 individuals), unidentified encrusting bryozoans (1,677 individuals), an unidentified orange sponge (1,486 individuals), the blood sea star *Henricia sanguinolenta* (1,298 individuals), the horse mussel *Modiolus modiolus* (1,279 individuals), and a white sponge encrusting brachiopod shells (1,039 individuals). Additionally, the drumlin habitats were also inhabited by numerous other sponges and encrusting organisms. The most abundant fish observed in the still photographs was the cunner *Tautogolabrus adspersus* (1,593 individuals). Other fish observed were sculpin *Myoxocephalus* spp. (9 individuals), cod *Gadus morhua* (7 individuals), rock gunnel *Pholis gunnellus* (4 individuals), winter flounder (4 individuals), dogfish (2 individuals), ocean pout *Macrozoarces americanus* (1 individual), and the sea raven *Hemitripterus americanus* (1 individual).

Coralline algae was one of the most widely distributed taxa encountered during the survey. This encrusting alga was seen at 21 of the 23 waypoints, being absent from the two diffuser sites. Mean areal coverage of coralline algae ranged from 53.6% cover at T4/6-1 to 0.1% cover at T10-1. Figure 6-3 shows the relationships between depth, sediment drape, percent cover of coralline algae, and topography. The strongest relationship was observed between percent cover of coralline algae and degree of sediment drape. Corallines were most abundant in areas that had moderately light sediment drape on the rock surfaces and least abundant in areas that had moderately heavy sediment cover. Amount of sediment drape did not show a strong relationship with either depth or topography. Additionally, percent cover of coralline algae was variable and showed a weak general trend of higher cover at shallower depths. In contrast to the wide distribution of coralline algae, the two most abundant upright algae, *Palmaria palmata* and *Ptilota serrata* had much more restricted distributions, with *P. palmata* being common at only eight of the sites (one of the northern reference sites (T7-1), five sites on a drumlin immediately north of the outfall (T1-1, T1-2, T1-3, T1-4, and T2-3), and two of the southern reference sites (T8-1 and T12-1)) and *P. serrata* being common at only the two northernmost reference sites (T7-1 and T7-2). These upright algae were common in areas characterized by moderate to moderately high relief and moderate to heavy sediment drape. The reduced percent cover of coralline algae in areas supporting high abundances of upright algae may be related to fine particles being trapped by the holdfasts of the upright algae and blanketing the rock surfaces. In areas with heterogeneous substrate characteristics, *P. serrata* and *P. palmata* frequently dominated on the tops of boulders, whereas corallines dominated on the cobbles and smaller boulders in between.

Several of the commonly seen invertebrates also had wide distributional patterns. Juvenile and adult northern sea stars *Asterias vulgaris* were found at all of the sites. The blood sea star *Henricia sanguinolenta* was also observed at all of the sites. This species was most abundant on larger boulders.

Table 6-2. Taxa observed during the 2006 nearfield hard-bottom survey.

	Name	Common Name
	Algae	
	Coralline algae	pink encrusting algae
	Ptilota serrata	filamentous red algae
	Palmaria palmata	dulse
	Agarum cribosum	shotgun kelp
	Invertebrates	
	Sponges	
	general sponge	
*	*Aplysilla sulphurea*	sponge (yellow encrust)
	Haliclona oculata	finger sponge
	Haliclona spp. (encrusting)	sponge
	Melonanchora elliptica	warty sponge
	Polymastia sp. A	encrusting yellow sponge
	Polymastia sp. B	siphon sponge
*	*Phakellia* spp.	chalice sponge
	Suberites spp.	fig sponge (globular)
	white divided	sponge on brachiopod
*	orange/tan encrusting	sponge
*	orange encrusting	sponge
*	gold encrusting	sponge
*	tan encrusting	sponge
*	pink fuzzy encrusting	sponge
*	white translucent	sponge
*	cream encrusting	sponge
	thick cream with projections	sponge
	yellowish-cream encrusting	sponge
*	general encrusting	
*	globular translucent encrusting	
	Cnidarians	
	general hydroid	
	Obelia geniculata	hydroid
	Tubularia sp.	hydroid
	general anemone	
	Metridium senile	frilly anemone
	Urticina felina	northern red anemone
	Cerianthus borealis	northern cerianthid
	Gersemia rubiformis	red soft coral
	Alcyonium digitatum	dead man's fingers
*	*Astrangia danae*	northern stony coral
	Mollusks	
*	*Tonicella marmorea*	mottled red chiton
*	*Crepidula plana*	flat slipper limpet
	Buccinum undatum	waved whelk
*	*Neptunea decemcostata*	ten-ridged whelk
*	general nudibranch	
	Modiolus modiolus	horse mussel
	Placopecten magellanicus	sea scallop
	Arctica islandica	ocean quahog
	Crustaceans	
*	*Balanus* spp.	acorn barnacle
	Cancer spp.	Jonah or rock crab
	Homarus americanus	lobster
	hermit crab	
	Echinoderms	
	Strongylocentrotus droebachiensis	green sea urchin
*	general starfish	
	small white starfish	juvenile *Asterias*
	Asterias vulgaris	northern sea star
	Crossaster papposus	spiny sunstar
	Henricia sanguinolenta	blood star
	Pteraster militaria	winged sea star
	Solaster endeca	smooth sunstar
	Psolus fabricii	scarlet holothurian
	Tunicates	
*	general tunicate	
	Aplidium spp.	sea pork tunicate
*	*Boltenia echinata*	cactus tunicate
	Boltenia ovifera	stalked tunicate
	Botrylloides violaceus	Pacific tunicate
*	*Dendrodoa carnea*	drop of blood tunicate
*	*Didemnum albidum*	northern white crust tunicate
	Halocynthia pyriformis	sea peach tunicate
	Bryozoans	
*	general bryozoan	
*	?*Crisia* spp.	bryozoan
*	red crust bryozoan	bryozoan
	Miscellaneous	
	Myxicola infundibulum	slime worm
	spirorbids	
*	sabellid	
	Terebratulina septentrionalis	northern lamp shell
	Fish	
	general fish	
	Dogfish	
	Gadus morhua	cod
	Hemitripterus americanus	sea raven
	Macrozoarces americanus	ocean pout
	Myoxocephalus spp.	sculpin
*	*Pholis gunnellus*	rock gunnel
	Pseudopleuronectes americanus	winter flounder
	Tautogolabrus adspersus	cunner

* Seen only on still photographs

Table 6-3. Taxa seen in still photographs taken during the 2006 nearfield hard-bottom survey, arranged in order of abundance.

Taxon	Count
Algae	
Coralline algae	3364*
Palmaria palmata	1548
Ptilota serrata	451*
Agarum cribosum	38
Total algae	**5401**
Invertebrates	
Metridium senile	3644
small white starfish	2915
Asterias vulgaris	2645
Didemnum albidum	2533
Terebratulina septentrionalis	2307
orange/tan encrusting sponge	1824
general bryozoan	1677
orange encrusting sponge	1486
Henricia sanguinolenta	1298
Modiolus modiolus	1279
white-divided sponge	1039
Halocynthia pyriformis	659
pink fuzzy encrusting sponge	508
general encrusting organism	389
Dendrodoa carnea	368
Polymastia sp. A	359
white translucent sponge	323
Myxicola infundibulum	282
Aplidium spp.	271
?*Crisia* spp.	236
Aplysilla sulphurea	224
globular translucent organism	218
general sponge	209
Gersemia rubiformis	203
Psolus fabricii	195
red crust bryozoan	193
Strongylocentrotus droebachiensis	145
Suberites spp.	126
cream encrusting sponge	118
Alcyonium digitatum	112
gold encrusting sponge	110
yellowish-cream encrusting sponge	102
Tubularia sp.	89
Botrylloides violaceus	83
Cancer spp.	61
Arctica islandica	39
thick creamy sponge (projections)	33
Crepidula plana	33
general anemone	30
Obelia geniculata	25
Urticina felina	23
Haliclona oculata	19
Homarus americanus	19
Boltenia echinata	18
Melonanchora elliptica	16
Balanus spp.	12
general tunicate	10
Haliclona spp. (encrusting)	7
Phakellia spp.	6
general nudibranch	5
Astrangia danae	4
Polymastia sp. B	4
Pteraster militaria	4
Tonicella marmorea	3
Placopecten magellanicus	3
Crossaster papposus	3
Buccinum undatum	2
Boltenia ovifera	2
sabellid	2
tan encrusting sponge	1
Cerianthus borealis	1
Neptunea decemcostata	1
hermit crab	1
general starfish	1
Solaster endeca	1
hydroid	**
spirorbids/barnacles	**
Total invertebrates	**28302**
Fish	
Tautogolabrus adspersus	1593
Myoxocephalus spp.	9
Gadus morhua	7
general fish	4
Pseudopleuronectes americanus	4
Pholis gunnellus	4
Dogfish	2
Macrozoarces americanus	1
Hemitripterus americanus	1
Total fish	**1625**

* Estimated ** Not counted

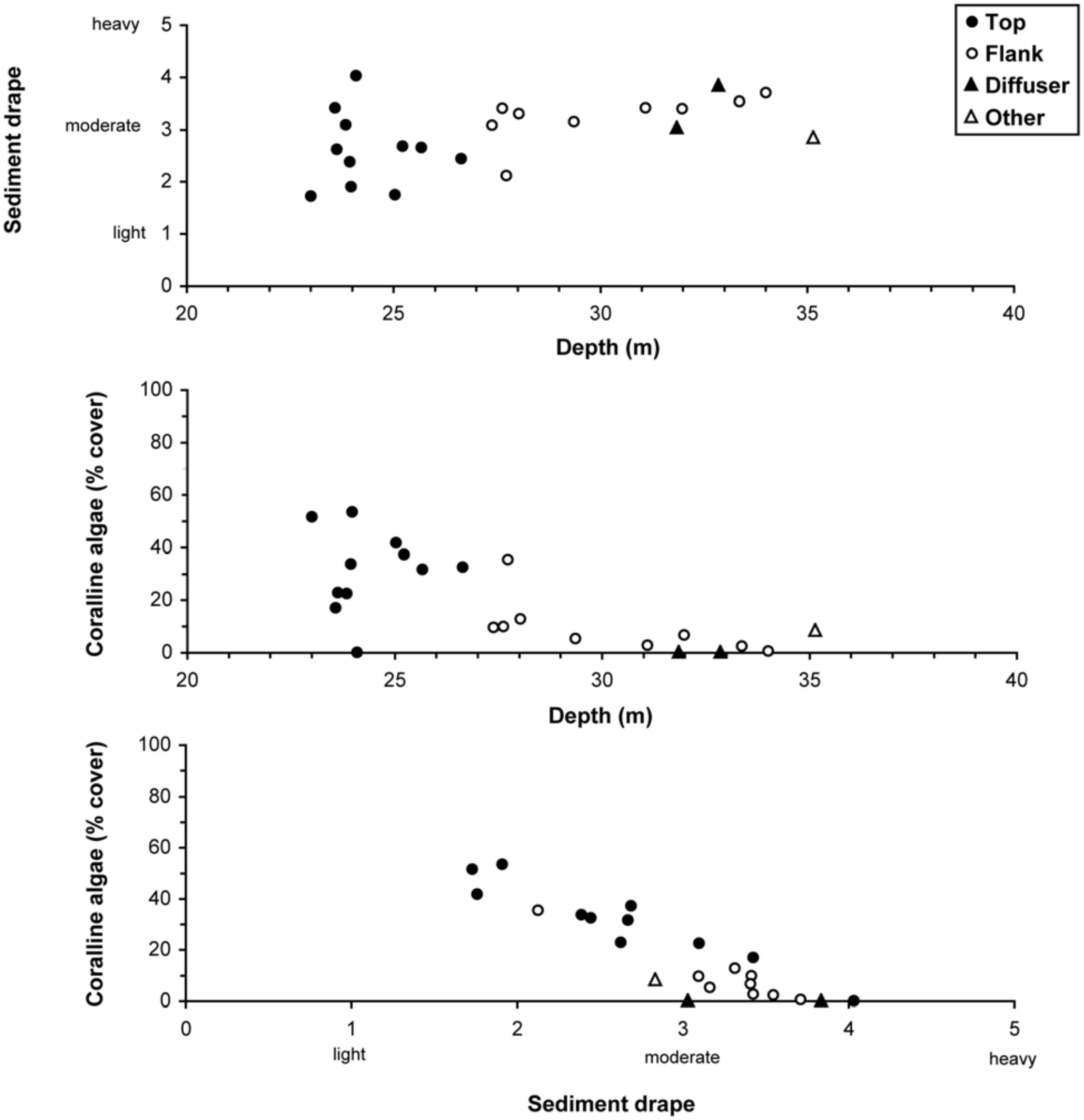


Figure 6-3. Depth, sediment drape, and percent cover of coralline algae of the sites from the 2006 nearfield hard-bottom survey.

The northern white crust tunicate *Didemnum albidum* was also widely distributed, being found at all 23 sites and abundant at 11 of them. This encrusting species was most abundant in areas with larger boulders and light to moderate sediment drape. The horse mussel *Modiolus modiolus* was also very widely distributed, being found at all sites but the inactive diffuser. This mussel was most abundant on the top of drumlins, where large numbers were observed nestled among cobbles and at the bases of boulders. Because of the mussel's cryptic nature of being nestled in among rocks, being encrusted by organisms and being draped with sediment or partially buried, the observed abundances are very conservative. The number of mussels would be underestimated even more in areas of high relief, because the bases of larger boulders were rarely visible in the images. Seventy-six individuals of this mussel were observed near one of the ports of the head of Diffuser #2. This mussel clump was first observed in 2004. This clump has grown during the last two years, but the mussels do not appear to be obstructing the discharge stream. The sea peach tunicate *Halocynthia pyriformis* was found at 18 sites but was only found in high abundances on the head of the inactive diffuser (Diffuser #44). With the exception of the diffuser heads, this species was usually only seen on the sides of larger boulders.

Three additional species were also primarily restricted to large boulders. The brachiopod *Terebratulina septentrionalis* was found at 13 of the sites, but was only seen in high abundances at six of them (T2-4, T4-2, T9-1, T10-1, T11-1, and T12-1). This species was largely restricted to the sides of large boulders, where it is partially protected from sediment loading, which could clog the brachiopod's filtering apparatus. The frilled anemone *Metridium senile* was another species that was markedly more abundant on large boulders. This anemone was found at ten sites, but was common to abundant at only four of them. *Metridium senile* was quite abundant at most of the diffuser heads, and exceptionally abundant on the head of the active diffuser (Diffuser #2) where it almost completely covered the surface. Additionally, it occluded the closed ports on the diffuser head and extended down onto the riprap at its base. This anemone was much less abundant on the head of the inactive diffuser. In two other hard-bottom areas, this anemone was observed on the larger boulders found at sites T1-2 and T2-3, where it was usually seen on the tops and upper sides of large boulders. One species with a very restricted distribution was the red soft coral *Gersemia rubiformis*, which was seen at only one of the sites, where it inhabited the tops of large boulders found at T10-1.

Encrusting invertebrate taxa generally were most abundant in moderate to high relief areas that had light to moderate sediment drape on the rock surfaces. This is not surprising because most juveniles of attached taxa require sediment-free surfaces for settlement. Additionally, clean rock surfaces are indicative of strong currents that could provide adequate food supplies for suspension-feeding organisms. Boulders and large cobbles also provide a physically more stable environment than smaller cobbles as they are more resistant to mechanical disturbance.

The green sea urchin *Strongylocentrotus droebachiensis* was relatively widely distributed, being found at 16 sites. This urchin was common only in regions that had a moderately high percent cover of coralline algae (T1-2, T1-3, T2-1, T4/6-1, T8-2, and T9-1), on which it grazes (Sebens 1986). The red holothurian *Psolus fabricii* also was widely distributed. This holothurian was found at 17 sites, but was abundant at only six of them (T1-2, T1-4, T4-2, T4/6-1, T8-2, and T12-1). Reasons for its high abundance in some areas, and not in others, were not readily apparent.

This year (2006) was the first time that many dead-man's finger coral *Alcyonium digitatum* were observed. A total of 112 individuals of *A. digitatum* was seen at nine of the stations, whereas only 43 individuals were observed in all previous years combined. This coral was usually attached to the upper surface of medium to large boulders.

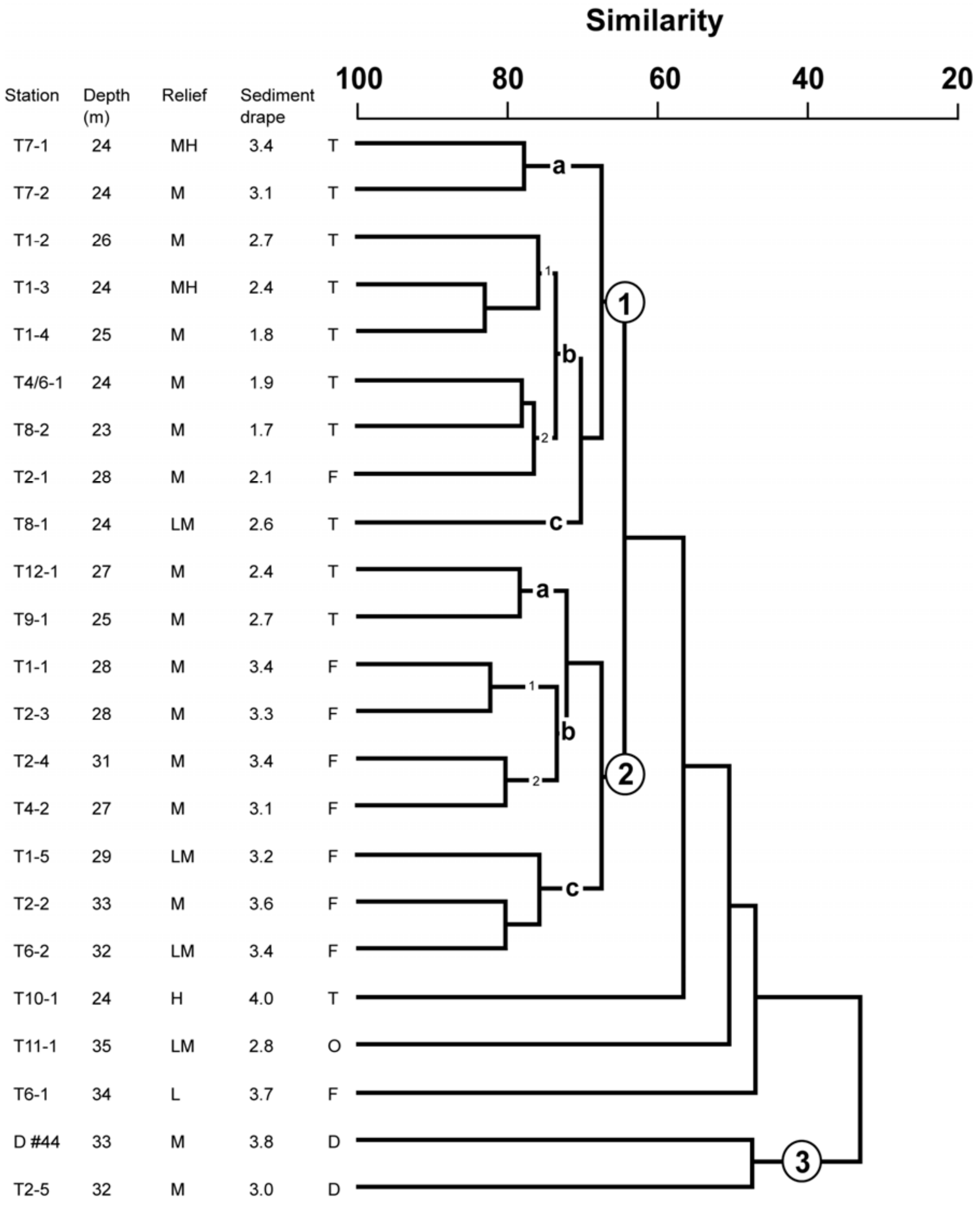
Four invertebrate taxa were newly recognized this year. Two of these taxa were sponges that were unique to the far southern reference station T11-1. These were two unidentified sponges that were commonly observed encrusting some of the smaller boulders at that station. One was a thick cream-colored encrusting sponge with numerous asymmetric projections. The other was a thinner yellowish-cream colored encrusting sponge that tended to sheet over the rock surfaces and had no projections. These species were seen at T11-1 before and coded as general sponges. Another taxon that was newly recognized this year was a clear attached globular organism with opaque matter at its center. This unidentified organism was seen in the past and was coded as translucent sponge or general unknown organism. The fourth newly recognized species was the northern stony coral *Astrangia danae*. This species has not been seen in the past and appears to be new to the area. It is usually restricted to waters south of Cape Cod and its presence in the area may represent a northward range extension.

One taxon that was “newly” designated last year, the invasive tunicate *Botrylloides violaceus*, was found at 13 sites and was common at only two of them (T2-4 and T11-1). Eighty colonies were identified as *B. violaceus* this year, compared to 146 colonies observed last year. Another taxon “newly” encountered in 2005, a large unidentified holothurian found only at T11-1, was not observed this year. Several of the large pale yellowish encrusting sponges first observed on large boulders at T4/6-1 in 2005 were also seen in 2006. These colonies frequently had upright projections that appeared to be instances where the sponge may have overgrown other organisms. These colonies were assigned to the general sponge category. Two species that were first observed in 2004 on rocks that had previously been heavily colonized by barnacles, a frilly white encrusting sponge? (possibly a nudibranch egg case) and a dark grey translucent material (tentatively identified as *Diplosoma listerianum*), were not seen in 2006.

The fish fauna was dominated by the cunner *Tautogolabrus adspersus*, which was observed all 23 waypoints. This fish was most abundant in moderate to high relief areas, where it tended to congregate among large boulders (T1-2, T4/6-1, T7-1, and T10-1). In areas of heterogeneous or low relief, *T. adspersus* was usually seen only in the immediate vicinity of boulders. Seven other fish species, cod (*Gadus morhua*), rock gunnel (*Pholis gunnellus*), winter flounder (*Pseudopleuronectes americanus*), sculpin (*Myoxocephalus* spp.), ocean pout (*Macrozoarces americanus*), sea raven (*Hemitripterus americanus*), and dogfish, also were seen on the still photographs. The sculpin and flounder were usually seen in flat low-relief areas, while cod and ocean pout were only seen around boulders. Two dogfish were seen at T12-1. This coincided with the presence of gill nets in the vicinity of T12-1, which may explain the unusual sighting since dogfish are usually only observed when “bait” has attracted them.

6.3.3 Community Structure

Classification analysis of the 23 waypoints and 47 taxa defined one large grouping of stations loosely joined to a small group of the two diffuser stations (Figure 6-4). The large grouping of stations further subdivided into two more cohesive clusters of stations and three solitary stations. The clustering structure reflected a combination of topography, habitat characteristics, and geographic proximity. The first cluster consisted mainly of drumlin top stations, while the second cluster consisted mainly of drumlin flank stations. Neighboring waypoints with similar habitat characteristics tended to cluster together (T7-1 and T7-2; T1-2, T1-3, and T1-4). Non-metric multidimensional scaling of the same data set is presented on Figure 6-5. The two stations that consisted of diffuser heads and the surrounding riprap (T2-5 and Diffuser #44) were omitted from the NMDS because their benthic communities differed substantially from the remaining stations, and hence skewed the ordination space. Within this constraint, the NMDS results generally reflected the groupings defined by the clustering, with sites within a cluster being closer together than sites from other clusters. However, the one flank station (T2-1) in cluster 1 was closer in NMDS space to the flank stations in cluster 2, than to the drumlin top stations in cluster 1. Habitat characteristics and the range of abundance of dominant taxa for each of the cluster groups are presented in (Table 6-4). Biotic differences among the hard-bottom stations generally reflected shifts in the relative proportion of only a few dominant taxa.



Station	Depth (m)	Relief	Sediment drape	
T7-1	24	MH	3.4	T
T7-2	24	M	3.1	T
T1-2	26	M	2.7	T
T1-3	24	MH	2.4	T
T1-4	25	M	1.8	T
T4/6-1	24	M	1.9	T
T8-2	23	M	1.7	T
T2-1	28	M	2.1	F
T8-1	24	LM	2.6	T
T12-1	27	M	2.4	T
T9-1	25	M	2.7	T
T1-1	28	M	3.4	F
T2-3	28	M	3.3	F
T2-4	31	M	3.4	F
T4-2	27	M	3.1	F
T1-5	29	LM	3.2	F
T2-2	33	M	3.6	F
T6-2	32	LM	3.4	F
T10-1	24	H	4.0	T
T11-1	35	LM	2.8	O
T6-1	34	L	3.7	F
D #44	33	M	3.8	D
T2-5	32	M	3.0	D

Figure 6-4. Cluster analysis of data collected from still photographs taken during the 2006 nearfield hard-bottom survey. T= drumlin top, F = drumlin flank, D = diffuser head, and O = other.

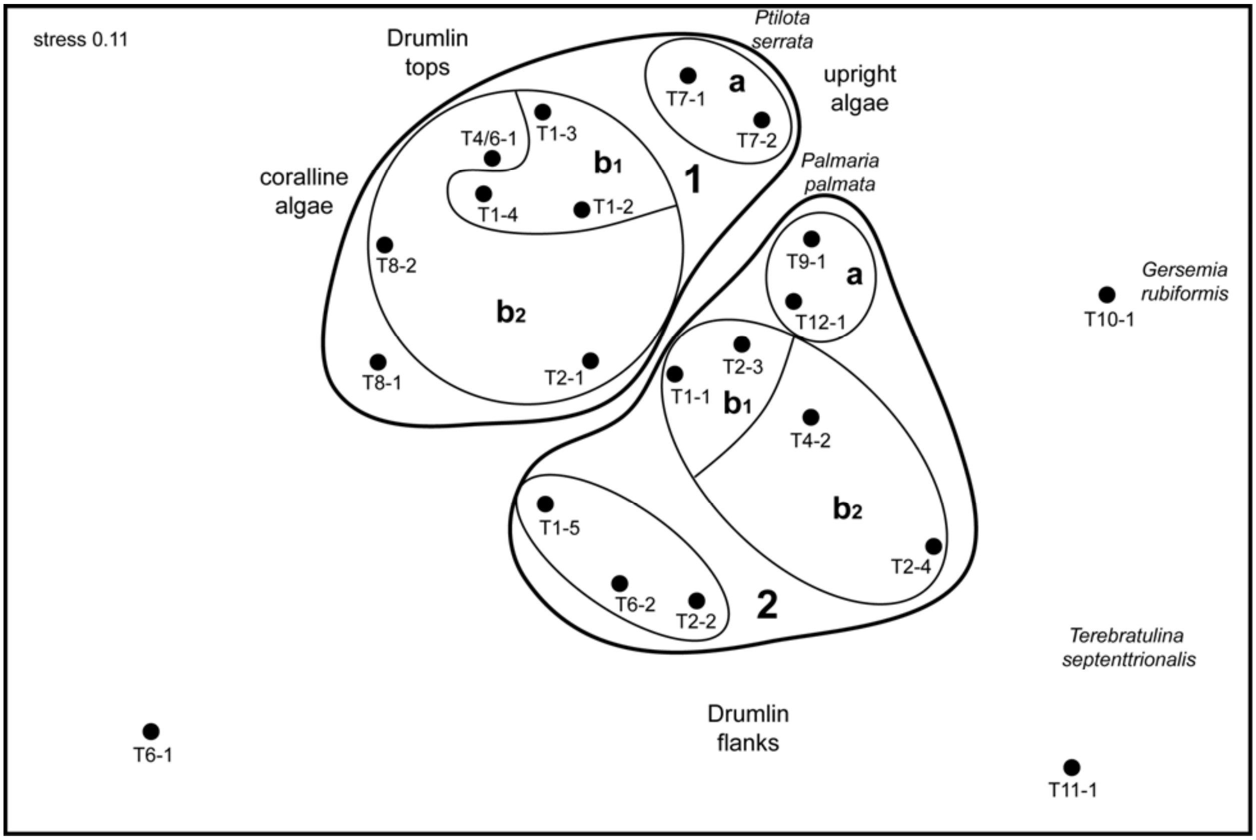


Figure 6-5. Non-metric multidimensional scaling plot of the 2006 nearfield hard-bottom still photograph data, with cluster designations from hierarchical classification superimposed.

Table 6-4. Habitat characteristics and range of abundance (number per slide) of selected taxa in clusters defined by classification analysis. Numbers in bold highlight major differences among clusters and subgroups.

Cluster	1				2				T10-1	T11-1	T6-1	3
	1a	$1b_1$	$1b_2$	T8-1	2a	$2b_1$	$2b_2$	2c				
Depth(m)	24	24-26	23-28	24	25-27	28	27-31	29-33	24	35	34	32-33
Substrate[1]	b+c	b+mx	b+mx	cp+mx	mx+b	mx+b	b+mx	mx	b+mx	mx	cp+g	d+rr
Relief[2]	M-MH	M-MH	M	LM	M	M	M	LM-M	H	LM	L	M
Drape[3]	m-mh	lm-m	lm	lm-m	lm-m	m-mh	m-mh	m-mh	mh-h	m	mh	m-mh
Coralline algae (% cover)	**17.12-22.61**	**31.83-41.88**	**35.63-53.64**	**22.97**	**32.67-37.34**	9.97-12.91	2.82-9.75	2.52-6.78	0.12	8.26	0.74	-
Coralline algae (numerical)	**4.00-5.48**	**7.73-9.58**	**8.41-12.76**	**5.19**	**8.00-8.75**	2.59-3.25	0.94-2.47	0.76-1.75	0.06	2.13	0.61	-
Palmaria palmata	**1.61-6.70**	**2.94-6.39**	0.41-1.42	**6.06**	**1.13-4.33**	**5.47-6.79**	0.15-0.56	0.00-0.03	1.73	-	-	-
Ptilota serrata	**2.39-8.36**	0.00-1.84	0.00-0.03	-	0.00-0.30	0.03-0.09	-	0.00-0.48	0.12	-	-	-
juvenile *Asterias*	**5.61**	**4.58-7.77**	**2.91-5.91**	**2.81**	**3.96-9.38**	**4.88-6.07**	2.41-2.52	2.00-5.00	1.82	1.77	1.97	0.62-2.81
Asterias vulgaris	**2.33-9.55**	**2.13-5.81**	**3.58-13.97**	**3.53**	**3.44-13.78**	0.59-1.97	0.91-1.59	1.45-3.06	0.15	0.52	1.26	0.19-0.66
Henricia sanguinolenta	**2.24-2.94**	**1.97-2.42**	1.03-2.67	1.06	1.89-2.72	1.90-2.81	1.52-2.63	1.13-1.65	**3.27**	0.32	0.58	0.31-0.74
Modiolus modiolus	1.00-3.00	0.97-2.09	**3.22-4.15**	1.72	0.96-4.63	1.90-2.44	1.61-1.84	0.39-0.91	0.64	0.52	0.19	0.00-2.62
Didemnum albidum	1.67-1.84	**3.52-5.20**	1.24-2.22	**6.13**	**2.91-4.26**	**5.90-6.34**	**5.09-5.45**	**4.15-5.97**	**2.70**	0.16	1.81	0.31-2.48
orange encrusting sponge	**2.39-3.84**	0.52-1.03	1.15-2.78	1.03	**2.96-5.44**	**2.76-2.81**	**2.72-3.00**	**1.55-3.87**	1.27	2.84	0.10	-
orange/tan encrusting	0.84-1.64	0.36-1.23	2.30-3.59	4.63	**2.00-3.16**	**2.69-3.03**	**4.28-4.91**	**3.90-5.45**	0.67	2.52	1.39	-
Polymastia sp. A	0.09-0.29	0.00-0.03	0.09-0.56	0.03	0.56-0.75	0.55-0.78	**1.91-2.09**	0.23-0.76	1.42	0.26	0.06	-
Gersemia rubiformis	-	-	-	-	-	-	-	-	**6.15**	-	-	-
Terebratulina septentrionalis	0.06-1.97	-	-	-	**7.06-12.44**	0.07-0.72	**5.88-17.06**	0.00-0.97	**7.39**	**20.00**	-	0.00-0.07
Metridium senile	-	0.00-1.90	0.00-0.03	-	0.00-0.03	0.00-2.34	0.00-0.03	-	0.27	-	-	**9.26-110.72**
Halocynthia pyriformis	0.09-0.48	0.06-0.20	0.06-0.27	-	0.81-1.19	0.83-1.28	0.44-1.61	-	0.97	0.03	-	**0.07-12.65**
Tautogolabrus adspersus	**2.13-3.82**	1.36-5.70	1.00-5.33	0.19	1.37-1.94	**2.03-2.88**	**1.73-3.78**	0.50-0.91	**3.97**	0.52	0.23	**2.16-3.34**
Species	36-39	31-36	33-41	33	**44-45**	**45-46**	**43-49**	32-39	38	**43**	29	20
Total algae	**10.00-19.70**	**11.07-16.35**	**8.84-13.85**	**11.25**	**9.88-12.63**	**8.81-9.41**	1.09-3.03	0.76-1.90	1.94	2.13	0.61	-
Total invertebrates	28.12-34.58	24.91-28.93	28.88-37.27	28.06	**47.00-63.81**	**34.45-41.13**	**41.31-68.61**	29.15-32.25	36.21	54.94	9.81	**35.97-120.55**
Total fish	**2.19-3.85**	1.42-5.73	1.00-5.39	0.22	1.52-1.94	2.10-2.91	**1.82-3.81**	0.56-0.94	**3.97**	0.58	0.26	**2.19-3.34**

[1] b=boulder, c=cobble, g=gravel, m=mix of boulders, cobbles, and gravel, cp=cobble pavement, d=diffuser, rr=riprap

[2] L=low, LM=moderately low, M=moderate, MH=moderately high, H=high l=light, lm=moderately light, m=moderate, mh=moderately heavy, h=heavy

The first cluster (cluster 1) consisted mainly of drumlin top sites that grouped together at a faunal similarity of 67.5 percent. All of the stations in this cluster had moderate percent cover of coralline algae and supported some upright algae. Additionally, the stations in this cluster also supported moderate numbers of invertebrates and varying numbers of fish. Species richness was moderate at the drumlin top stations, ranging from 33 to 39 species, and slightly higher (41 species) at the drumlin flank station. Several subgroups within this cluster appeared to reflect geographic differences among the stations. The two northernmost reference sites (T7-1 and T7-2) comprised the first subgroup (1a). Substrate at these stations consisted of a mix of boulders and cobbles, with moderate to moderately heavy sediment drape. These stations supported a modest percent cover of coralline algae (17.12 and 22.61 percent) and the highest number of upright algae (both dulse *Palmaria palmata* and filamentous red algae *Ptilota serrata*). All six of the sites in subgroup 1b had seafloors that consisted of boulders interrupted by patches of cobbles and gravel. These stations all had less sediment drape than the northern reference stations and supported a moderately high percent cover of coralline algae (31.83 to 53.64 percent). The first three of theses sites (subgroup $1b_1$) were located on the top of the drumlin located directly north of the outfall. They supported slightly less percent cover of coralline algae and moderate numbers of *P. palmata*. The remaining three sites (subgroup $1b_2$) were widely spread geographically, supported higher percent cover of coralline algae, few upright algae, and more invertebrates than subgroup $1b_1$. The final station in cluster 1 was one of the southern reference stations (T8-1). The seafloor at this station consisted primarily of a cobble pavement interrupted by occasional patches of boulders and gravel. This resulted in a moderately low relief habitat. Station T8-1 supported a moderate percent cover of coralline algae (22.97 percent) and moderate numbers of *P. palmata*.

The second cluster (cluster 2) consisted mainly of drumlin flank stations (seven flank and two top stations) that grouped together at a similarity of 67.4 percent. The stations in this cluster varied widely in habitat characteristics and faunal constituents. This cluster also further divided into several subgroups of stations. The first subgroup (1a) consisted of the two drumlin top stations, a northern reference station (T9-1) and a southern reference station (T12-1). Both of these sites had moderate relief and moderately light to moderate sediment drape. These two sites supported moderately high percent cover of coralline algae (32.67 to 37.34 percent), some dulse, numerous brachiopods (*Terebratulina septentrionalis*), many other invertebrates, and a relatively high number of species (44 and 45 species). The second subgroup (2b) consisted of four flank stations that divided two groups of two stations each. All four of these stations had moderate relief with moderate to moderately heavy sediment drape. These four stations supported moderate to high numbers of invertebrates, relatively high numbers of fish, and also a high number of species (43 to 49 species). The first two stations (subgroup $2b_1$) supported more algae (both coralline and dulse) than the second two stations (subgroup $2b_2$), In contrast, the second two stations supported very few algae, but numerous brachiopods and other invertebrates. The last subgroup within this cluster (subgroup 2c) consisted of three deep flank stations that had moderately low to moderate relief and moderate to moderately heavy sediment drape. These stations supported very few algae, moderate numbers of invertebrates, few fish, and fewer species (32 to 39 species) than the other stations in this cluster.

The two main clusters joined together at a similarity of 64.5 percent. Three solitary stations individually joined this main cluster at lower levels of similarity. The first station, one of the southern reference stations (T10-1), joined the main cluster at a similarity of 56.6 percent. The seafloor at this station consisted mainly of large boulders with cobbles nestled at their bases, resulting in a high relief habitat, with moderately-heavy to heavy sediment drape. This station supported few algae, moderate numbers of invertebrates, many fish, and a moderate number of species (38 species). The large boulders at this site provided suitable attachment sites for numerous brachiopods and the soft coral *Gersemia rubiformis* (which was found nowhere else). The second solitary station, the farfield southern reference station T11-1, joined the main cluster at a similarity of 50.4 percent. The seafloor at this station was a moderately low relief mix of mostly cobbles interspersed with occasional large boulders, covered with a moderate sediment drape. This station supported many invertebrates, few algae, few fish, and many species (43 species). Brachiopods dominated the faunal community at this station, where they were found on many of the boulders throughout the site. The final solitary station that joined the main cluster at a similarity of 47.0 percent was a deep flank station (T6-1). The seafloor at this station consisted of a low-relief cobble pavement interrupted by occasional patches of gravel, covered by a moderately heavy sediment drape. This station was relatively depauperate, supporting very few algae, few invertebrates, few fish, and relatively few species (29 species).

The final cluster of stations (cluster 3) consisted of the two diffuser stations that joined the main group of stations at a similarity of 33.0 percent. These sites consisted of the diffuser heads and the riprap immediately surrounding them. Both of these stations supported no algae and moderately high numbers of fish. The head of the active diffuser (#2 at T2-5) was colonized by numerous frilled anemones (*Metridium senile*), where dense aggregations of this anemone covered most of the exposed surfaces of the dome, as well as the indentations of the discharge ports (Figure 6-6a and b). *Metridium* were also very abundant on the diffuser head prior to diversion of the outfall. In contrast, the head of the inactive diffuser (#44) was much more sparsely populated and was colonized primarily by the sea peach tunicate *Halocynthia pyriformis* (Figure 6-6c and d). Both stations supported relatively few species (20 species each) compared to the drumlin sites (29 to 49 species).

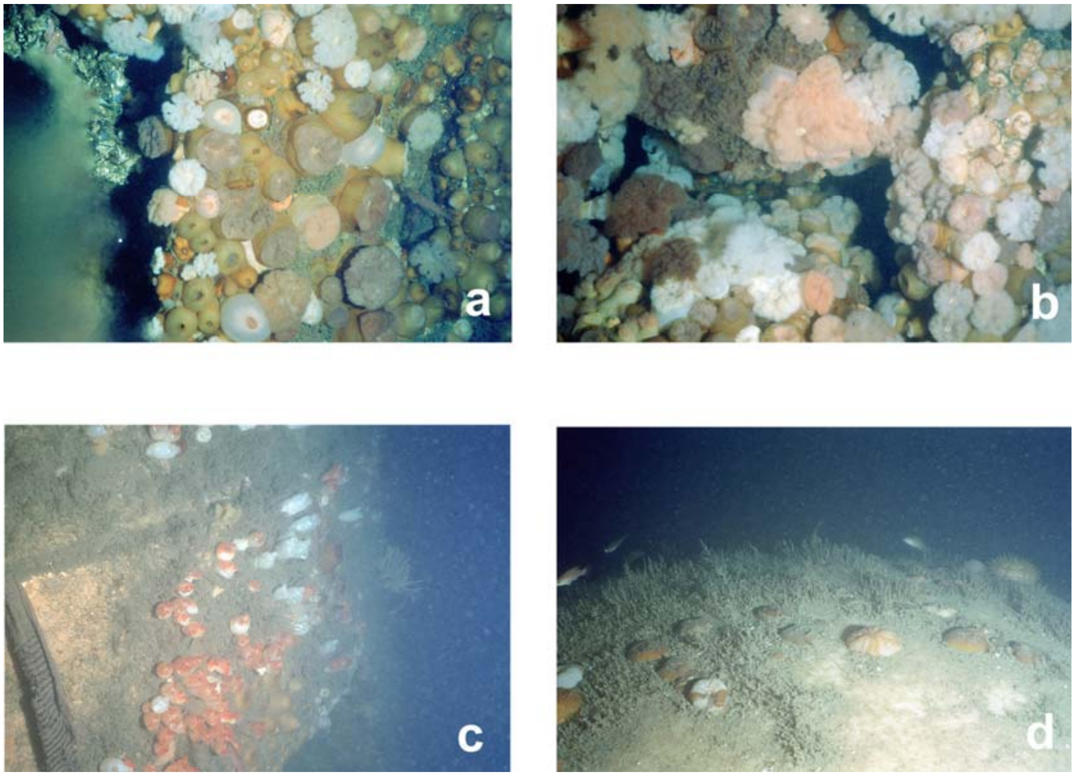


Figure 6-6. Photographs showing colonization of the diffuser heads. (a) An open port of the active diffuser head #2 (T2-5) showing many frilled anemones *Metridium senile* and mussels surrounding the port opening. (b) A closed port on the active diffuser head showing the high number of *M. senile* colonizing this diffuser. (c) The side of the inactive diffuser head (#44) showing colonization by numerous sea peach tunicates *Halocynthia pyriformis*. (d) The top of the inactive diffuser head showing sparse colonization by *M. senile*.

6.3.4 Comparison of Pre- and Post-Diversion Communities

The nearfield hard-bottom communities in the vicinity of the outfall have been surveyed annually for 13 years. Seven of the surveys occurred under pre-discharge baseline conditions, while the last six surveys occurred under post-discharge conditions. The baseline surveys provided a substantial database that allowed characterization of the habitats and benthic communities found on the drumlins in the vicinity of the outfall. The sampling design and approach has evolved to maximize the probability of detecting potential impacts of outfall operations. The present design includes 13 sites near the outfall, 7 nearfield reference sites (3 north and 4 south of the outfall), one farfield reference site off Scituate, and both inactive and active diffuser heads. Additionally, the emphasis on data products also has evolved. Still photographs and video footage are both utilized to provide a detailed characterization of the seafloor and of the biota inhabiting the hard-bottom sites. The still photographs provide the high resolution required to provide detailed data on habitat characteristics (substrate size classes and amount of sediment drape), estimated percent cover of encrusting algae, estimated relative abundances of upright algae, and faunal composition of the benthic communities. In contrast, the much broader areal coverage provided by the video images has allowed assessment of habitat relief, spatial heterogeneity, and the occurrence of large, rare biota.

The hard-bottom habitats, though spatially quite variable, have shown consistent trends over time. At many of the waypoints, year-to-year variations in habitat characteristics tended to be relatively small. Habitat relief does not vary over time, but slightly different areas of the sites were surveyed each year, so varying relief at a site indicates habitat heterogeneity. Figure 6-7 shows the mean habitat relief observed during the 1996 to 2006 surveys. Location on the drumlins appeared to be a primary factor in determining habitat relief. The seafloor on the tops of drumlins usually consisted of a mix of boulders and cobbles. Habitat relief varied from moderate to high on drumlin tops dominated by boulders (T1-2, T1-3, T2-3, T4/6-1, T7-1, T7-2, T9-1, T10-1, and T12-1) to moderate to low on drumlins that consisted of a mix of cobbles and boulders (T1-4, T2-1, T8-1, and T8-2). The seafloor on the flanks of drumlins was quite variable, but usually consisted of a cobble pavement interspersed with patches of sand, gravel, and occasional boulders. Habitat relief on the flanks ranged from low to moderately low on the drumlin south of the outfall (T4-1, T4-2, T4-3, T6-1, and T6-2) to moderately low to moderately high on the drumlin north of the outfall (T1-1, T1-5, T2-2, T2-3, and T2-4). The variance shown by the error bar indicates that some sites are quite homogeneous (T1-3, T8-1, T10-1, T12-1, and the diffuser stations), while other sites tend to be more heterogeneous (T2-2, T4-2, T4/6-1, T6-2, and T7-1).

Figure 6-8 shows the amount of sediment drape seen on the rock surfaces during the 1996 to 2006 surveys. Sediment drape was lightest on the shallowest part of the two drumlins adjacent to the outfall (T1-2, T1-3, T1-4 and T4/6-1), slightly more at the southernmost reference sites (T8-1, T8-2 and T12-1), and moderate to moderately heavy at the northern reference sites (T7-1, T7-2, and T9-1). Drape was also heavy on the deeper part of the drumlin north of the outfall (T1-1, T2-2, and T2-3), as well as on the flanks (T2-4, T4-2, and T6-1). Drape was consistently heaviest at T10-1, the southern reference site west-southwest of the outfall. Sediment drape has consistently increased at several of the stations north of the outfall (T1-2, T1-3, T1-4, T7-1, and T7-2) during the post-diversion years.

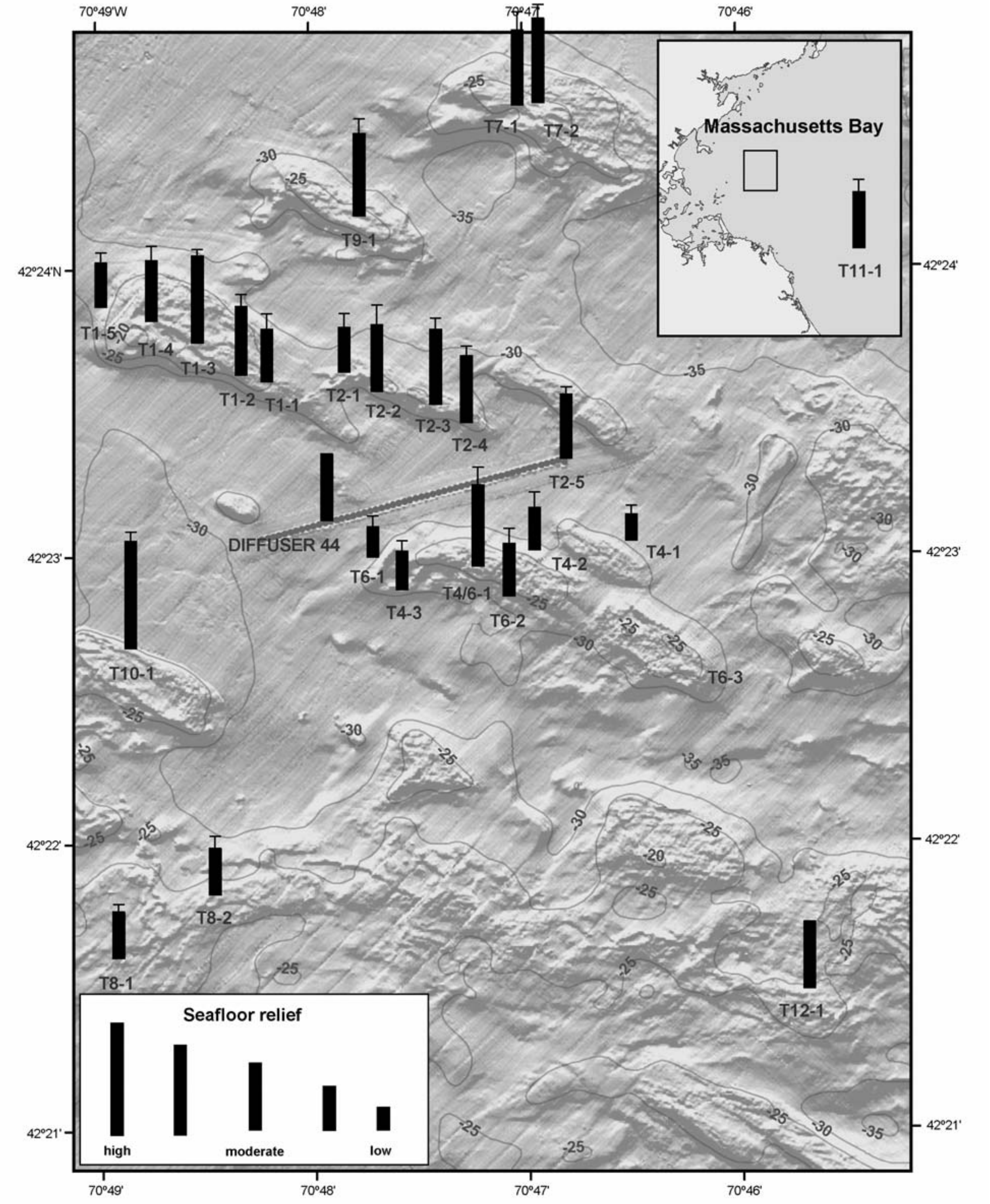


Figure 6-7. Habitat relief (mean values) determined from the 1996 to 2006 nearfield hard-bottom surveys. Error bars are one standard deviation. To generate the relief bars, habitat relief was coded as: low=1, moderately low=2, moderate=3, moderately high=4,and high=5.

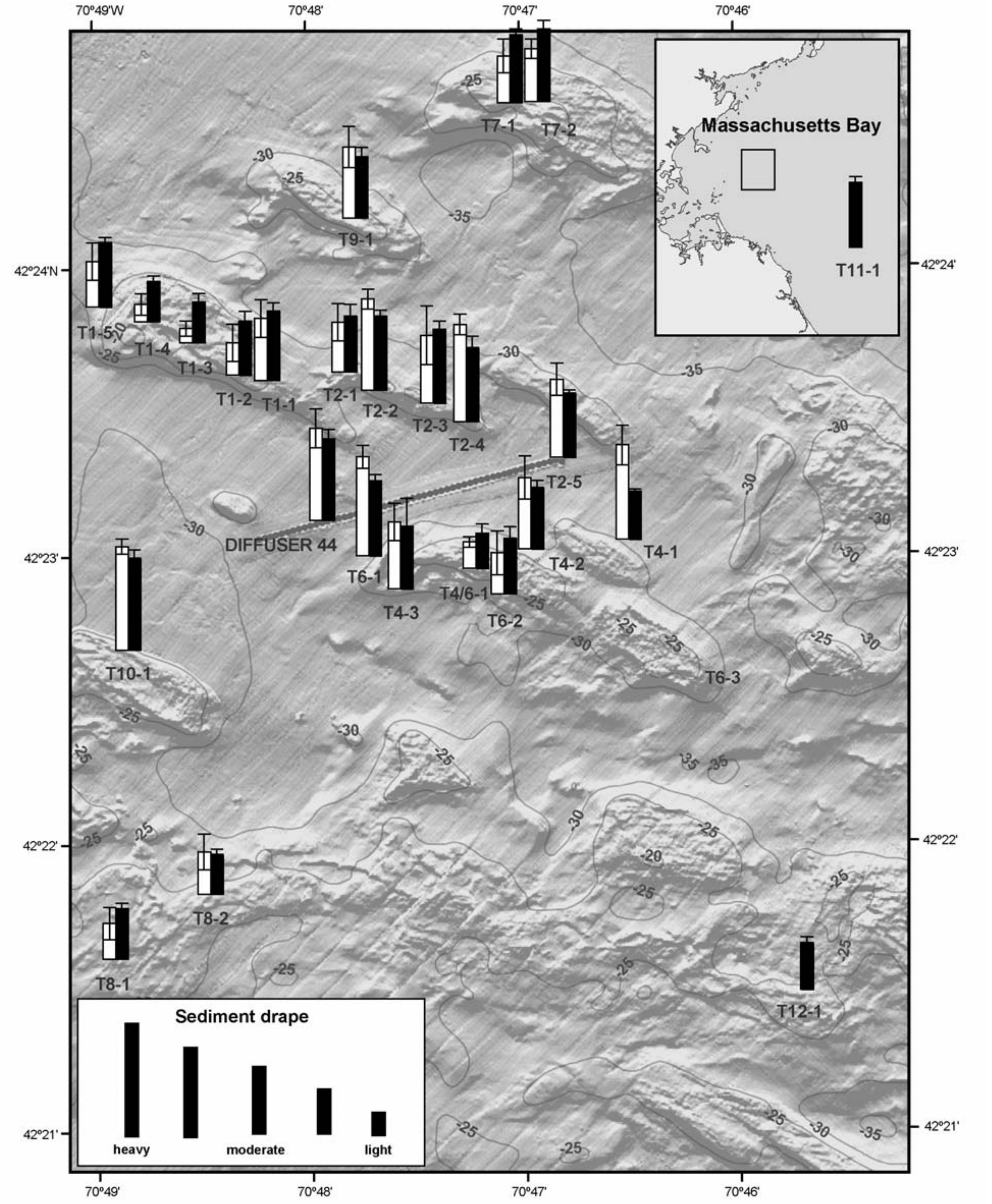


Figure 6-8. Sediment drape determined from 35-mm slides collected during the 1996 to 2006 nearfield hard-bottom surveys. White bars are mean pre-diversion values and black bars are mean post-diversion values. Error bars are one standard deviation.

Encrusting coralline algae has historically been the most abundant and widely distributed taxon encountered during the hard-bottom surveys. Figure 6-9 shows the percent cover of coralline algae estimated from the slides taken during the 1996 to 2006 surveys. Coralline algae were generally most abundant on the top of drumlins (T1-3, T1-4, and T4/6-1) and least abundant on the flanks (T2-2, T2-4, T4-1, and T6-1). The percent cover of coralline algae was most variable near the edges of the tops of drumlins or on the flanks, where small lateral shifts in location frequently resulted in large differences in coralline algal cover. Percent cover of coralline algae was quite stable during the "baseline" period and remained stable at most of the stations during the first four years of the post-discharge period. The major exception to this occurred at five stations located north of the outfall (T1-2, T1-3, T1-4, T7-1, and T7-2), which consistently had less percent cover of coralline algae during each of the post-diversion years.

Table 6-5 shows the estimated percent cover of coralline algae for the 1996 to 2006 time period. The decrease in percent cover of coralline algae at the northern stations mentioned above was particularly pronounced in 2005 and 2006. Additionally, concurrent decreases in percent cover of coralline algae were observed at several sites south of the outfall starting in 2005. The marked decrease in percent cover of coralline algae noted at many of the stations in 2005 also extended into 2006. A flank station T4-2 also had less percent cover of coralline algae during the last four post-diversion years. One additional station (T4/6-1) has shown a decrease in coralline algae during the last three years, but this may reflect variability within the site (note the variability observed at two different locations within this station in 2002).

It is unlikely that light attenuation with depth is a limiting factor for coralline algae, within the range of depths covered during this survey (Sears and Cooper 1978, Vadas and Steneck 1988). However, in previous years of this study, percent cover of coralline algae has been found to be inversely related to sediment drape (Kropp et al. 2002, Maciolek et al. 2004). Percent cover is usually highest in areas that have little drape and lowest in areas that have moderate to heavy drape. This is not surprising, because the encrusting growth form of coralline algae would make them quite susceptible to smothering by fine particles.

Changes in percent cover of coralline algae and sediment drape at each of the stations over time can be seen on Figure 6-10. The widespread decreases in percent cover of coralline algae observed in the last two years can be seen at 13 of the stations. In the past, post-diversion decreases in coralline algal cover were seen at only five stations and were usually accompanied by increases in sediment drape. This did not appear to be the case in 2005 and 2006, where only slight increases in sediment drape were noted at several of the stations. Reasons for the dramatic decrease in coralline algae starting in 2005 are not readily apparent. Reasons for the post-diversion increases in sediment drape and decreases in coralline cover at some locations and not at others are not readily apparent, but may be related to the discharge. Additionally, some of the decreases in percent cover of coralline algae noted at the northern reference stations may be related to increases in anchoring activity of LNG tankers at these stations since 2001.

In contrast to the wide distribution of coralline algae, the distributions of the three upright algae commonly inhabiting the drumlins, the filamentous red alga *Ptilota serrata,* the dulse *Palmaria palmata*, and the shotgun kelp *Agarum cribosum*, were quite restricted. Additionally, their abundances varied quite widely during both the pre- and post-diversion periods. Some of this variability appears to reflect patchiness in the small-scale (within station) spatial distributions of the upright algae. Dense stands of upright algae were frequently seen neighboring areas totally devoid of them. This spatial patchiness may reflect that upright algae were most abundant on the top of larger boulders in areas of moderate to high relief. However, much of the variability observed appears to reflect yearly changes in the abundance of upright algae, rather than changes related to outfall diversion.

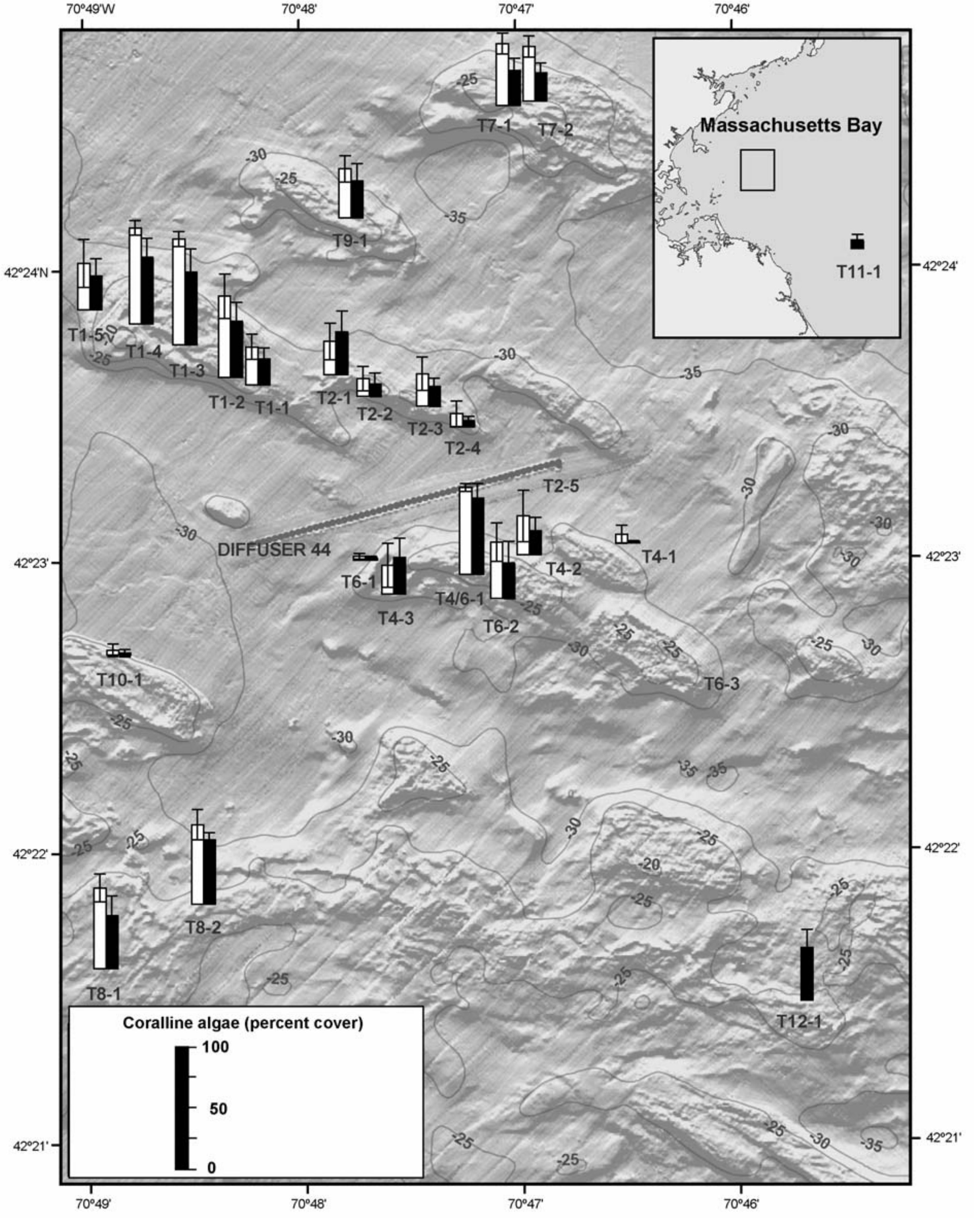


Figure 6-9. Percent cover of coralline algae determined from 35-mm slides collected during the 1996 to 2006 nearfield hard-bottom surveys. White bars are mean pre-diversion values and black bars are mean post-diversion values. Error bars are one standard deviation.

Table 6-5. Estimated percent cover of coralline algae 1996−2006. Differences between pre- and post-diversion are shaded. (*= differences related to shifts in position of the areas surveyed.)

Station	Pre-diversion					Post-diversion					
	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006
T1-1	33	42	37	26	16	15	34	28	25	18	10
T1-2	67	72	79	36*	79	47	61	67	27	44	32
T1-3	90	96	80	83	86	68	69	80	70	38	34
T1-4	85	83	82	70*	77	58	71	63	65	32	42
T1-5	67*	12	37	37	37	29	36	45	34	17	5
T2-1	46	33	9*	35	14	18	39	53	53	13	36
T2-2	5	13	33*	13	10	9	28	8	7	8	3
T2-3	26	41	39	21	8*	17	23	25	15	6	13
T2-4	7	27	18	4	1	2	12	6	5	4	3
T4-1		15*	<1	0	11	1	2				
T4-2	41	53	9*	8*	47	37	28	12	22	11	10
T4-3	12	12	56*	25	16	19	41				
T4/6-1	72	67	77	72	71	73	80 (50)*	66	57	48	54
T6-1	2	4	5	2	2	3	3	2	3	2	1
T6-2	69*	55	45	29	36	42	56	23	32	14	7
Northern reference											
T7-1	65*	43	49	47	52	32	36	39	33	15	17
T7-2	52	54	45	36	36	24	28	30	27	8	23
T9-1		40	54	28	38	30	36	19	51	11	37
Southern reference											
T8-1		73	74	69	49	58	59	47	50	24	23
T8-2	82	75	65	51	58	48	56	59	58	46	52
T10-1		12	0	2	3	0	1	<1	8	<1	<1
T12-1								63	48	30	33
Others											
T11-1								1	8	11	8
T2-5	<1	<1	<1			0	0	0	0	0	0
Diff #44		0	<1		<1	0	0	0	0	0	0

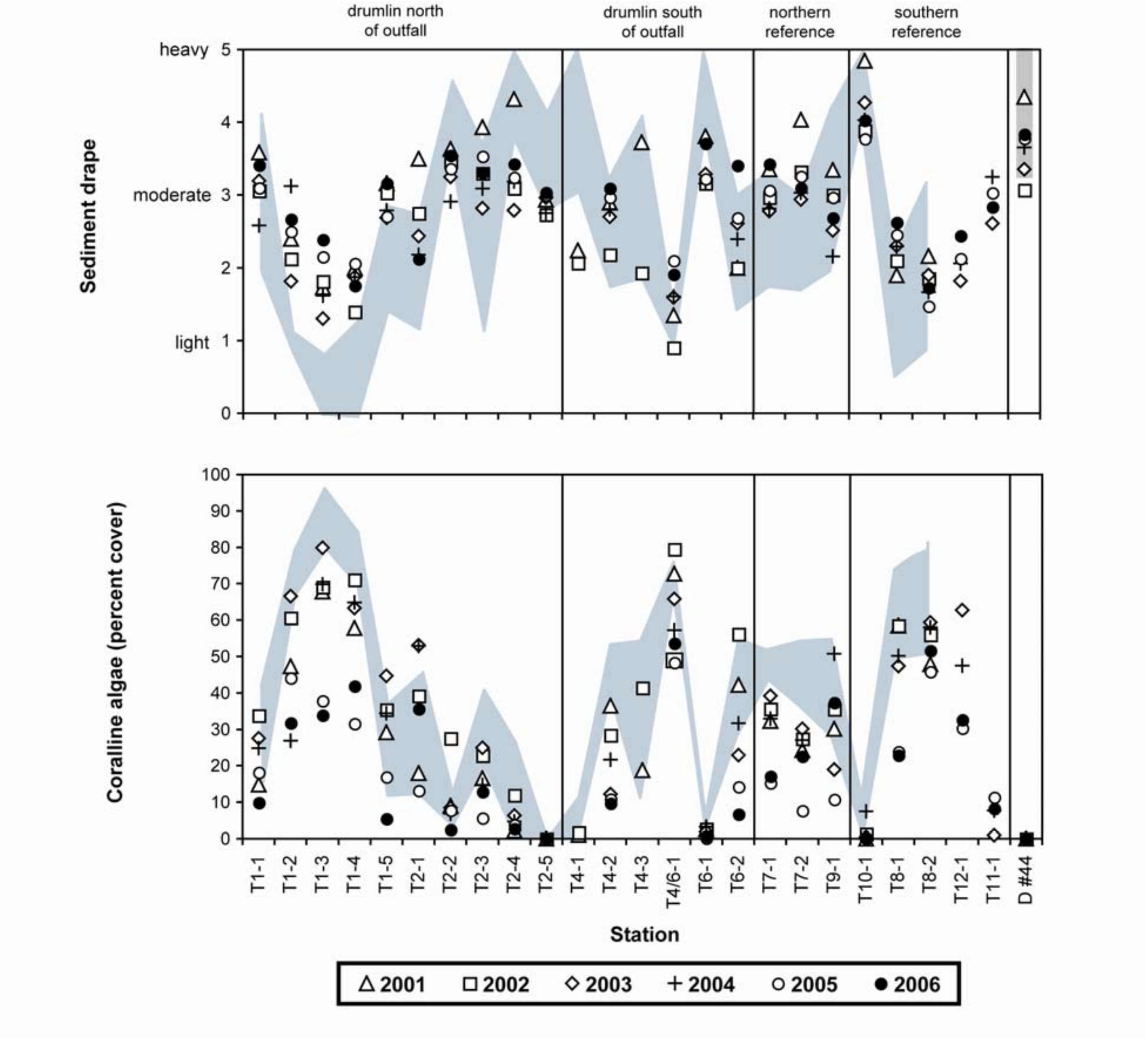


Figure 6-10. Sediment drape and percent cover of coralline algae at the nearfield hard-bottom sites determined from 35-mm slides taken during the 1996 to 2006 surveys. The dashed line shows the mean baseline value and the shaded area shows the range of baseline values.

Upright algae were generally most abundant at the northern reference stations (Figures 6-11 and 6-12). Both *P. palmata* and *P. serrata* were commonly observed at the three northern reference sites (T7-1, T7-2, and T9-1) and on the drumlin immediately north of the outfall (T1-1, T2-2, T2-3, and T2-4). *Palmaria palmata* was most abundant in 1997, decreased in 1998, slowly increased until 2001 or 2002, decreased in 2003, and has remained relatively steady for the last 3 years. On the drumlin immediately north of the outfall, dulse was present but variable at several stations until 2003, when it decreased at all of the stations. Since then it has been increasing again at several of the stations. Dulse has been largely absent from most of the southern stations, though it was abundant at two of them (T4/6-1 and T10-1) in 1997. This alga increased modestly in abundance at the southern reference stations in 2006.
In contrast, *P. serrata* was most abundant in 1996 and 1998, and least abundant in 1997 (Figure 6-12). Additionally, the density of this filamentous red alga has declined since 1998 at many of the stations. This alga has never been common at any of the southern stations. In contrast, *Agarum cribosum* had the most restricted distribution of the upright algae, and was abundant only at the northernmost reference sites. This alga was most abundant at T7-2 where peak numbers were observed in 2000, then rapidly declined in 2001 and 2002, increased again between 2003 and 2005, and disappeared in 2006. The peak density of shotgun kelp in 2000 coincided with the appearance of numerous lacy bryozoans *Membranipora* sp. encrusting many of the kelp fronds. The dramatic decline in shotgun kelp after 2000 may be related to the appearance of this invasive bryozoan, rather than the start of outfall discharge. There does appear to be a general trend of decreased abundances of upright algae over time, particularly since 2003. Again, part of this decrease may be related to the above mentioned anchoring activity at the northern reference stations.

One pronounced biotic change was noted in 2003, when dense aggregations of adult barnacles were observed at 13 of the 23 stations. This massive influx of barnacles appeared to reflect a large recruitment event that occurred in the fall of 2002 (Maciolek *et al*. 2004b Appendix D3). By 2004 most of these barnacles had died because of overcrowding, leaving large surfaces of rocks covered with barnacle bases and valves. Rocks covered with barnacle debris were observed at 11 stations. Two species newly observed in 2004 were a frilly white encrusting sponge(?) and a grey translucent encrusting organism that were seen only on boulders that had previously been colonized by the barnacles. Both of these species were very sparse in 2005 and absent in 2006.

The total number of species seen on the still photographs at each of the stations does not appear to have been impacted by diversion of the outfall (Figure 6-13). The number of species seen during the post-diversion period was well within the range of species seen pre-diversion at most of the stations. The fewest species were seen at the diffuser stations, and deep drumlin flank stations tended to support fewer species than drumlin top stations.

Figure 6-14 shows the results of hierarchical classification of data collected from still photographs taken during the 1996 to 2006 time period. The clustering structure appeared to be controlled by a combination of geographic location and topography, and to a lesser degree by outfall diversion period. Several smaller groupings of stations also appeared to reflect yearly differences. The stations grouped into ten clusters of stations joined by one individual station. The overwhelming structuring factor appeared to be geographic location with neighboring stations frequently clustering together or different years of the same station clustering together. Examples of this can be seen in cluster 1, which consisted mostly of northern reference stations (T7-1, T7-2, and T9-1); the largest group in cluster 3, which consisted mainly of southern reference stations (T8-1 and T8-2); cluster 4, which consisted of stations located on the tops of drumlins on either side of the outfall (T1-2, T1-3, T1-4, and T4/6-1); cluster 9, which consisted of diffuser stations (T2-5 and D#44); and cluster 10, which consisted of a deep drumlin flank station (T4-1). Some cluster groups were comprised of both pre- and post-diversion years, while others consisted mainly of years from one diversion period. The first group in cluster 1 consisted of both pre- and post-diversion years, while the remaining groups in this cluster consisted entirely of pre-diversion years. The same pattern was seen in cluster 3, where the first two groups also consisted of both pre- and post-diversion

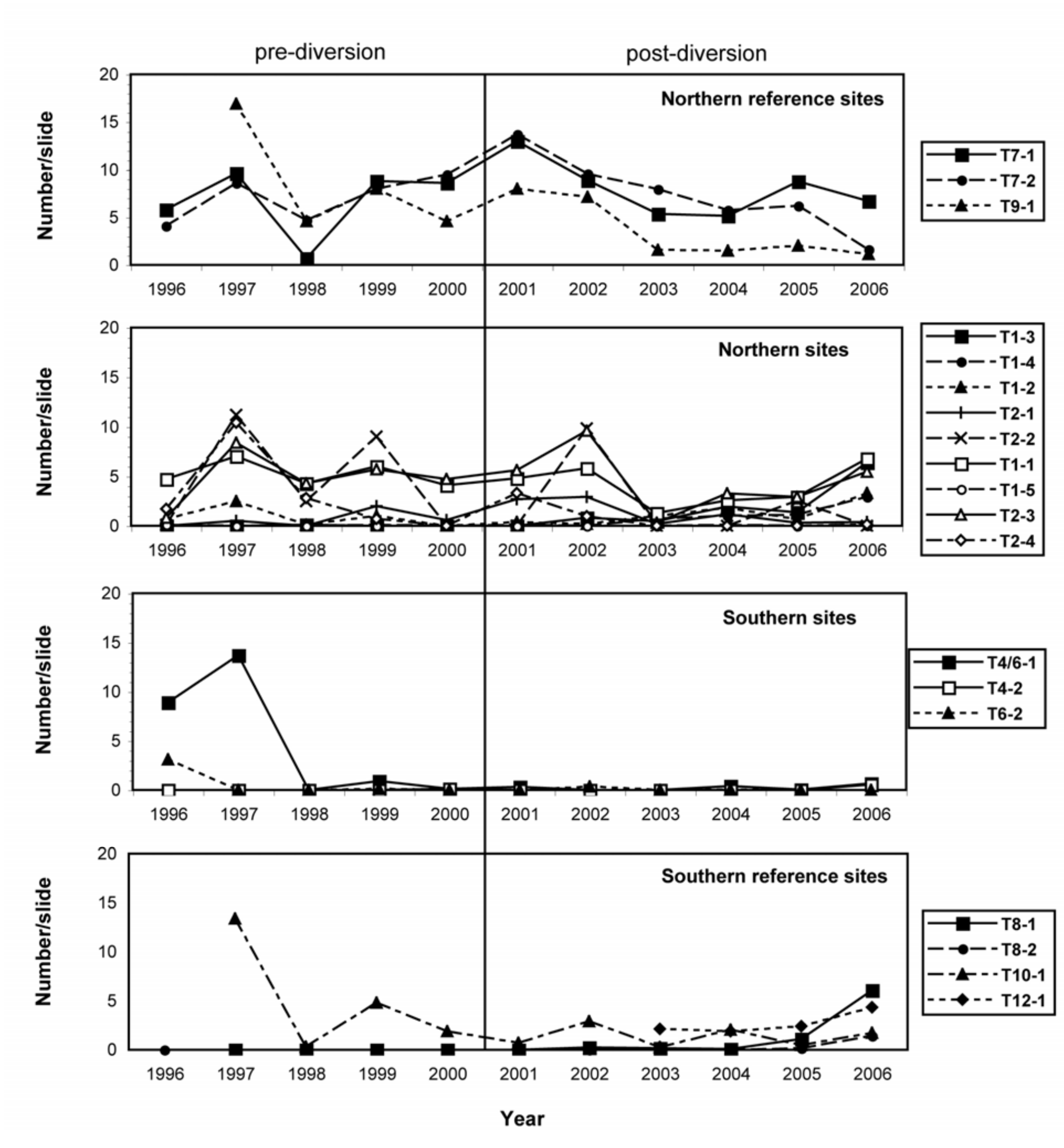


Figure 6-11. Abundance of dulse *Palmaria palmata* over time at the nearfield hard-bottom sites, as determined from 35-mm slides taken during the 1996 to 2006 surveys.

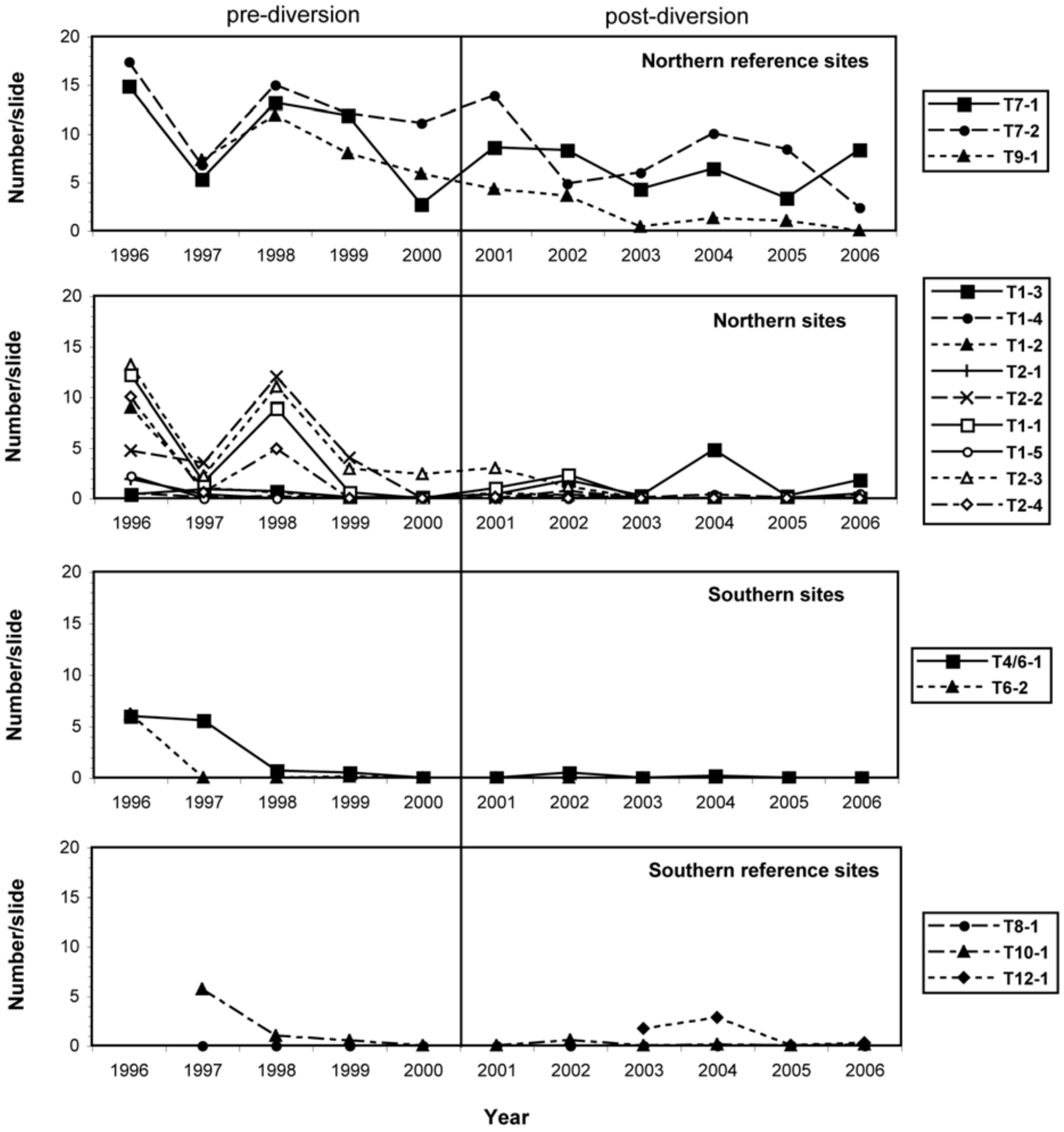


Figure 6-12. Abundance of the filamentous red alga Ptilota serrata over time at the nearfield hard-bottom sites, as determined from 35-mm slides taken during the 1996 to 2006 surveys.

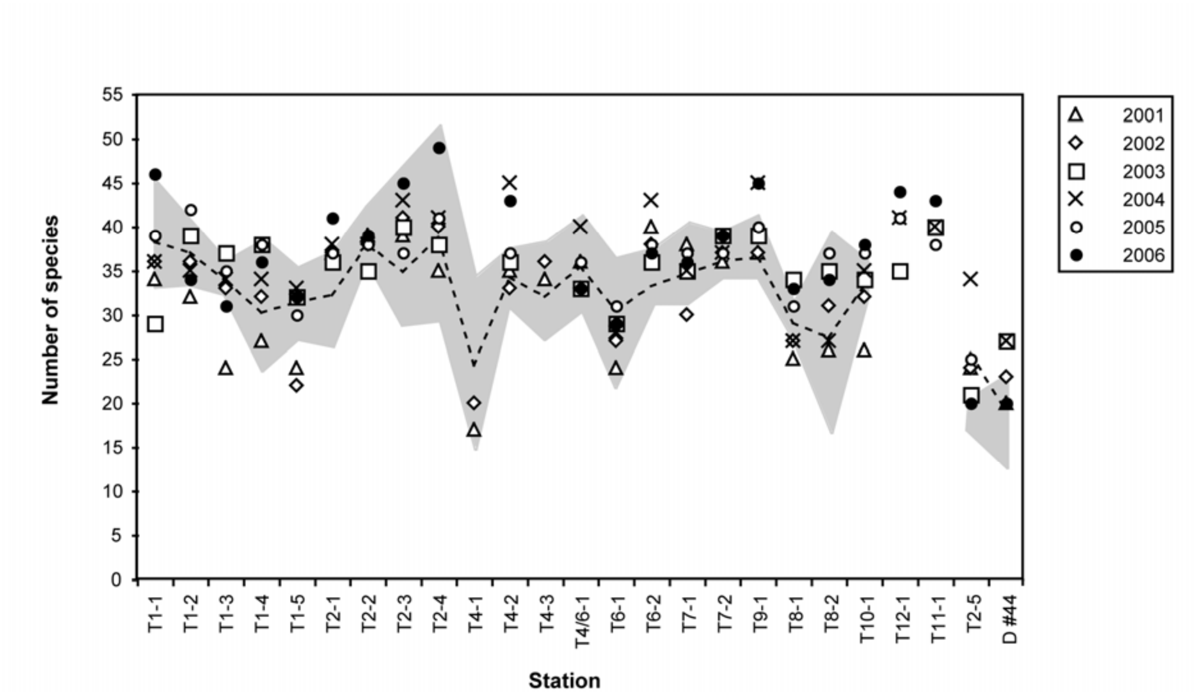


Figure 6-13. Total number of species seen on still photographs collected at the nearfield hard-bottom sites during the 1996 to 2006 surveys. The dashed line shows the mean baseline value and the shaded area shows the range of baseline values.

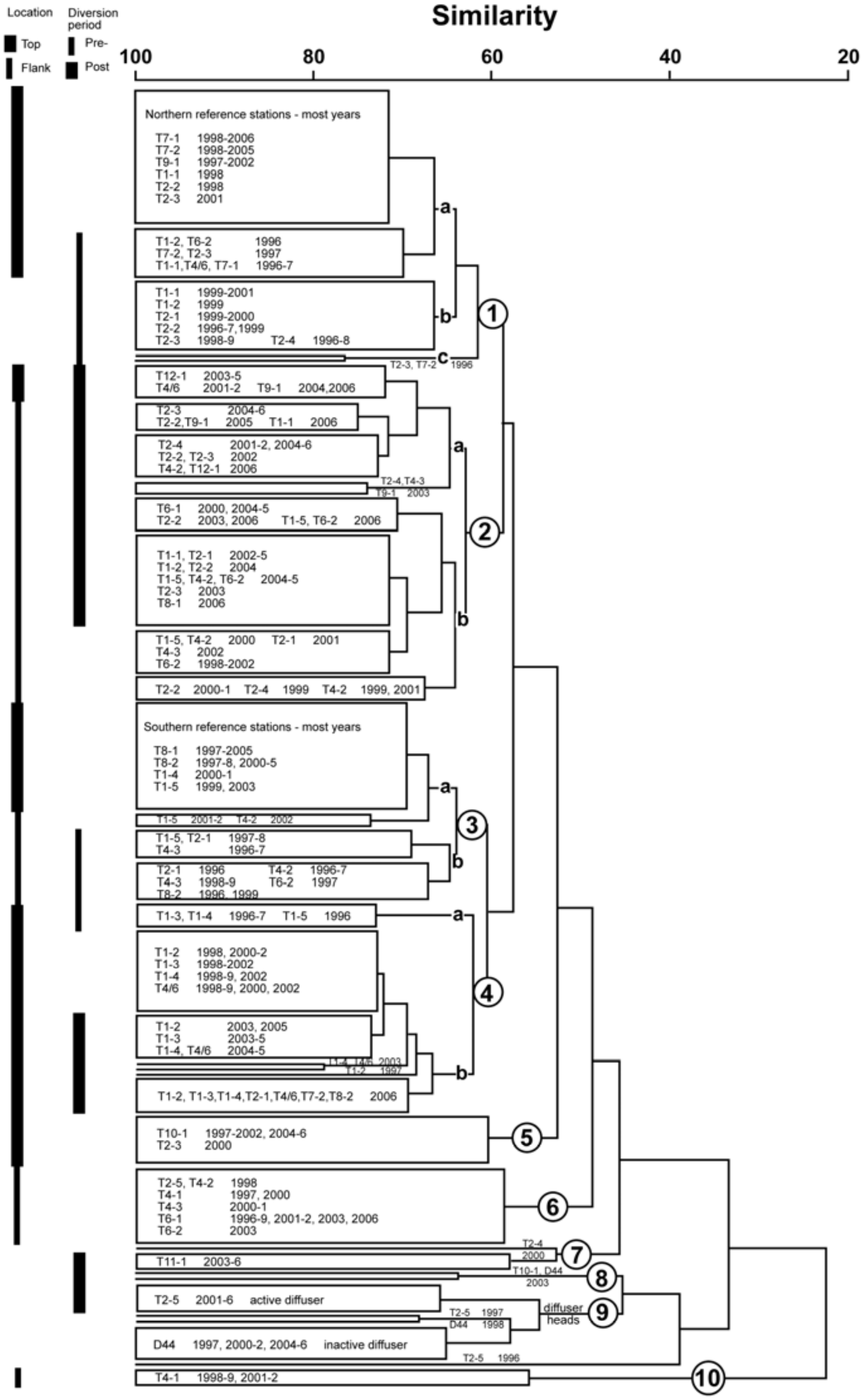


Figure 6-14. Summarized cluster analysis of data collected from still photographs taken during the 1996 to 2005 nearfield hard-bottom surveys. Location, topography, and diversion period are noted for cohesive clusters.

years, while the remaining two groups consisted only of pre-diversion years. One large group in cluster 4 consisted of both pre- and post-diversion years, while several of the groups consisted of post-diversion years. In contrast, most of the groups in cluster 2 consisted of flank stations in post-diversion years. The subtle grouping of stations by diversion period may reflect minor shifts in benthic communities due to outfall diversion, or it may merely reflect changes in benthic communities over time. It is interesting to note that both the northern (first group in cluster 1) and southern reference stations (first group in cluster 3) generally do not separate on the basis of diversion period, while some of the stations on the tops and flanks of drumlins nearer the outfall do separate into pre- and post-diversion periods.

Table 6-6 shows the dominant species that control much of the clustering structure. Stations in the first four clusters (clusters 1 to 4) all supported coralline algae, while the remaining clusters (clusters 5 to 10) only supported trace amounts or none. Areas in clusters 3 and 4 (southern reference stations and drumlin tops north of the outfall, respectively) supported the most coralline algae, while those in cluster 2 (mostly post-diversion flank stations) supported the least. Not surprisingly most of the stations in cluster 1, the northern reference stations, were the only ones that supported substantial numbers of upright algae (namely *Ptilota serrata* and *Palmaria palmata*). The stations in clusters 2, 3, and 4 all supported few if any upright algae. The drumlin flank stations in cluster 2 supported the least coralline algae, but did support a wide variety of invertebrate taxa. The stations in cluster 2 also supported northern white crust tunicates (*Didemnum albidum*), while the stations in cluster 3 supported another tunicate (*Aplidium* sp.). The drumlin top stations in cluster 4 (T1-3 and T1-4) supported the most coralline algae and many horse mussels (*Modiolus modiolus*). With one exception, cluster 5 consisted of southern reference station T10-1, which supported only trace amounts of coralline algae, but numerous red soft corals *Gersemia rubiformis*, sea stars, and fish (the cunner *Tautogolabrus adspersus*). The stations in cluster 6 consisted of drumlin flank stations that had few coralline algae and no other distinctive taxa. Cluster 7 consisted mainly of the farfield southern reference station T11-1, which supported very little coralline algae and many brachiopods (*Terebratulina septentrionalis*). Cluster 8 consisted of three stations from 2003, when dense aggregations of adult barnacles (*Balanus* spp.) were encountered following a major settlement event in fall of 2002. Cluster 9 consisted of the two diffuser stations, with the active diffuser (T2-5) clustered separately from the inactive diffuser (D#44). The frilled anemone *Metridium senile* was the dominant inhabitant of the active diffuser head, while the sea peach tunicate *Halocynthia pyriformis* was the dominant inhabitant of the inactive diffuser head. Finally cluster 10, which consisted entirely of flank station T4-1 was generally quite depauperate during all the years that it was surveyed (it was dropped from the program in 2003) and supported relatively few taxa. This was the only station where the burrowing anemone *Cerianthus borealis* and the sea scallop *Placopecten magellanicus* were routinely encountered.

Figure 6-15 shows the NMDS analysis of the 1996 to 2006 data. The stations in clusters 8 (the 2003 barnacle settlement), 9 (diffuser stations), and 10 (depauperate flank station, T4-1) separated away from the main grouping of stations. Additionally, the one outlier to clusters 8 and 9 (T2-5 in 1996) also clustered separated from the main group. Clusters 5 (T10-1 with high relief and a relatively unique community), 6 (deeper, low relief flank station), and 7 (T11-1 the deep farfield southern reference station) also separated somewhat from the other clusters, with a little spatial overlap with adjacent clusters. In contrast, the remaining clusters (clusters 1 to 4) had a fair amount of spatial overlap with neighboring clusters in the NMDS space. The overlap of stations indicates that the two dimensional NMDS does not provide a good solution for the data. This lack of a good fit to the data is also shown by the stress value of 0.17. The stress value indicates the degree to which the similarity data fit the solution provided by the NMDS space. Generally stress values below 0.1 provide good solutions with little chance of misinterpretation. Results with stress values between 0.1 and 0.2 are still useful but require more care in interpretation. The data was also run in a three dimensional NMDS space, which provided a better solution with a stress value of 0.12. However, clear graphic representation of the stations in three dimensions was not feasible.

Table 6-6. Abundance (mean number per slide) of selected taxa in clusters defined by classification analysis of hard-bottom stations from 1996 to 2006. Numbers indicating major differences among clusters are highlighted by shading.

Cluster	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Average similarity (percent)	57.16	52.05	62.25	60.34	49.64	54.17	41.47	47.13	45.65	56.02
Coralline algae	**8.08**	**5.63**	**11.37**	**15.48**	-	1.98	1.49	-	-	0.46
Palmaria palmata	**6.37**	1.45	-	-	**3.3**	-	-	-	-	-
Ptilota serrata	**6.86**	-	-	-	-	-	-	-	-	-
juvenile *Asterias*	**3.98**	**5.1**	**2.39**	**6.47**	**3.84**	**2.32**	1.16	1.58	2.11	0.61
Didemnum albidum	1.33	**3.8**	-	1.69	1.55	-	-	-	-	-
Aplidium spp.	1.21	1.88	**2.7**	-	-	0.6	-	-	-	-
Modiolus modiolus	3.33	1.87	1.98	**5.22**	2.07	0.22	1.48	-	-	-
Henricia sanguinolenta	1.16	1.37	0.53	1.66	**2.78**	0.35	-	-	-	-
orange/tan encrusting sponge	1.16	2.61	1.15	1.07	1.92	1.35	2.82	1.45	-	-
orange encrusting sponge	1.08	1.34	-	0.88	0.99	0.26	1.52	-	-	-
Asterias vulgaris	-	1.11	-	1.63	-	0.77	-	-	1.28	0.39
Myxicola infundibulum	-	0.55	-	-	-	-	-	-	-	-
Terebratulina septentrionalis	-	3.17	-	-	1.91	-	**18.24**	-	-	-
Dendrodoa carnea	-	1.01	0.78	1.01	0.78	-	-	-	-	-
Balanus spp.	-	-	0.7	-	-	0.35	-	**52.77**	-	-
Strongylocentrotus droebachiensis	-	-	-	0.92	-	-	-	-	-	-
Gersemia rubiformis	-	-	-	-	**4.68**	-	-	-	-	-
Polymastia sp. A	-	-	-	-	0.89	-	-	-	-	-
Aplysilla sulphurea	-	-	-	-	0.64	-	0.63	-	-	-
Suberites spp.	-	-	-	-	-	0.23	-	-	-	-
white divided sponge	-	-	-	-	-	-	8.06	-	-	-
pink fuzzy sponge	-	-	-	-	-	-	0.43	-	-	-
Metridium senile	-	-	-	-	-	-	-	6.21	**37.94**	-
Halocynthia pyriformis	-	-	-	-	-	-	-	-	**8.25**	-
Placopecten magellanicus	-	-	-	-	-	-	-	-	-	0.45
Cancer sp.	-	-	-	-	-	-	-	-	-	0.15
Tautogolabrus adspersus	1.85	1.44	-	2.5	**3.05**	0.21	-	-	-	-

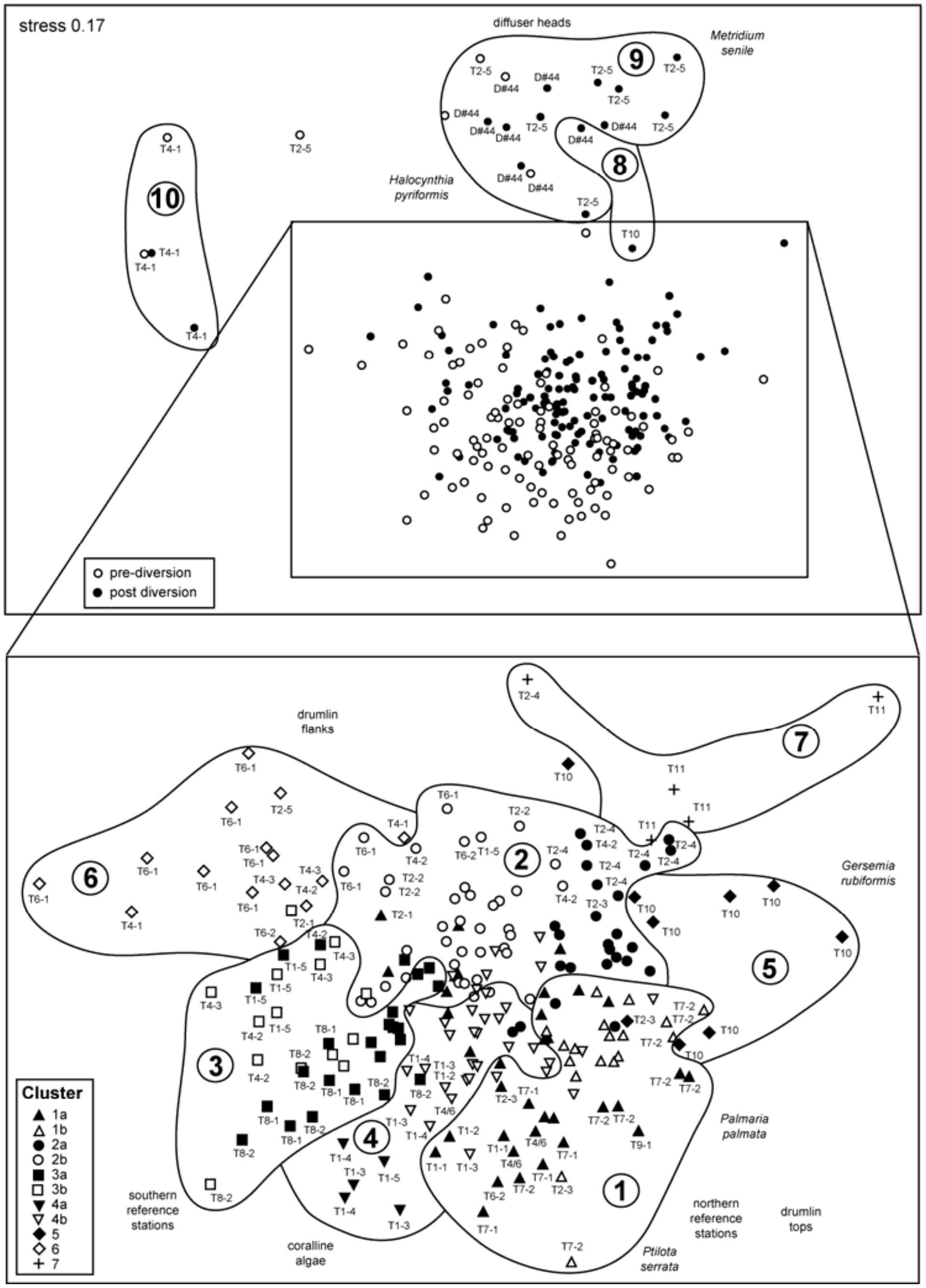


Figure 6-15. Non-metric multidimensional scaling plot of data collected from still photographs taken during the 1996 to 2006 nearfield hard-bottom surveys, with cluster designations from hierarchical classification superimposed.

Several points illustrated by the NMDS analysis were notable. Different years at a station were frequently close in NMDS space, even if they were in different clusters. A good example of this can be seen at the boundary between clusters 2 and 6, where three years at station T6-1 were in cluster 2 yet were in close proximity to the cluster 6 space (mostly T6-1 from other years). Numerous other instances of this phenomenon were also noted. Another interesting observation was a subtle shift of points representing the post-diversion period toward the upper right of the NMDS space. This shift may reflect subtle long-term changes in fauna over time or it may reflect changes due to outfall diversion. This shift in NMDS space may represent the decrease in coralline algae observed over time, since stations with high percent cover of coralline algae (cluster 4a) were located toward the bottom of the ordination space.

The benthic communities inhabiting the hard-bottom areas have been relatively stable over the years, with many of the sites remaining relatively unchanged from year to year. Figure 6-16 shows a map of the cluster designations of the hard-bottom stations over time. The benthic communities at both the northern (T7-1, T7-2, and T9-1) and southern (T8-1 and T8-2) reference stations have remained quite stable, with communities at the northern stations consistently dominated by upright algae and communities at the southern stations consistently dominated by coralline algae. A decrease in upright algae during the last four years has been noted at T9-1 and this is reflected by shifts in the cluster designation. Changes noted at T7-2 in 2006, where physical disturbance from LNG tanker anchorages occurred, are also reflected in a shift in cluster designation. The shallow drumlin top stations north (T1-2, T1-3, and T1-4) and south (T4/6-1) of the outfall have also remained relatively stable during both the pre- and post-diversion periods. Benthic communities at these stations have consistently been dominated by coralline algae, even though coralline algae have been decreasing over time. Both T1-3 and T1-4 had exceptionally high cover of coralline algae in 1996 and 1997. The benthic communities inhabiting the flank stations appear to be slightly more variable over time. However, this may just partially reflect greater spatial heterogeneity in terms of habitat characteristics. Additionally, the close proximity of different years of these stations on the NMDS plot indicates that the benthic communities have not changed substantially over time. One flank station that has remained quite stable was T6-1, a low-relief deep station south of the outfall, which supports a relatively depauperate fauna. No consistent shifts in community structure could be detected when comparing the pre- and post-diversion periods.

The taxa inhabiting the diffuser heads of the outfall have remained stable over time and did not change when the outfall went on line. The diffuser heads continue to provide suitable substrate for many frilled anemones (*Metridium senile*) and sea peach tunicates (*Halocynthia pyriformis*). The different cluster designation of T2-5 in 1998 occurred because the diffuser head was not found that year and only the surrounding sediment and riprap were surveyed. The differing cluster designation of Diffuser #44 in 2003 reflected the large barnacle settlement event, where the entire top was covered by barnacles. By 2004 the barnacles had all died and the community reverted to being dominated by sea peach tunicates. Additionally, the riprap in the immediate vicinity of the diffuser heads continues to be colonized by a variety of encrusting organisms.

Table 6-7, which includes only sites sampled every year, highlights several trends that appear to reflect widespread temporal changes in the population structure of individual taxa that have been noted over the time course of the nearfield hard-bottom surveys. These changes do not appear to be related to the outfall discharge, since they started before the outfall went on line and have continued post discharge. When only sites that were surveyed in each of the years are taken into account, several patterns become apparent. Abundances of the green sea urchin *Strongylocentrotus droebachiensis* appear to follow a cyclical pattern, declining from 0.88 individuals per photograph in 1996 to 0.26 individuals per photograph in 2000, then increasing slightly in 2001 and 2002 (0.31 and 0.38 individuals per photograph, respectively), and again decreasing between 2003 and 2006 (<0.23 individuals per photograph). Two other species, the crab *Cancer* sp. and the lobster *Homarus americanus*, increased until 2002 and 2003, respectively, and then started decreasing.

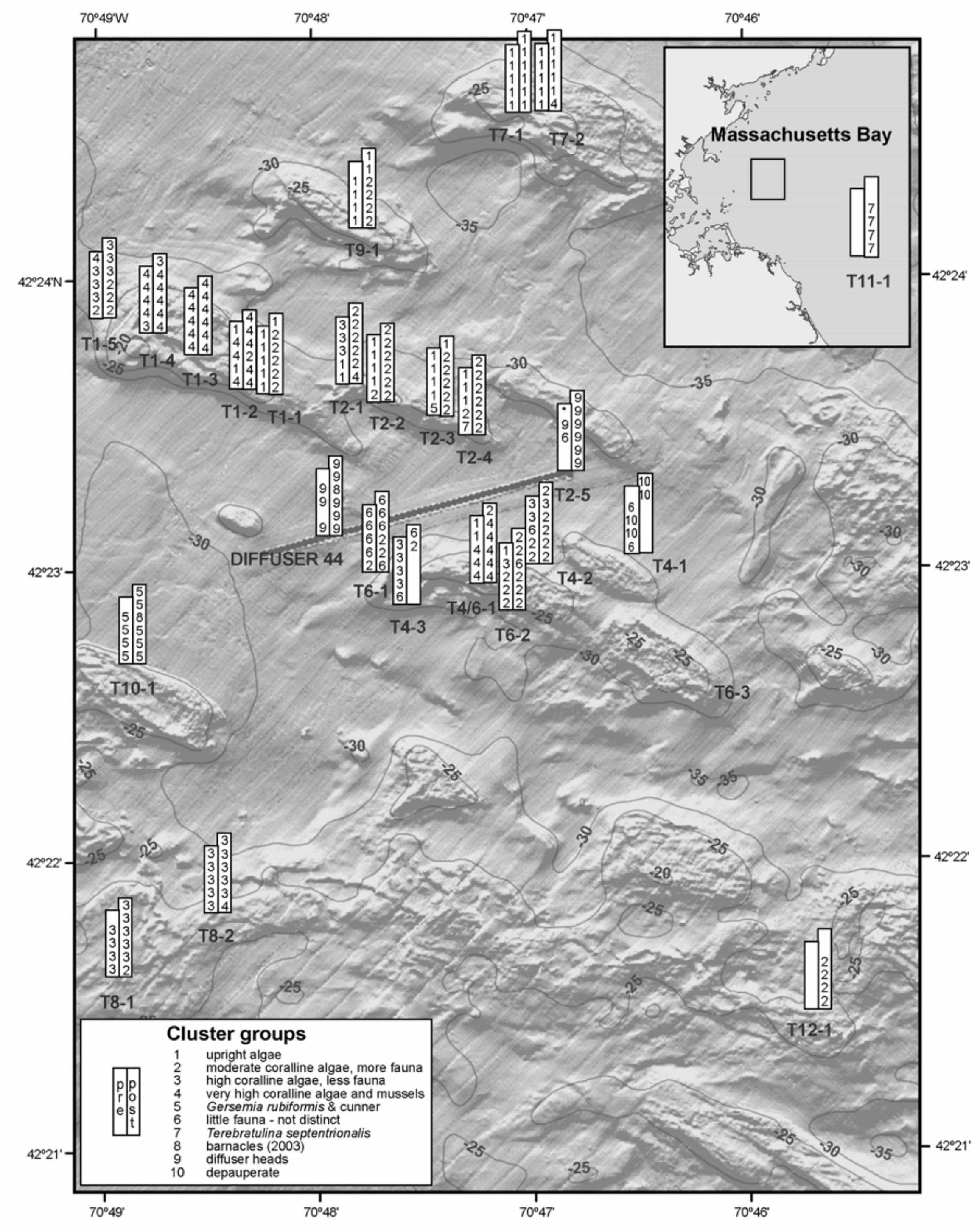


Figure 6-16. Benthic communities defined from classification of the 35-mm images taken during the 1996 to 2006 nearfield hard-bottom surveys. Bars show the successive years in the pre- and post-diversion periods. Asterisks indicate no cluster designation.

Table 6-7. Number of individuals of selected species observed during the nearfield hard-bottom surveys, adjusted to include only stations that were surveyed in all 11 years (with the exception of two stations added after 1996).

	Pre-discharge					Post-discharge					
	1996*	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**	**2004**	**2005**	**2006**
Video											
Minutes of video	381	471	385	422	431	397	450	428	417	424	377
Cancer spp. (rock crab)	5	3	4	15	72	118	164	144	112	66	80
Gadus morhua (cod)	-	6	12	22	11	27	38	7	39	58	52
Homarus americanus (lobster)	6	2	11	4	18	21	30	32	12	10	35
Still Photographs											
Number of photographs	501	504	575	551	603	525	618	604	614	605	606
Strongylocentrotus droebachiensis	441	339	281	299	155	164	232	89	110	77	140
Cancer spp. (rock crab)	4	1	4	6	13	44	60	46	14	21	56
Gadus morhua (cod)	-	-	2	3	-	7	11	-	2	9	5
Homarus americanus (lobster)	1	-	3	3	5	4	13	6	5	9	19

* did not include T9-1 and T10-1

In the still photographs, *Cancer* crabs increased from one to six individuals seen annually between 1996 and 1999, to 60 individuals seen in 2002, decreased in 2004 and 2005, and increased again to 56 individuals in 2006. A similar pattern was reflected in the video data, with 3 to 15 *Cancer* crabs observed annually between 1996 and 1999, increasing to 164 individuals in 2002, and decreasing again in 2004 to 2006. The video data for lobsters showed a similar trend, with the highest numbers of lobsters being seen in 2002, 2003, and 2006. With the exception of 2003, the number of cod observed during these surveys has steadily increased over time, with the highest numbers of cod observed during the last two years. Prior to the outfall going on-line, no cod had been seen at the diffuser stations, yet in all post-diversion years cod have been seen in the vicinity of both the active (Diffuser #2 at T2-5) and inactive (Diffuser #44) heads. Additionally, the codfish appear to be behaving differently at the outfall than at the other hard-bottom stations. At most of the stations codfish tend to shy away from the ROV, usually ducking behind large boulders, but at the diffuser sites they were much less hesitant and occasionally came right up to the vehicle. The presence of numerous cod in the vicinity of the outfall was particularly noticeable during a visual structural survey of the diffuser heads that was conducted in June of 2003, where the presence of codfish was frequently used as an indicator of proximity to an actively discharging diffuser head.

6.4 Monitoring Question

Has the hard-bottom community changed? (Question #30)

The hard-bottom benthic communities near the outfall remained relatively stable over the 1996 to 2000 baseline time period, and have not substantially changed with activation of the outfall in fall 2000. Major departures from baseline conditions have not occurred during the post-diversion years, however some modest changes have been observed. A decrease in the number of upright algae has been observed at many of the stations. However, it is unlikely that this decrease was attributable to diversion of the outfall, since the general decline had started in the late 1990s and the number of upright algae appears to be increasing again at a number of stations. The decline has been quite pronounced at the northern reference stations and may, in part, reflect an increase in anchoring frequency of LNG tankers at these locations after September 11, 2001. Abundances of upright algae were found to be quite variable throughout the baseline period, reflecting temporal changes in abundance as well as spatial heterogeneity in habitat characteristics. Some of the variability has continued into the post-diversion period and may also reflect inherent cyclical changes.

Another post-discharge change that has been observed in the hard-bottom communities has been an increase in sediment drape, and a concurrent decrease in percent cover of coralline algae, at several sites on the top of the drumlin north of the outfall and at the two northernmost reference sites (Figure 6-17). The decrease in coralline algae has been noticeable in all six post-diversion years. Additionally, in 2005 this decrease was more pronounced and extended to eight additional stations, located both north and south of the outfall. The dramatic decreases first observed in 2005 were not accompanied by concurrent increases in sediment drape and have extended into 2006. The baseline data indicated that coralline algae was the most promising indicator species for detecting habitat degradation as a result of the outfall coming on line. It was the most predictable taxon encountered in terms of abundance, distributional pattern, and habitat requirements. Coralline algae was the least patchily distributed taxon, dominated in all areas that were shallower than 33 m and had little sediment drape, and was common in areas of both high and low relief. Mechanisms relating the decrease in coralline algae to outfall diversion are not as clear, since the impact was noted further from the outfall rather than nearby. It is possible that some of the decreases in coralline algae noted at the northern reference stations are related to an increase in anchoring activity at these stations, and that the decreases closer to the outfall are related to the diversion. However, it is also possible that we are observing long-term changes in sedimentation, and hence coralline algae, patterns. However, similar declines of percent cover of coralline algae have not been observed at another site at 27 m in Massachusetts Bay surveyed for an unrelated project (Hecker, personal observation).

The outfall might be expected to alter the amount of particulate material reaching the seafloor. A continued increase of sediment drape, and/or a continued decrease in the percent cover of coralline algae might be expected if the discharge from the outfall were causing accumulation of materials in the vicinity of the drumlins. Changes might also be expected in the depth distribution of coralline algae and upright algae if discharges from the outfall alter properties of the water column that affect light penetration. If water clarity is reduced it is expected that the lower depth limit of both coralline and upright algae would be reduced. Conversely, if water clarity were increased, then it is expected that high coralline algal coverage or upright algae could extend into some of the deeper areas. No noticeable changes in the depth distribution of coralline algae have been observed since discharge began. Additionally, the decline observed in the numbers of upright algae in recent years appears to be reversing.

The first six years of discharge monitoring, have shown modest changes suggestive of outfall impact at a subset of 5 stations, and some additional subtler changes at a number of other stations. However, two of the five stations in this subset may have been compromised as “reference” stations by post-9/11 increases in anchoring activity of LNG tankers, and their physical disturbances of the seafloor at these sites. Evidence of substantial disturbance to the seafloor, such as turned over boulders and a large area of shell lag, was observed this year at northern reference site T7-2. Lush epifaunal growth continues to thrive on the diffuser heads surveyed for this study and throughout many of the other stations visited. However, despite the fact that outfall impacts appear to be minimal at this time, changes in the hard-bottom communities could be chronic and/or cumulative, and may take a longer time to manifest themselves.

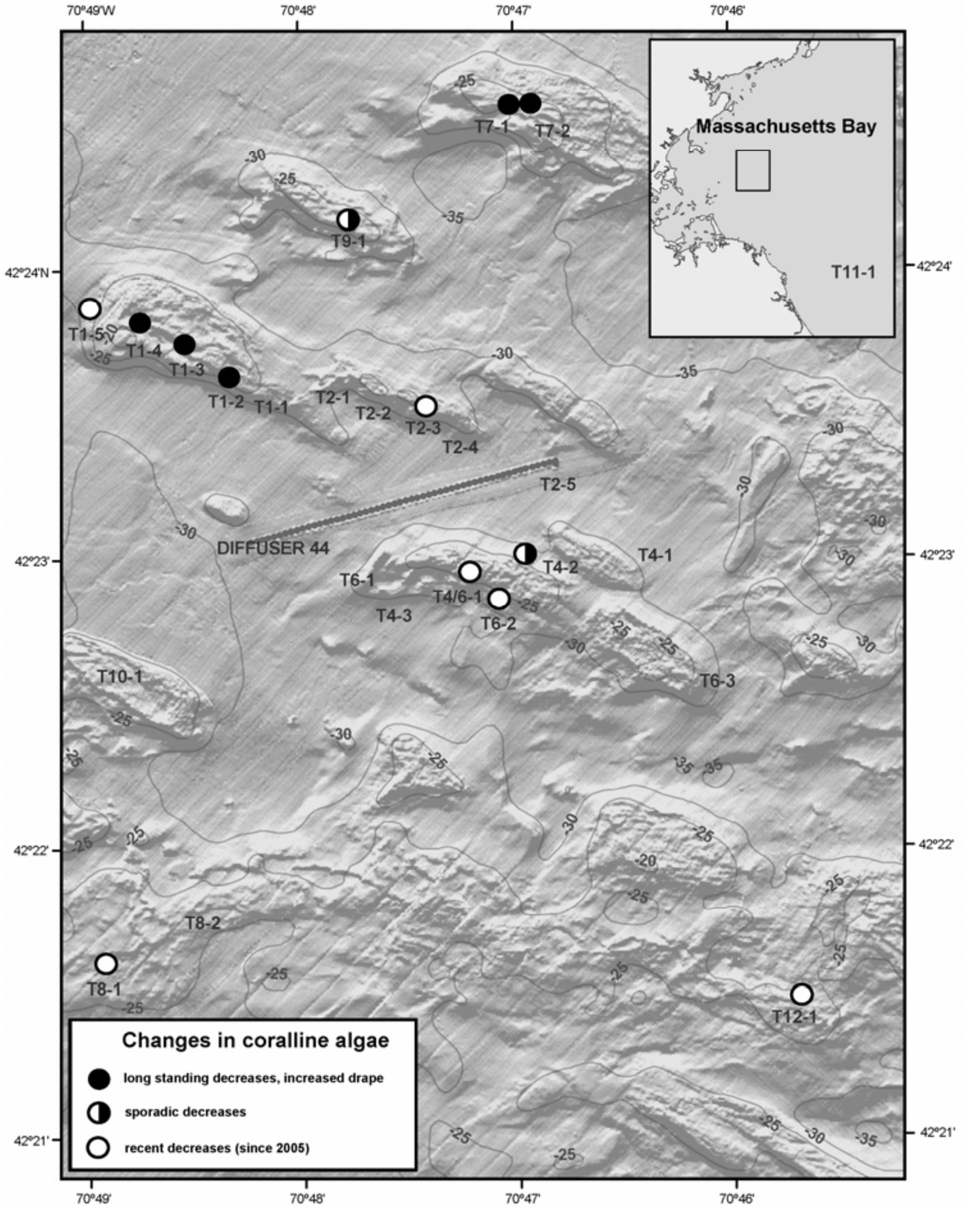


Figure 6-17. Changes observed in percent cover of coralline algae.

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