2005 Outfall Benthic Monitoring Report

Massachusetts Water Resources Authority

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2005 Outfall Benthic Monitoring Report

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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 2005, 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 prior to diversion of effluent discharge (1992–2000) ranged from undetected to 24,100 colony forming units per grams dry weight (Figure 1). In general, *C. perfringens* abundances were low throughout the bay, with higher levels observed closer to Boston Harbor. Abundances generally decreased with distance from the harbor, with farfield sediments located far way 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 mean abundances (normalized to percent fines) decreased between 1992 and 2000 while treatment upgrades were implemented (Figure 1, right). The post-diversion data (2001–2005) suggest a localized increase in the abundances of *C. perfringens* (normalized to percent fines) at nearfield stations located within 2 km of the Massachusetts Bay outfall. In contrast, the post-diversion mean abundances of *C. perfringens* (log-transformed) 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.

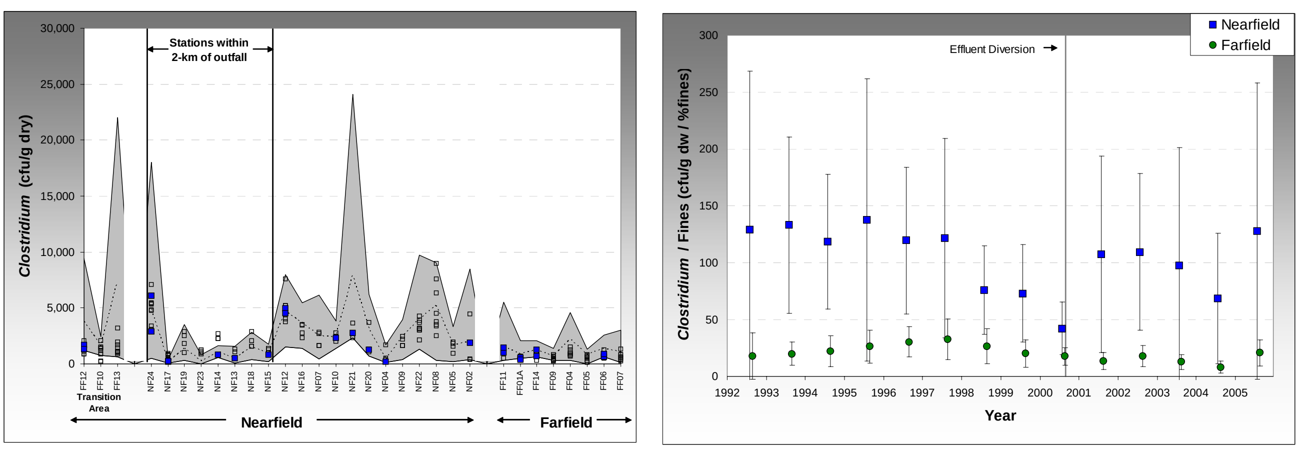

Figure 1. Abundances of *Clostridium perfringens* (left) in nearfield and farfield sediments during baseline (1992–2000 range of values, gray band) and post-diversion (▫ 2001-2004 and the ▪ 2005) periods. (The baseline mean values are indicated by a dashed line within the gray band.) Yearly mean abundance of *Clostridium perfringens* (normalized to percent fines, right) in nearfield and farfield sediments, 1992–2005.

Sediment Contaminants

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

The monitoring data from 1992 to 2005 show some subtle but localized changes in concentrations of anthropogenic contaminants in Massachusetts and Cape Cod Bays, which appear to reflect differences in bulk sediment characteristics such as grain-size distribution and TOC content, rather than an outfall impact. For example, concentrations of some anthropogenic contaminants (*e.g.,* aluminum, iron and nickel), which are primarily crustal in nature, decreased in 2005 compared with other post-diversion data (Figure 2). The observed decrease in 2005 is likely associated with a loss of fines, which has been attributed to storm activity from the May 2005 nor'easters. The monitoring data also show that the post-diversion mean concentrations of total DDT in the nearfield (excluding the transition area) and farfield have decreased significantly compared to the baseline mean value. A post-diversion decrease in total PCB was also observed in the farfield. These observed decreases may be associated with the banning of DDTs and PCBs in the 1970s and 1980s. Overall, in the first five years following effluent diversion, concentrations of most anthropogenic contaminants (except total DDT and total PCB) have not changed substantively compared with the baseline (1992–2000).

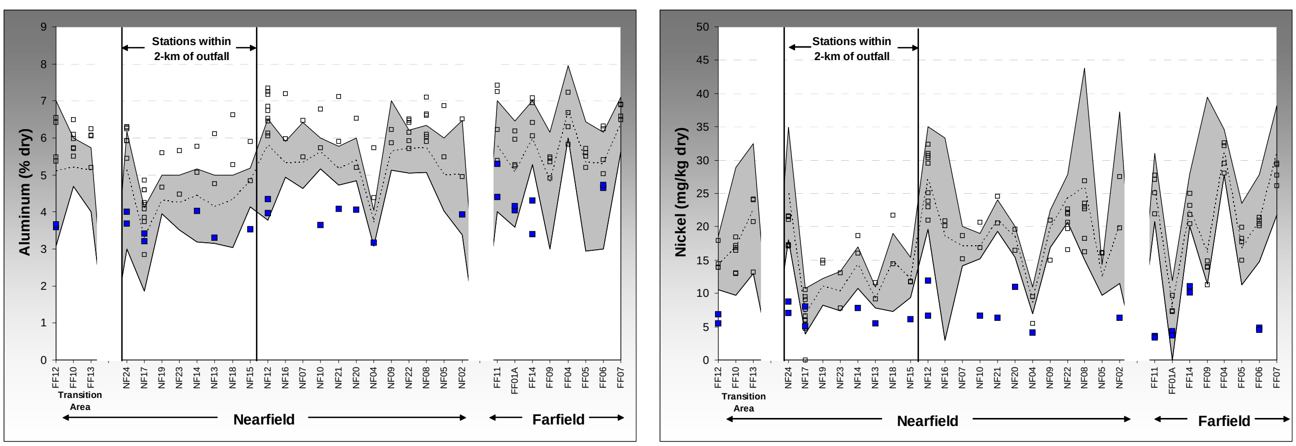

Figure 2. Concentrations of aluminum (left) and nickel (right) in nearfield and farfield sediments during baseline (1992–2000 range of values, gray band) and post-diversion (▫ 2001-2004 and the ▪ 2005) periods. (The baseline mean values are indicated by a dashed line within the gray band.)

Sediment Redox Potential Layer

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

There do not appear to be any regional trends between RPD layer depth and the outfall, which started operation in September 2000. 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 2005 of 2.6 cm was not significantly different from the baseline RPD of 2.3 cm. A 50% shallowing in RPD layer depth would require the mean RPD for a year to be 1.2 cm or less. The average RPD for 2005 was well within the range of annual RPDs, with 1998 being the shallowest year at 1.6 cm and 1995 the deepest year at 3.0 cm (Figure 3).

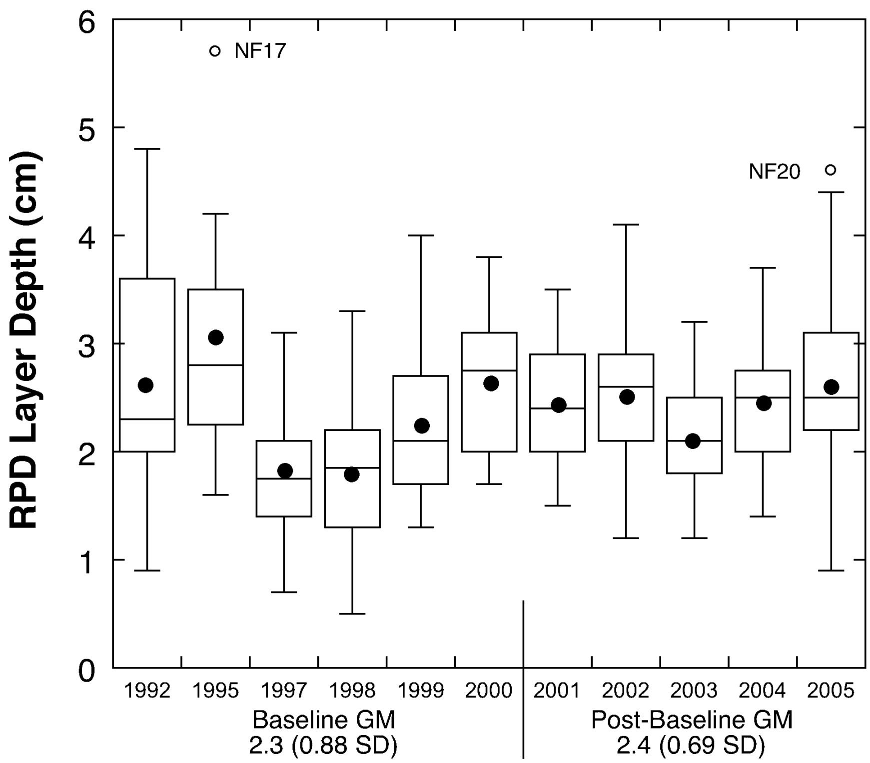

Figure 3. Apparent color RPD layer depth (cm) summarized by year for all data from nearfield stations. Box is interquartile range (IR), bar is median, circle is mean, and whiskers are data range. Outliers are >(2*IR).

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 (Figure 4). From 1997 *(i.e.*, the start of annual sampling) to 2005, nine stations had measurable RPD layer depths for all years. There was a general concordance between these nine stations and time with a significant deepening trend from 1997 to 2000 for both the four stations within the topographic feature that contains the outfall and the five stations in other features. Post-diversion—from 2001 to 2005—there were no significant trends in RPD layer depth for these nine stations.

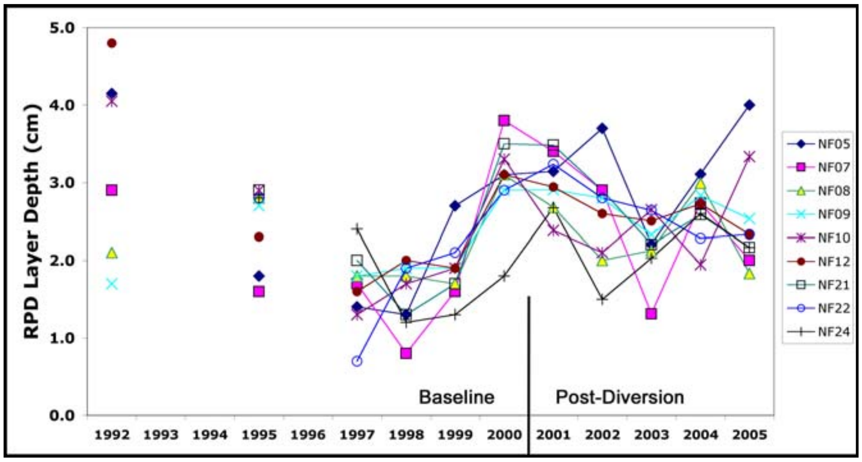

Figure 4. Apparent color RPD layer depth (cm) for the nine nearfield stations that had measured values for all years.

Based on the color and texture of sediments in the 2005 SPI images (Figure 5), there was little change in the sedimentary environment relative to baseline or other postdiversion years. Within a station, there did not appear to be any change in the sediment color or fabric, which would indicate there has not been an accumulation of organic matter in surface sediments of the nearfield stations. Similar conclusions were drawn from the TOC analysis and sediment flux studies (this report and Tucker *et al*. 2006).

Figure 5. SPI image from NF24, taken in August 2005.

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 of total infaunal density, species composition and richness, and, to a lesser extent, diversity. Infaunal abundance (per sample) had increased by 2003 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, *e.g*., *Prionospio steenstrupi*, which replaced another spionid polychaete, *Spio limicola*, as the dominant at the medium- to fine-grained stations. Species richness also increased, in 2003 reaching the highest mean values in both the nearfield and farfield areas. some of the calculated parameters appeared to fluctuate in a sine-wave-like pattern, with increases followed by declines (Figure 5-6). The apex values for density and species richness seen in 2003 were in fact followed by lower values in 2004, and again by a further decline in 2005. *P. steenstrupi* declined in abundance, and all calculated parameters also decreased, including species richness, Shannon diversity, evenness and log-series *alpha*. Species richness and *alpha* also declined in the farfield, but Shannon diversity and evenness increased at those stations (Figure 5-6). Although the subset of stations sampled in 2005 differed from those sampled in 2004, the decline in mean station parameters appears to be real when compared with the same subset of stations in 2003. However, based on the statistical analyses performed on the 2005 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 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* have suggested a modest impact of the discharge. The changes that have been documented in the benthic communities appear to be unrelated to 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 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 slight 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. 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. This variability of has continued into the post-diversion period and appears to reflect inherent cyclical changes.

Another post-discharge change that has been observed in the hard-bottom communities is 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. The decrease in coralline algae has been noticeable in all five 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 observed in 2005 were not accompanied by concurrent increases in sediment drape. 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.

The outfall might be expected to alter the amount of particulate material reaching the sea floor. 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 five years of discharge monitoring have shown only modest changes suggestive of outfall impact at a subset of five stations, and some additional subtler changes at a number of other stations. Lush epifaunal growth continues to thrive on the diffuser heads surveyed for this study (Figure 7), 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.

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 indicates only modest impacts at stations closest to the discharge, and no evidence for outfall-related change in the farfield. The only change that appears to be directly related to the operation of the outfall is a localized increase in the abundance of the sewage tracer *Clostridium perfringens* at stations located within 2 km of the discharge. Other changes, such as levels of anthropogenic contaminants 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.

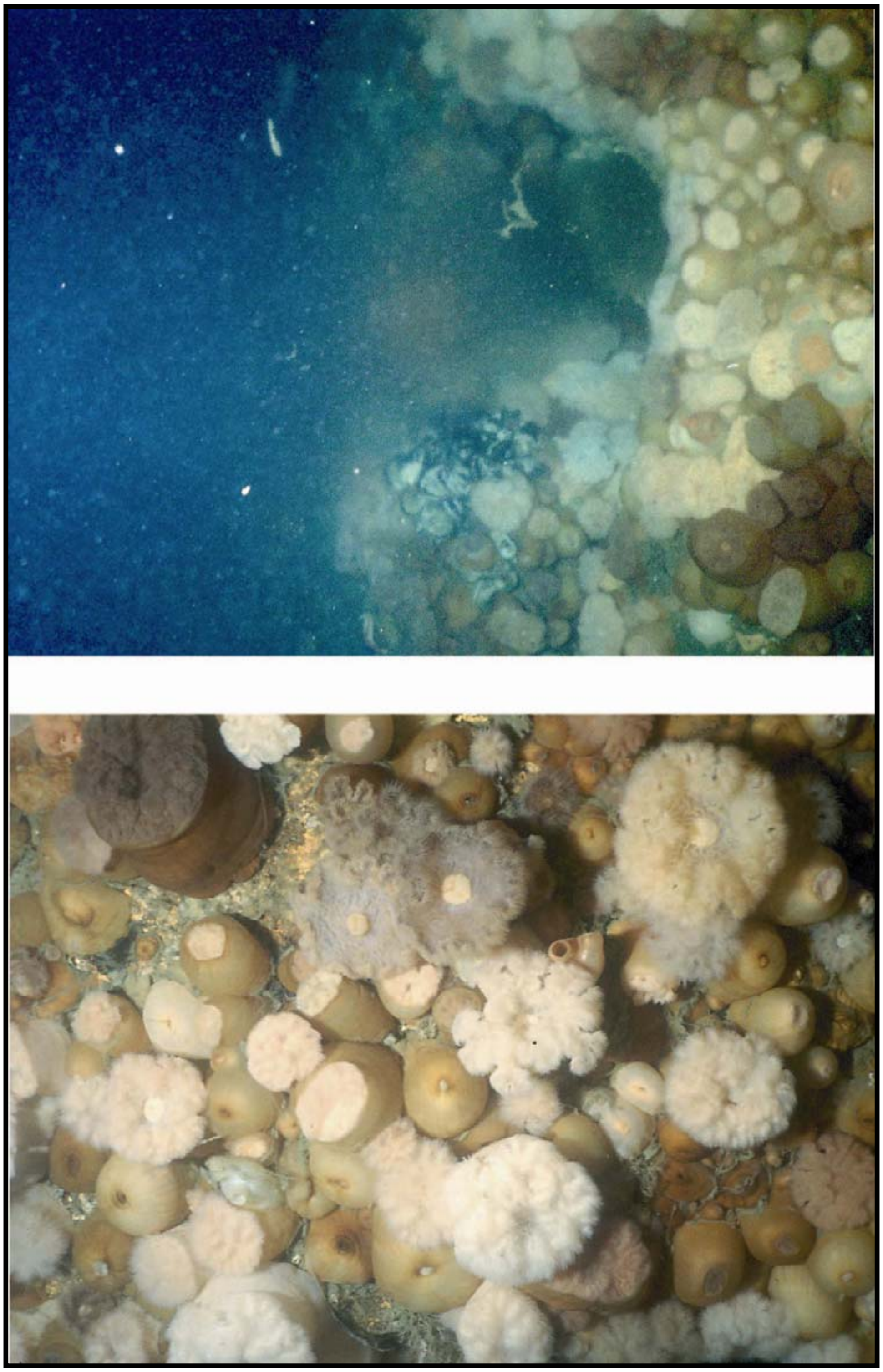

Figure 7. Photographs of the head of the active diffuser at T2-5 (Diffuser #2). The upper photograph shows numerous frilly anemones *Metridium senile* surrounding the discharge port, as well as a clump of horse mussels *Modiolus modiolus* immediately below it. The lower photograph shows the dense aggregations of *M. senile* seen on the remainder of the head, as well as a few sea peach tunicates *Halocynthia pyriformis*.

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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	Naphthalene	None	2100 ppb dry
	Nickel	None	51.6 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	3	2	2
2004 replicated nearfield (2 stations)	FF10, FF13	2004	3	0	2
2004 unreplicated nearfield (9 stations)	NF05, NF07, NF08, NF09, NF16, NF18, NF19, NF22, NF23	2004	1	0	1
2004 farfield (4 stations)	FF04, FF05, FF07, FF09	2004	3	0	2
2005 replicated nearfield (2 stations)	FF12, NF24	2005	3	2	2
2005 unreplicated nearfield (8 stations)	NF02, NF04, NF10, NF13, NF14, NF15, NF20, NF21	2005	1	1	1
2005 farfield (4 stations)	FF01A, FF06, FF11, FF14	2005	3	2	2

2. 2005 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). There was no sampling in the Stellwagen Bank National Marine Sanctuary in August 2005. Target locations for all soft-sediment stations are given in Table 2-1, and the actual station data for each biology and chemistry grab sample collected, along with a brief description of each, are in Appendix A1. In 2005, sediment grab samples were collected at 12 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 color 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 2005, sediment profile images were taken at all 23 nearfield stations. Specific locations of all sediment profile images collected in 2005 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 and SPI surveys in 2005 were conducted on Battelle's research vessel, the R/V *Aquamonitor*. The hard-bottom survey was performed using the F*/V Atlantis*, owned by Troy Dwyer and contracted through C.R. Environmental. 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.

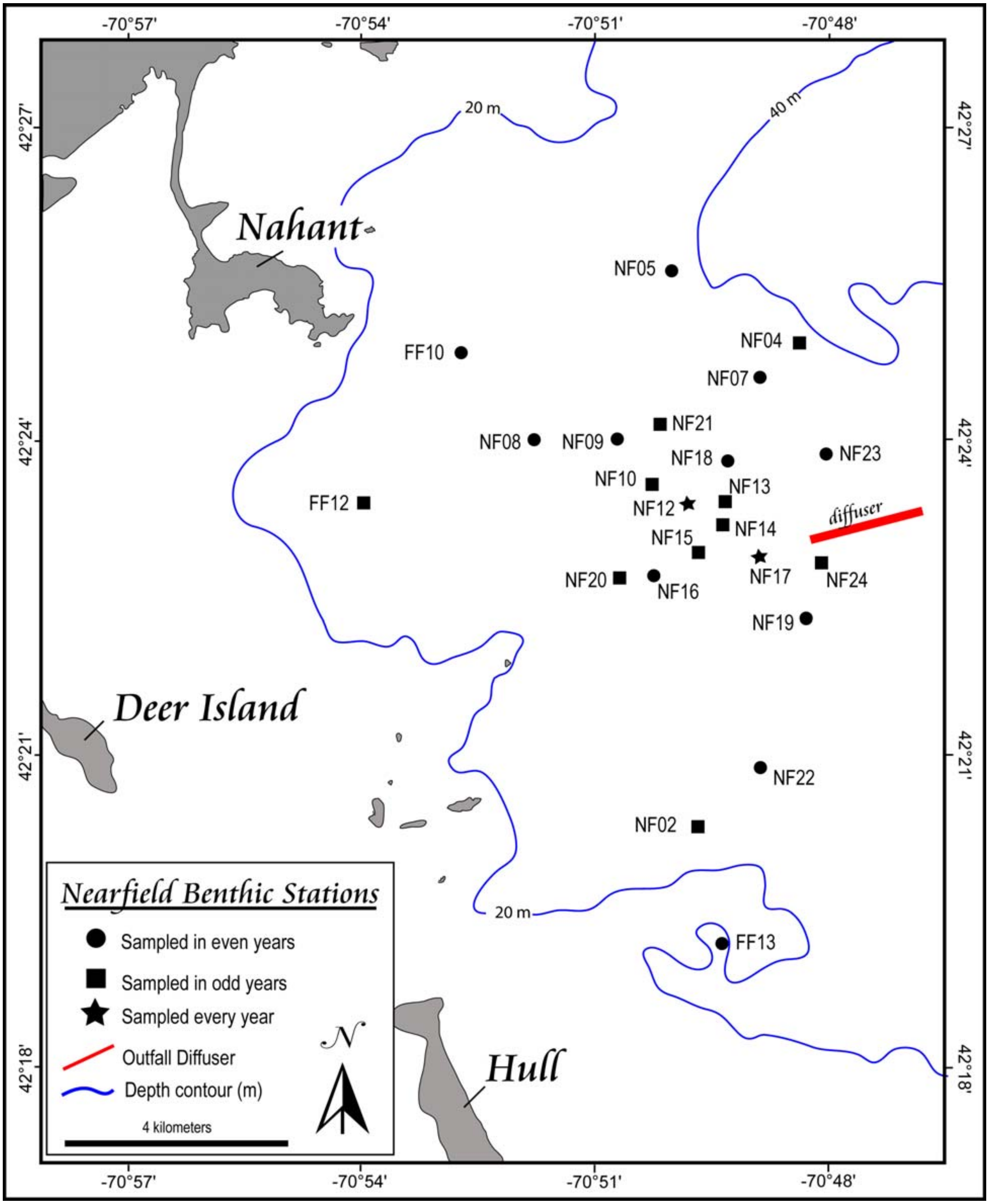


Figure 2-1. Locations of nearfield stations sampled in August 2005. All stations were sampled by SPI and those denoted by squares and star symbols were sampled by grab.

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

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

[1]Stations sampled by SPI in 2005 (all NF stations)
[2]Stations sampled by grab in 2005 (12 NF and 4 FF stations)
[3]Farfield stations not sampled in 2005

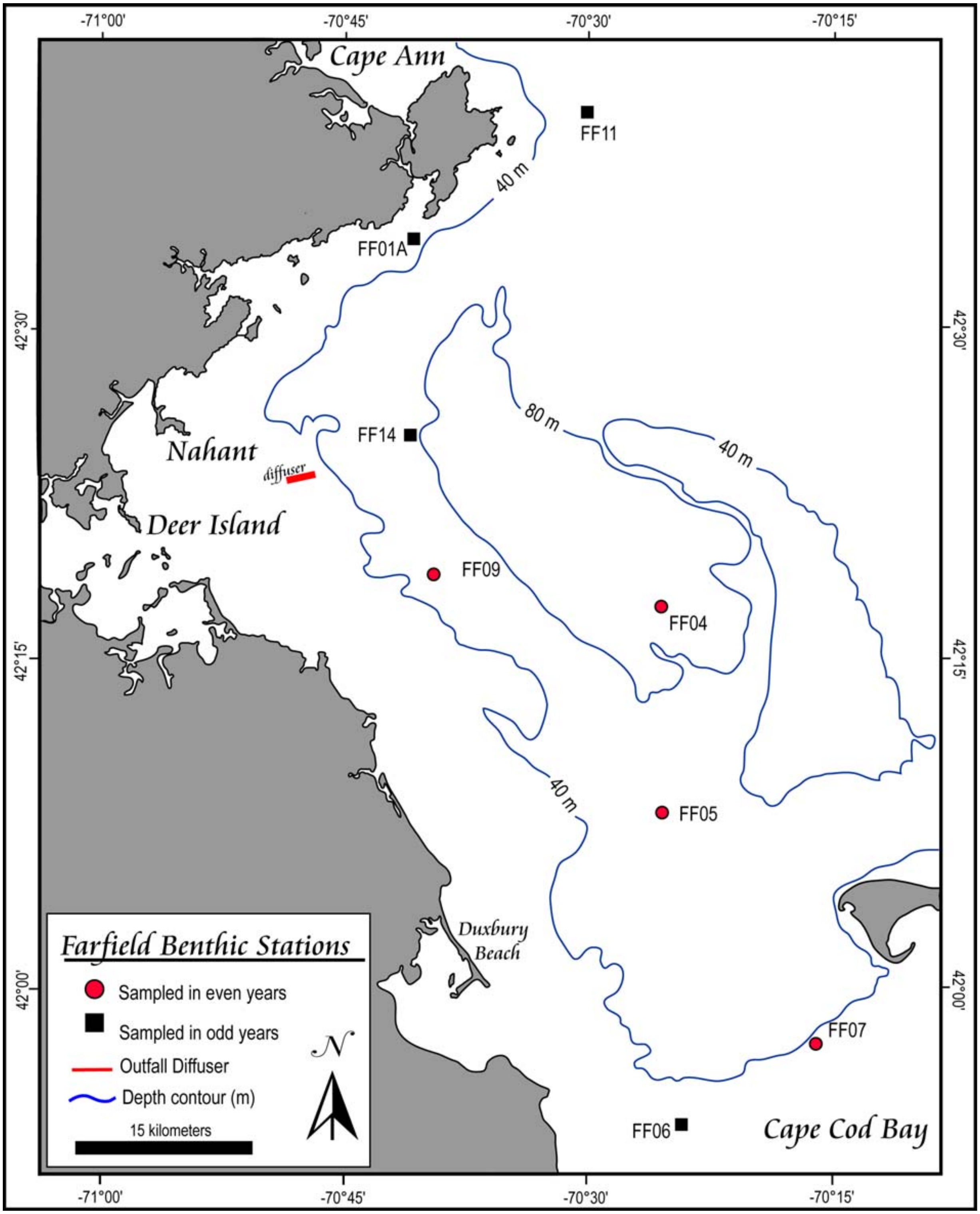


Figure 2-2. Locations of farfield grab stations sampled in August 2005.

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

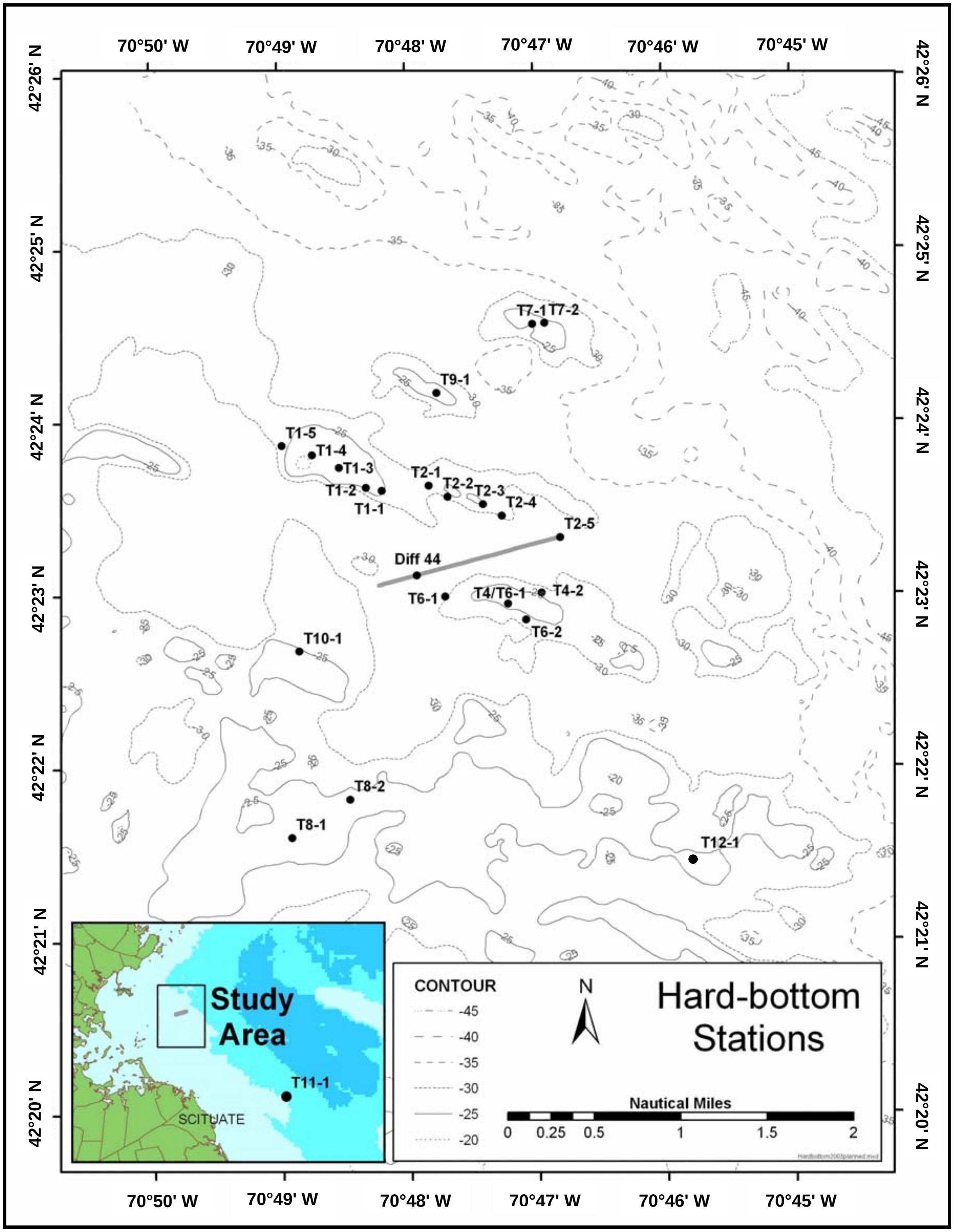


Figure 2-3. Hard-bottom stations sampled in June 2005.

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 2005, two sampling protocols were used for the sixteen stations sampled during the Nearfield/Farfield Benthic Survey BN051/BF051.

- At four nearfield stations, FF12, NF12, NF17, and NF24 and four farfield stations, FF01A, FF06, FF11, and FF14, three replicate samples for infaunal analysis and two replicate samples for chemical analyses were collected.

- At eight nearfield stations, NF02, NF04, NF10, NF13, NF14, NF15, NF20, and NF21, one faunal and one chemistry grab sample were collected.

Samples for total organic carbon , sediment grain size, and *Clostridium perfringens* as well as organic and metal contaminants were collected from all 16 stations. 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 2005.

Survey Type	Survey ID	2005 Date(s)	Samples Collected									
			Inf	TOC	GS	Cp	Org	TM	SPI	35	V	DVD
Nearfield Benthic	BN051	1-2 Aug	20	16	16	16	16	16				
Farfield Benthic	BF051	1 and 4 Aug	12	8	8	8	8	8				
SPI	BR051	22 Aug							71			
Hard-bottom	BH051	20–24 June								~750	~500	6

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. Robert Diaz, Wrenn Diaz, and Derek Kibler were SPI Specialists for the 2005 SPI Survey (BR051). 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 two 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. Barbara Hecker was Senior Scientist for the 2005 Hard-bottom Nearfield Survey (BH051) during which 23 waypoints were visited (Table 2-2; Appendix A-3). An Outland Technology "Outland 1000" ROV equipped with Outland Technology's 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 (DVD) also were produced as the ROV was filming the hard-bottom stations.

3. 2005 CHEMISTRY

by Deirdre T. Dahlen and Carlton D. Hunt

3.1 Introduction

The MWRA was created in 1985 with a mandate for short-term and long-term remediation activities to decrease anthropogenic contamination discharge into the harbor. Remediation activities are discussed in detail in Section 1.1; key actions included abatement of sewage sludge discharge into the harbor in late 1991, primary treatment in 1995, secondary treatment which was achieved in phases from 1998 to 2001, and diversion of secondarily treated effluent discharge to the Massachusetts Bay outfall in 2000.

A recent review on toxic contaminant issues in Boston Harbor and Massachusetts and Cape Cod Bays (Hunt *et al.* 2005) documents that the remediation activities 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 2005 Toxics Issue Review (Hunt *et al.* 2006) show that contaminant-related impacts have not been detected in the coastal environment from the diversion of effluent into Massachusetts Bay in September 2000. Moreover, although some influence of the Massachusetts Bay outfall discharge on nearby sediments has been found (Dahlen *et al.* In Press), the effluent has not caused substantive changes in the quality of the environment near to or far from the outfall location nor has the discharge acutely impacted marine life in the vicinity of the outfall and Bay at large.

2005 represents the most comprehensive sampling in Massachusetts Bay for anthropogenic contaminants since 2002. Results from the 2005 monitoring are evaluated in the context of the conclusions reached in Hunt *et al.* (2006), and more importantly, to assess the system response five years since outfall startup. Sediment contaminant data from 2005 are also discussed in context of the May 2005 nor'easters that brought strong winds, heavy rainfall, and coastal flooding to eastern Massachusetts.

3.2 Methods

Benthic investigations have been conducted 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 in 2003–2005. In 2003 and 2004, only nearfield stations NF12 and NF17 were sampled. In 2005 a more comprehensive sampling effort was conducted; *i.e*., 12 nearfield (FF12, NF02, NF04, NF10, NF12, NF13, NF14, NF15, NF17, NF20, NF21 and NF24) and four farfield (FF01A, FF06, FF11 and FF14) stations were sampled (Figures 2-1 and 2-2).

Surface sediment samples collected in 2005 were analyzed for physicochemical, microbiological and anthropogenic parameters according to Williams *et al.* (2005). 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 evaluations is 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 Folk (1974). Data were presented in 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 GeoPlan Associates.

Total Organic Carbon (TOC)—Samples were analyzed for TOC by using a DC-190 analyzer following Prasse *et al.* (2004). 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 those developed by Emerson and Cabelli (1982), as modified by Saad (1992). Data are reported here as colony-forming units (cfu) per gram dry weight of sediment. This analysis was performed by MTH Environmental Associates.

3.2.2 Anthropogenic Contaminants

Sediment samples were analyzed for a suite of anthropogenic contaminants including polycyclic aromatic hydrocarbons (PAH), PCBs, pesticides, and inorganic constituents. PAH, PCB, and pesticide analyses were conducted using gas chromatography with mass spectrometry detection. Inorganic constituents, aluminum, chromium, copper, iron, and zinc, were analyzed using flame atomic absorption; cadmium was analyzed using inductively coupled plasma/mass spectrometry; lead, nickel, 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 data from system-wide and station-specific perspectives. Graphical representations of the results are presented as ternary plots, box plots, histograms, and range plots. The total concentration for each contaminant class studied (see Appendix B1) was used in the data evaluations, including total PAH, total PCB, total DDT and total linear alkyl benzenes (total LAB); note that LAB analyses were discontinued in 2004 consistent with revisions to the monitoring plan (MWRA, 2004). In cases where an individual analyte was not detected, a value of zero (0) was used in the summation.

Sediment data (*i.e.,* station mean values) were also evaluated by using statistical analyses, including 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, total LAB, 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 in the baseline and post-diversion means. Output from the test is a comparison circles plot, which is a visual representation of group mean comparisons. 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.

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, yearly mean station values (*i.e.,* average of all station replicates for a given station and year) were compared with published marine effects range-low (ER-L) and effects range-median (ER-M) (Long *et al.* 1995) concentrations using a matrix of stations and 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 1992 to 2005, with focus on how the post-diversion data (2001–2005) compare to the baseline data (1992–2000). Results are presented from system-wide and station-specific perspectives. Stations sampled in 2005 are highlighted, because 2005 represents the most comprehensive sampling for anthropogenic contaminants since 2002. The 2005 results are also discussed in context of the May 2005 nor'easters, which are believed to have affected bulk sediment characteristics and potentially contaminant concentrations in the surface sediments of the Bay (see Sections 3.3.1 and 3.3.2 below). All sediment results are discussed in terms of dry weight.

3.3.1 Sediment Grain Size and Total Organic Carbon 1992–2005

Nearfield stations include a series of locations having heterogeneous sediments (Figure 3-1) located west of the Massachusetts Bay outfall and within 15 km of Boston Harbor. Nearfield stations FF10, FF12, NF02, NF04, NF05, NF13, NF14, NF15, NF17, NF18, NF19, NF20 and NF23 were comprised of coarse-grained sediments; stations NF08, NF12, NF21, and NF24 were comprised of fine-grained sediments; and stations FF13, NF07, NF09, NF10, NF16 and NF22 had more intermediate grain-size composition, with roughly equal percentages of coarse- and fine-grained sediments (ternary plots showing grain-size distribution for each station are provided in Appendix B2). Grain-size distribution at NF24 in 1995 contained an unusually high percentage of clay compared to other monitoring years (Figure 3-1); an explanation for this anomalous result is not evident. Farfield stations were generally comprised of fine-grained sediments, except FF01A and FF09, which were comprised of coarse-grained sediments (Figure 3-1). Further, there appears to be less scatter in the grain size data at most farfield stations (excluding FF01A, FF09, and FF07) following effluent diversion (Figure 3-1).

In general, substantive changes in grain-size and TOC data, between the baseline and post-diversion periods, were difficult to discern due to the high variability among the data, both system-wide (Figure 3-2) and by station (Appendix B2, Figures B2-17 through B-24), except at farfield stations FF04 and FF07 where the post-diversion TOC mean was significantly higher (at the 95% level of confidence) compared to the baseline mean (see Tukey-Kramer means comparison results in Appendix B2). Variability among post-diversion data for sand, silt, and clay content decreased nearly by a factor of two compared to the baseline data at nearfield stations located in the transition area between the mouth of Boston Harbor and the outfall (*i.e.,* FF10, FF12, FF13) and at nearfield stations location within 2 km of the Massachusetts Bay outfall (Appendix B2, Table B2-1). Apparent impacts to the sediment bed associated with storm activity have also been observed in the MWRA data. For example, the percentages of sand and gravel measured in 2005 at nearfield stations NF13, NF14, NF15, NF10, NF17, NF20 and NF21 were high relative to 1992–2004 values (Figure 3-3). This coarsening of sediment grain size was also mirrored by lower TOC content (Figure 3-3), and in some cases lower concentrations of anthropogenic contaminants (see Section 3.3.2). TOC values measured in 2005 were among the lowest values observed in this program at several nearfield and farfield stations (Figure 3-3). The coarsening of grain size and reduced TOC content is likely associated with sediment bed disturbance resulting from the May 2005 nor'easter, the strongest late-May winterlike nor'easter since 1967[1].

[1] According to the National Oceanic and Atmospheric Administration's National Climatic Data Center (NCDC) (http://www4.ncdc.noaa.gov/cgi-win/wwcgi.dll?wwevent~storms) 'an unusually usual late season and long duration nor'easter brought strong winds, heavy rainfall, and coastal flooding to eastern Massachusetts. A preliminary check suggested this was the worst late May winterlike nor'easter since May 25-26, 1967. Moderate coastal flooding occurred during two high tide cycles. Numerous shore roads along the eastern Massachusetts coast were flooded to the extent of being impassible for a time. Considerable rock and sand debris were washed onto shore roads, and there were spotty reports of damage to structures.' According to NCDC, the nor'easter was approximately nine hours in durations, beginning at May 24, 2005 at 2:50PM and ending at May 24, 2005 at 11:35PM. The magnitude of storm is reported by NCDC as 50 knots.

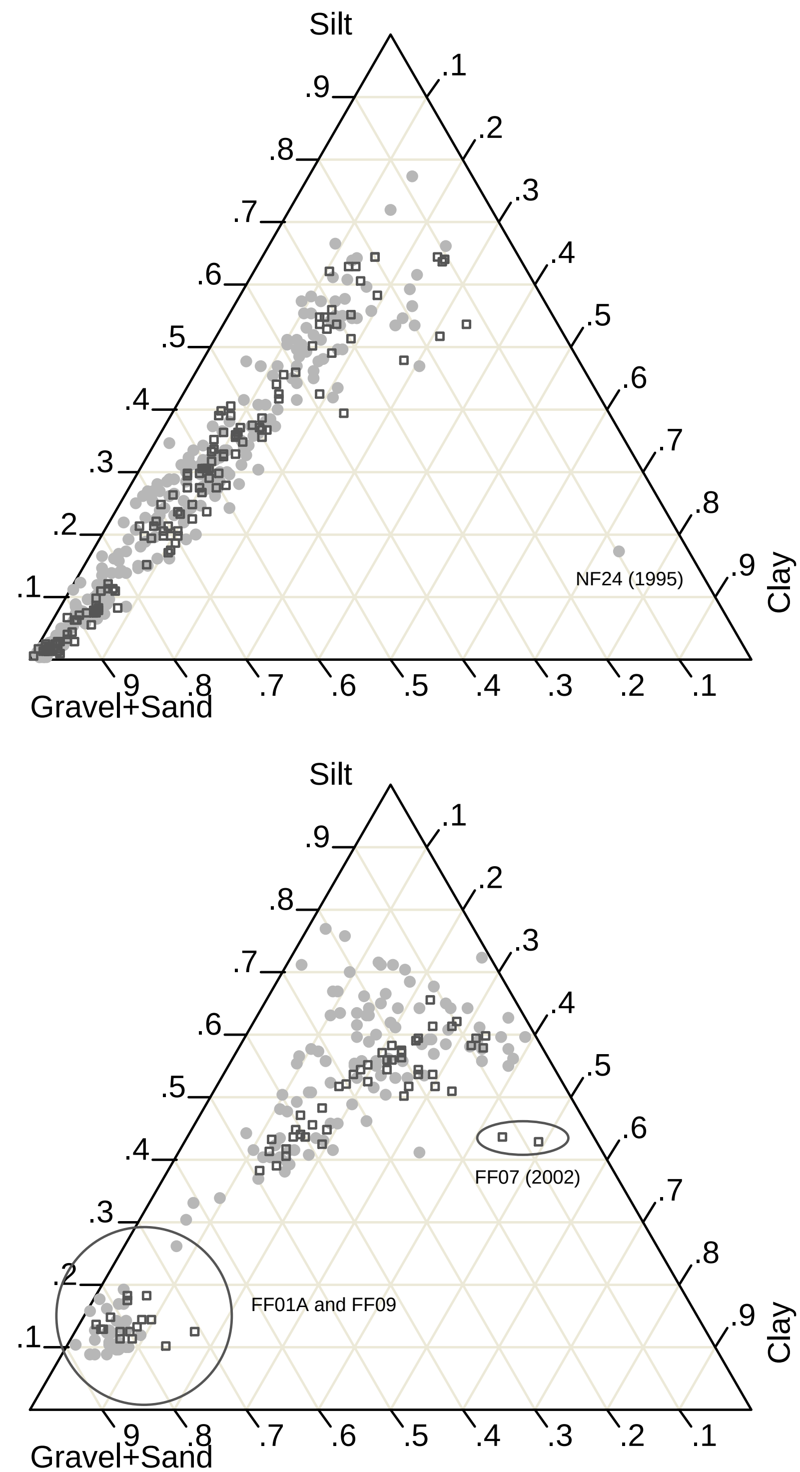


Figure 3-1. Ternary plot showing the distribution of percentages gravel + sand, silt, and clay at nearfield (top) and farfield (bottom) stations during baseline (1992-2000, gray circles) and post-diversion (2001-2005, open squares) periods.

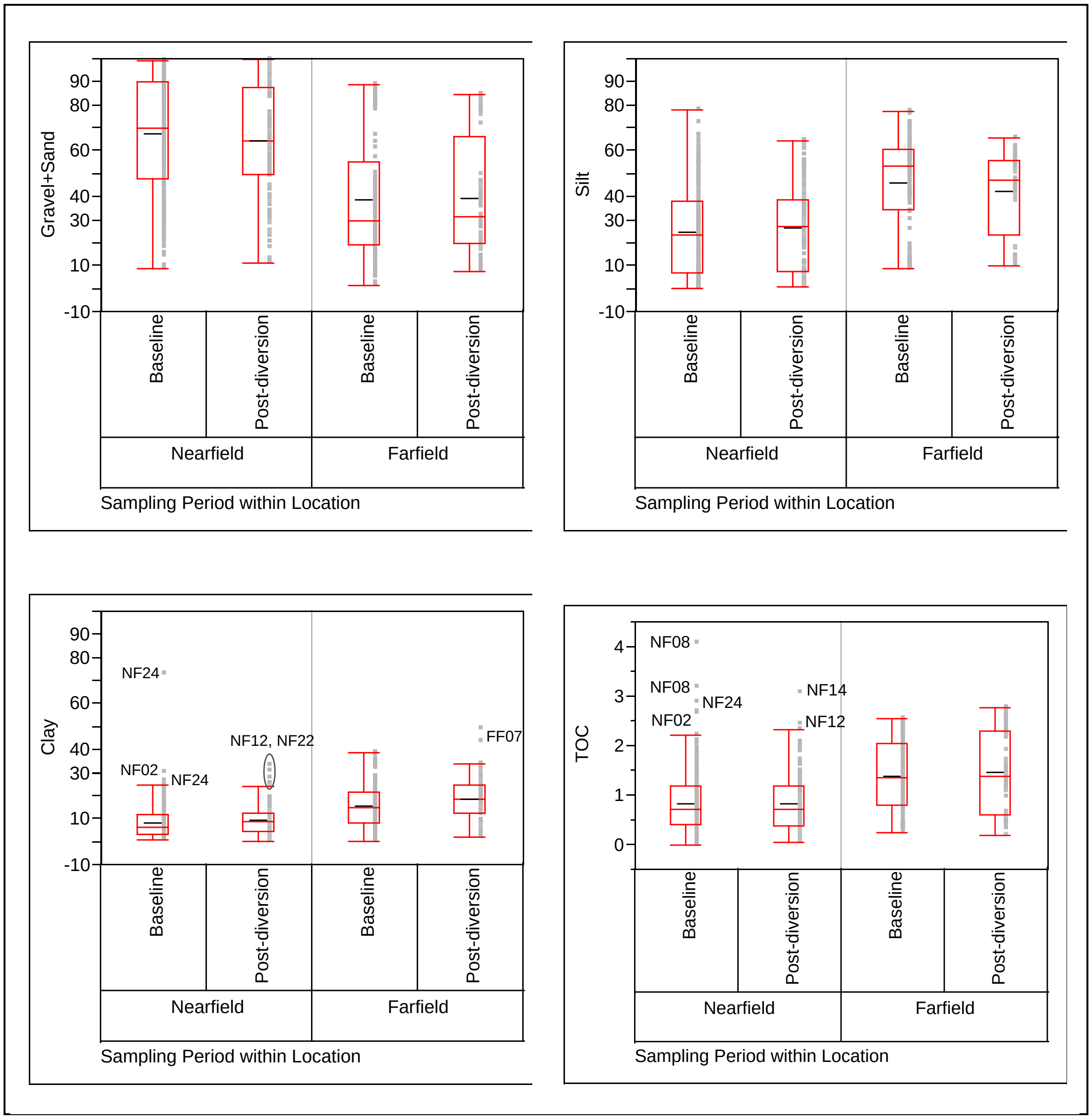


Figure 3-2. Distribution of percentages gravel + sand, silt, clay and TOC in nearfield and farfield sediments during baseline (1992–2000) and post-diversion (2001–2005) sampling periods. (Station-specific data distributions are provided in Appendix B2) The ends of the box represent the 25th and 75th quartiles, the line across the middle represents the median value, and the dash line across the middle represents the mean value. 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.

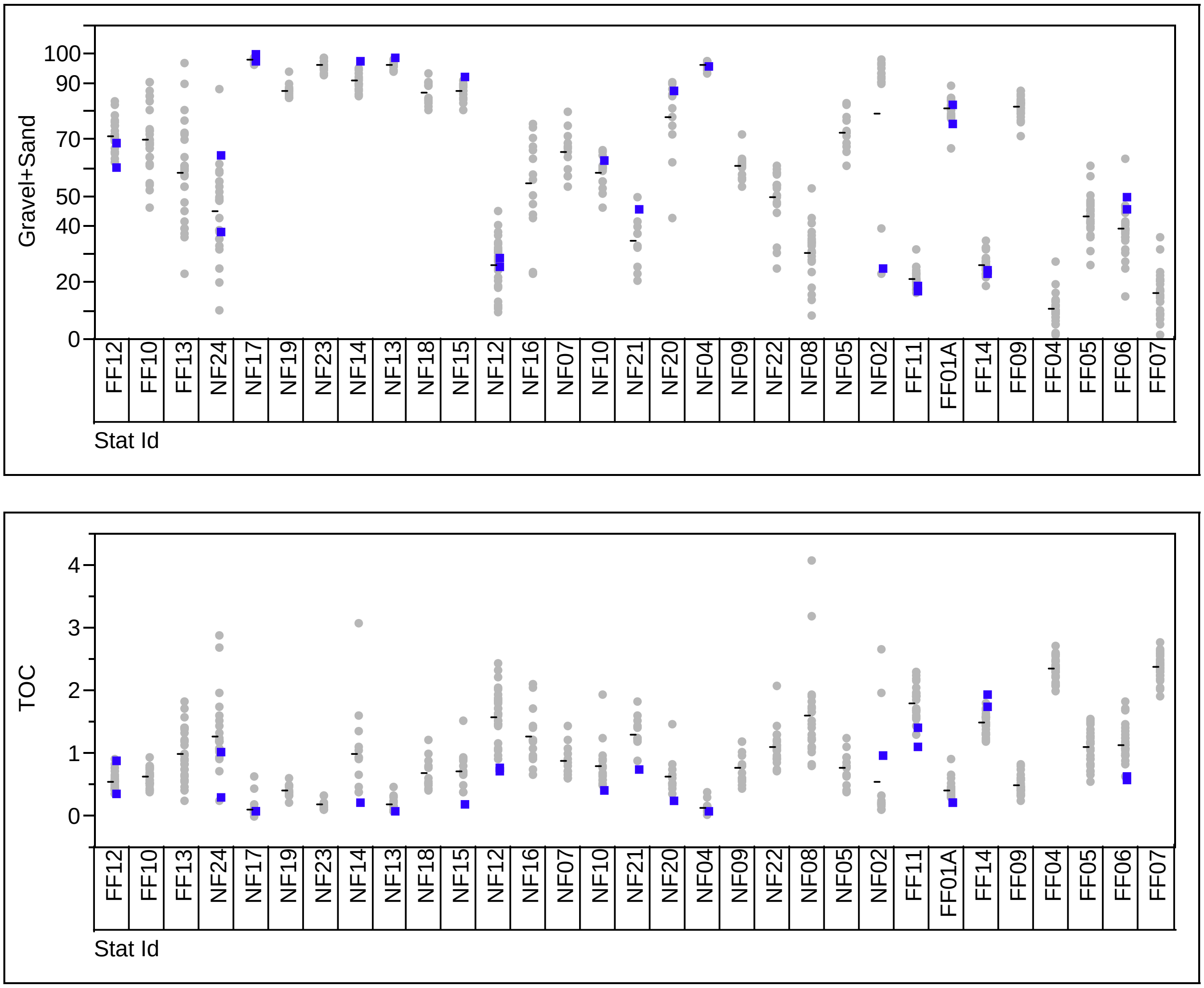


Figure 3-3. Distribution of percentages gravel + sand (top) and TOC (bottom) in nearfield and farfield sediments from 1992 to 2005. The ● symbol represents the 1992–2004 data; the ▪ symbol represents the 2005 data; and the dash line across the middle represents the mean value of all data (1992–2005) at the station. Nearfield stations FF12, FF10 and FF13 are located in the transition area between the mouth of Boston Harbor and the offshore outfall; remaining nearfield stations are sorted by proximity to the outfall; and farfield stations are sorted by north to south.

3.3.2 Anthropogenic Contaminants 1992–2005

From a system-wide perspective, concentrations of anthropogenic contaminants in surface sediments throughout Massachusetts and Cape Cod Bays are highly variable (e.g., see total PAH, total PCB, silver and nickel in Figures 3-4 and 3-5; all contaminant data in Appendix B3), which often reflects differences in bulk sediment characteristics such as grain-size distribution and TOC content. 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 data was sand content, and that secondary factors were associated with anthropogenic analytes and fine particles (Maciolek *et al.* 2003). 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 (for example, see total PAH, total PCB and silver in Figures 3-4 and 3-5; all data in Appendix B3). PCA confirmed that many nearfield stations had higher concentrations during the early baseline years. Importantly, the PCA 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 concentration of total DDT decreased significantly (at the 95% level of confidence) compared to the baseline mean value in all regions (sampled) of Massachusetts and Cape Cod Bays, except in the transition area between the mouth of Boston Harbor and the outfall (see Tukey-Kramer means comparison results in Appendix B3). A post-diversion decrease was also evident for total PCB in the farfield; whereas the post-diversion mean concentration of aluminum increased significantly (at the 95% level of confidence) compared to the baseline mean at nearfield stations located within two kilometers of the outfall (see Tukey-Kramer means comparison results in Appendix B3). The observed decreases in total DDT and total PCB are likely associated with reduced inputs resulting from the banning of these contaminants in the 1970s and 1980s.

For most of the baseline and post-diversion periods, mean concentrations of aluminum, iron, nickel and zinc were slightly higher in farfield sediments than nearfield sediments (for example, see nickel in Figure 3-5; iron and zinc shown in Appendix B3, Figures B3-15 and B3-25). These findings were consistent with the PCA, which found that most farfield sediments contained high silt and clay without a large anthropogenic chemical content (Maciolek *et al.* 2003). Mean concentrations of aluminum, chromium, iron, nickel, and silver decreased considerably in 2005 at nearfield and farfield locations compared to 2001–2004 post-diversion data (for example, see nickel and silver in Figure 3-5; all data in Appendix B3). The observed decrease is likely associated with the May 2005 nor'easters which were believed to have contributed to a loss of fines, resulting in a coarsening of sediment grain size. A coincident decrease was not observed in other anthropogenic contaminants (*e.g.,* total PAH and cadmium).

A station-specific evaluation of the sediment data also showed that most of the post-diversion data were within the general range of samples collected during the baseline period, except aluminum, which was greater than the baseline in 2002 at most stations and nickel, which was less than the baseline in 2005 at all but two of the stations sampled (see for example total PAH, total PCB, lead and nickel in Figures 3-6 and 3-7; all data in Appendix B3). Concentrations of total PCB, total DDT, aluminum, chromium, iron, and silver in 2005 were also low at several stations compared to other post-diversion contaminant data.

The small decrease in total PCB and total DDT concentrations in 2005 may be method-related[2]. The observed decreases in aluminum, chromium, iron, nickel, which are primarily crustal in nature (*e.g*., less anthropogenic), are consistent with the system-wide decreases discussed above, and likely reflect the loss of fines (*e.g*., coarsening of grain size) (see Sections 3.3.1 and 3.3.4). An explanation for the observed decrease in silver, which is not primarily crustal in nature, is not evident.

Although some localized increases in post-diversion contaminant concentrations at one or more stations were observed; the largest increases (for example, see lead in Figure 3-7, which shows an unusually high lead concentration (235 mg/kg) at station NF15 in 2002; all data in Appendix B3) do not appear to be related to the outfall. Instead, the post-diversion increases appeared to be associated with analytical interferences, random spikes, or unknown contamination, as contaminant values generally returned to baseline in subsequent sampling surveys (Maciolek *et al.* 2005). Thus, the localized increases in contaminant concentrations do not persuasively suggest an effluent signal.

Overall, the system response five years since outfall startup indicates 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. The ability to draw definitive conclusions is confounded by the large intra- and inter-annual variability observed in the data.

[2] Lefkovitz *et al.* (1999) compared two analytical methods for the measurement of chlorinated pesticides and PCB congeners in biological tissue; methods included traditional gas chromatography with electron capture detection (GC/ECD) and gas chromatography with mass spectrometry in the selected ion monitoring mode (GC/MS SIM). The evaluation revealed that measured concentrations of certain chlorinated pesticides and PCBs by GC/ECD were biased high (approximately 10% to 25%) compared to the GC/MS results. The bias was attributed to co-elution of certain chlorinated pesticides and PCBs with other PCB congeners or other environmental contaminants such as phthalate esters. For the HOM program, chlorinated pesticide and PCB analyses were conducted by using GC/ECD from 1992 to 2003. However, sediment samples collected in 2004 and 2005 were analyzed for chlorinated pesticides and PCBs by using GC/MS SIM. This method change may have contributed to the small decrease in total PCB and total DDT concentrations (in sediment) observed in 2005.

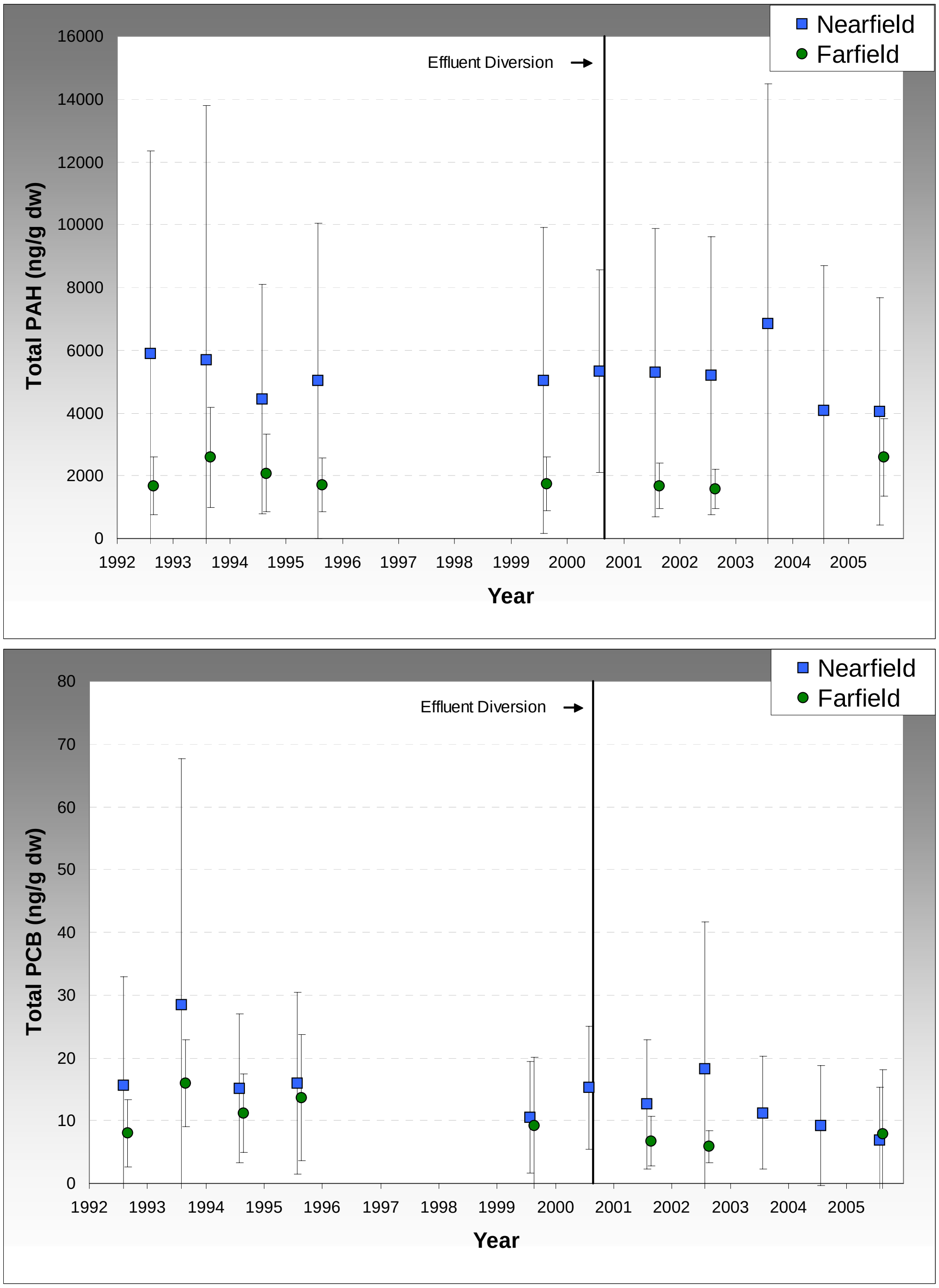


Figure 3-4. Yearly mean concentrations of total PAH (top) and total PCB (bottom) in the nearfield and farfield regions of Massachusetts and Cap Cod Bays, 1992 to 2005. Yearly mean abundance is the average of all stations and replicates for a given year, by region. Vertical bars represent one standard deviation. The number of observations (n) typically ranged from 20 to 35 for nearfield and 14 to 16 for farfield; except in 2003 (n = 6 for nearfield and 0 for farfield), 2004 (n = 4 for nearfield and 0 for farfield), and 2005 (n = 16 for nearfield and 8 for farfield).

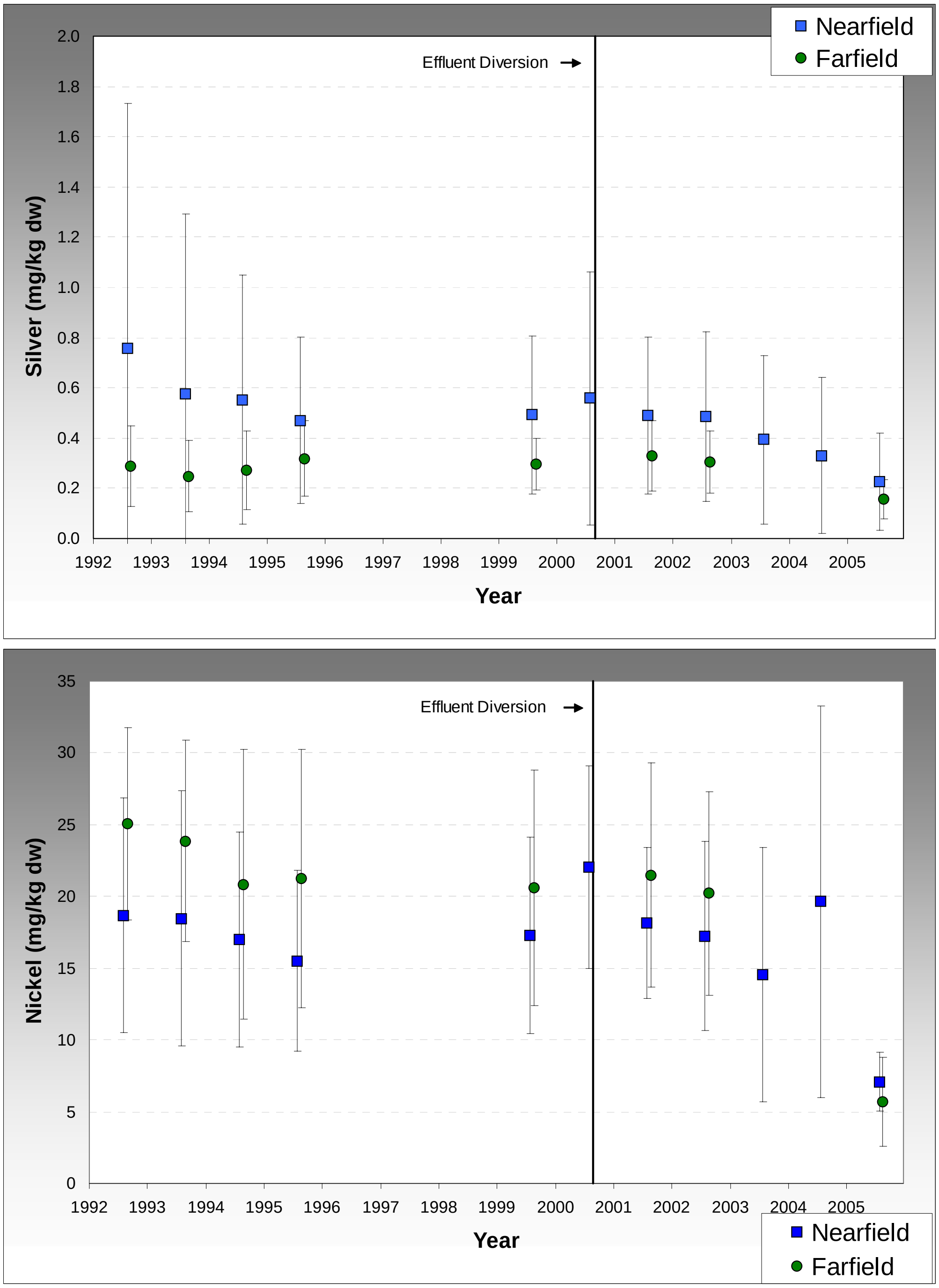
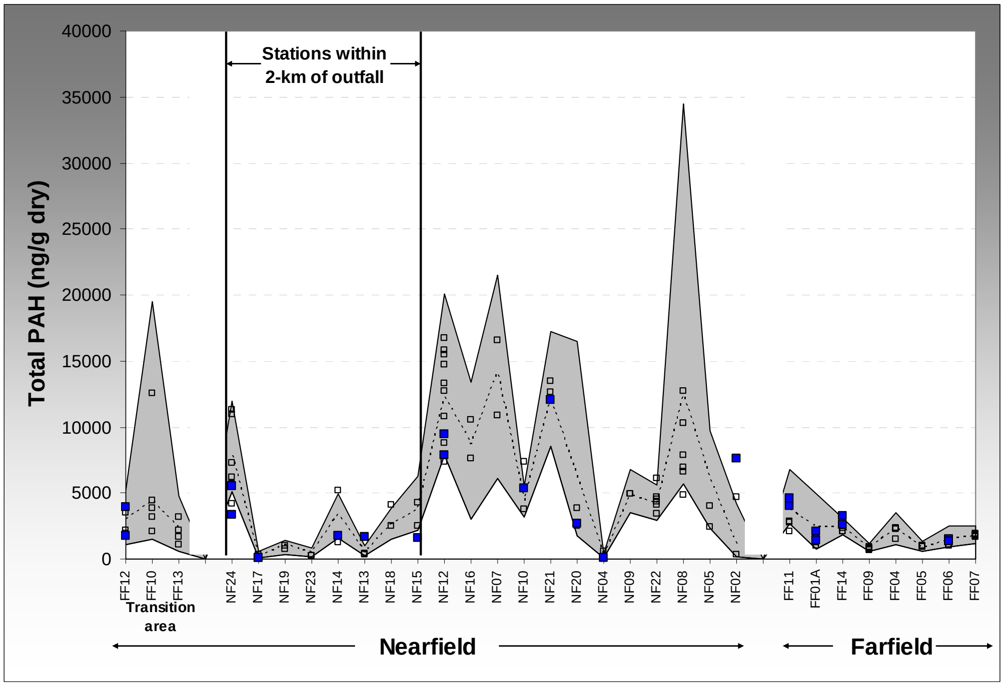


Figure 3-5. Yearly mean concentrations of silver (top) and nickel (bottom) in the nearfield and farfield regions of Massachusetts and Cape Cod Bays, 1992 to 2005. Yearly mean abundance is the average of all stations and replicates for a given year, by region. Vertical bars represent one standard deviation. The number of observations (n) typically ranged from 20 to 35 for nearfield and 14 to 16 for farfield; except in 2003 (n = 6 for nearfield and 0 for farfield), 2004 (n = 4 for nearfield and 0 for farfield), and 2005 (n = 16 for nearfield and 8 for farfield).



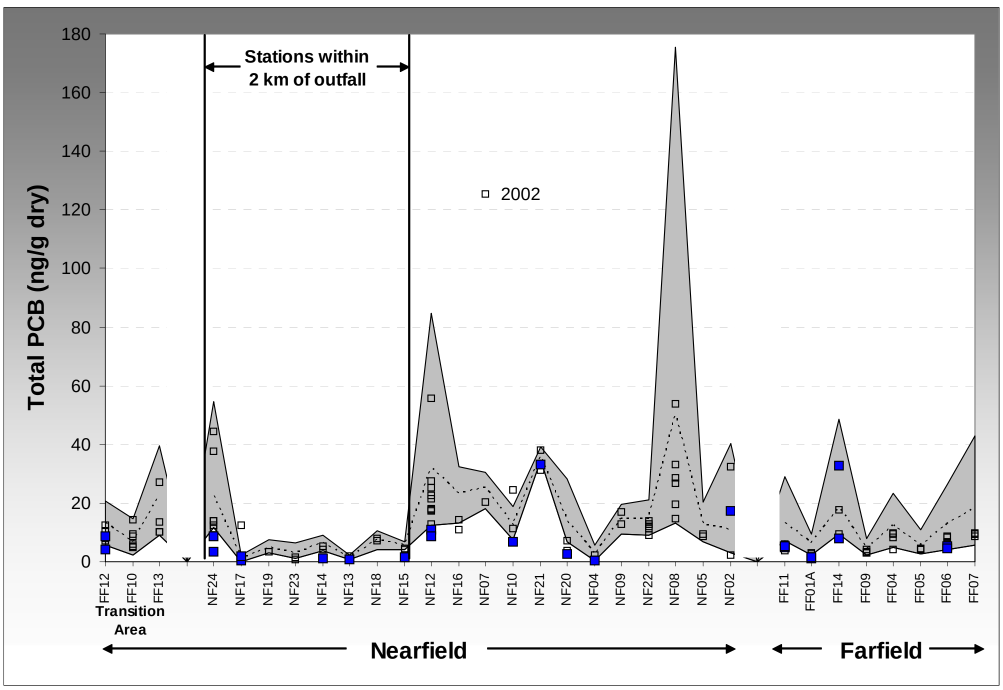


Figure 3-6. Concentrations of total PAH (top) and total PCB (bottom) in nearfield and farfield sediments during baseline (1992–2000 range of values, gray band) and post-diversion (▫ 2001-2004 and the ▪ 2005) periods. The baseline mean values (1992–2000 mean) are indicated by a dashed line within the gray band. Stations FF12, FF10, and FF13 represent the transition area between Boston Harbor and the Massachusetts Bay outfall.

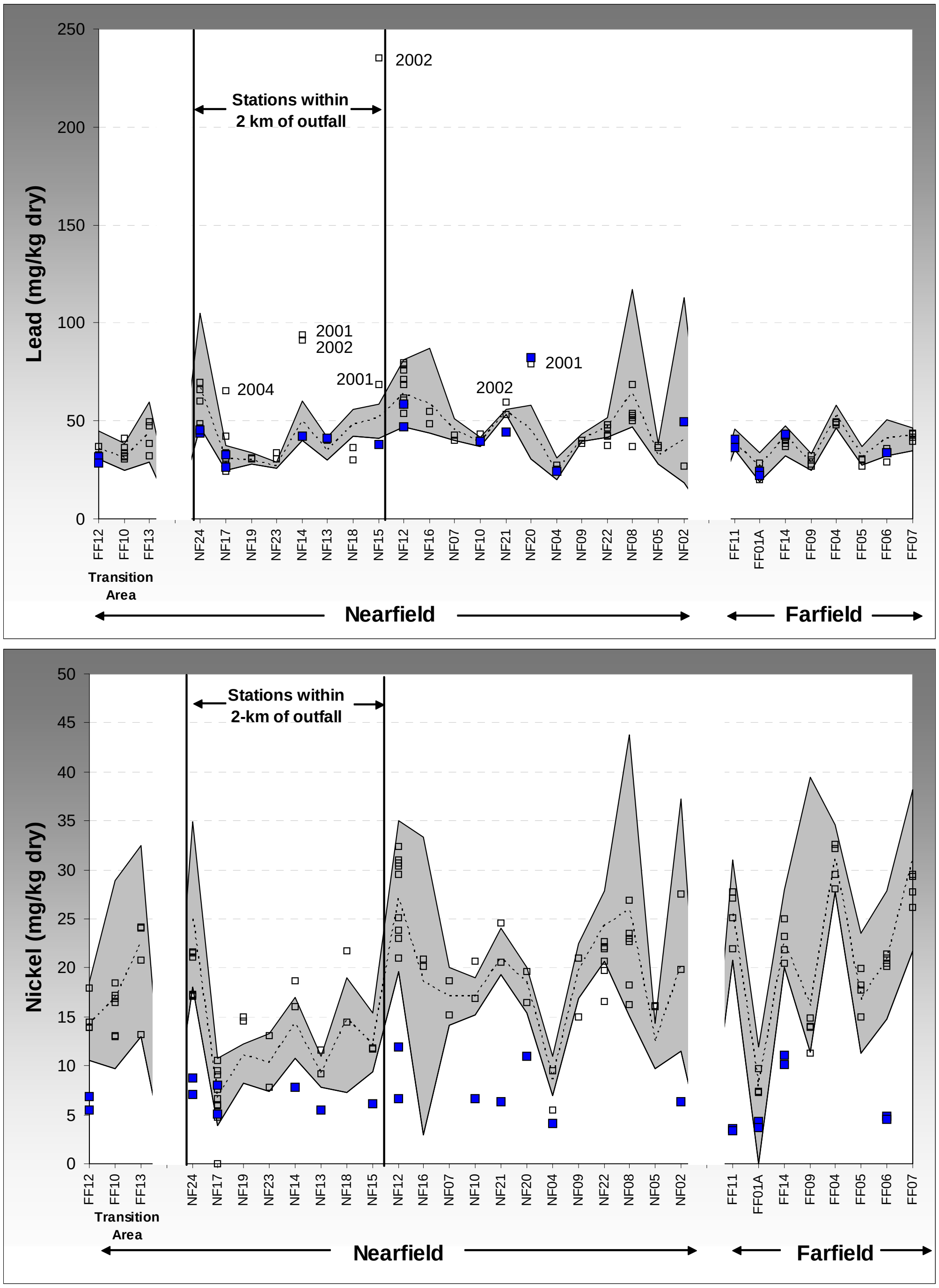


Figure 3-7. Concentrations of lead (top) and nickel (bottom) in nearfield and farfield sediments during baseline (1992–2000 range of values, gray band) and post-diversion (□ 2001-2004 and the ■ 2005) periods. The baseline mean values (1992–2000 mean) are indicated by a dashed line within the gray band. Stations FF12, FF10, and FF13 represent the transition area between Boston Harbor and the Massachusetts Bay outfall.

3.3.3 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). Because the distribution of *C. perfringens* has been found to vary with the amount of fine-grained sediments (Parmenter and Bothner, 1993), the concentrations typically are normalized to the percent fines in the sediments. This provides a more conservative means of evaluating the data for trends.

Normalized *C. perfringens* abundances were less variable and decreased with increasing distance from Boston Harbor (Figure 3-8). Farfield stations located more than 20 km from Deer Island Light had the lowest abundances, frequently fewer than 50 cfu/g dw/% fines (Figure 3-8). Normalized *C. perfringens* abundances increased in nearfield sediments one year after effluent diversion compared to 2000 pre-diversion values (Figure 3-8), and this pattern has generally held in 2002 through 2005. Abundances decreased slightly in harbor sediments, but remained comparable in farfield sediments (Figure 3-8).

From a system-wide perspective, normalized *C. perfringens* abundances were generally higher and more variable in the nearfield region of Massachusetts Bay than in the farfield (Figure 3-9). Mean abundances of *C. perfringens* (normalized) decreased in the late 1990s at nearfield locations (Figure 3-9), likely from the Boston Harbor cleanup efforts. Since outfall activation, however, there has been a nearfield-wide increase, with normalized *C. perfringens* abundances returning to levels measured in the early 1990s (Figure 3-9). Close examination of the nearfield data shows that most of the post-diversion increase is attributed to increased abundances measured at nearfield stations located within 2 km of the Massachusetts Bay outfall (Figures 3-9 and 3-10). A statistical analysis confirmed that the post-diversion increase, at nearfield stations located within 2 km of the outfall, was significant (see Tukey-Kramer mean comparison results in Appendix B4). While an effluent signal was evident in nearfield sediments located near the Massachusetts Bay outfall, the post-diversion mean abundance of *C. perfringens* (log-transformed[3]) in the transition area and farfield decreased significantly compared to the baseline mean (see Tukey-Kramer mean comparison results in Appendix B4).

Consistent with conclusions from the 2005 Toxics Issue Review (Hunt *et al*., 2006), the *C. perfringens* data from 2005 continued to trace the major improvements made in sewage treatment and demonstrated less influence of effluent on the harbor sediments and the sediments in the transition area. The data also showed a distinct signature of effluent discharge in the sediments within 2 km of the outfall. The latter conclusion contrasts with those drawn by Bothner and Butman (2005) based on data from the surface 0-0.5 cm interval from sediment cores collected at a single station, which showed no significant increase in post-diversion *C. perfringens* abundances (and metals such as silver) compared to the average baseline at the 95% level. The ability of MWRA's monitoring to detect this change documents the importance of a spatially replicated sampling design when evaluating the impact of a relatively clean discharge on coastal sediments with a history of modest levels of contamination.

[3] Statistical evaluations (ANOVA and linear regressions) were evaluated using log-transformed data to ensure that data were normally distributed.

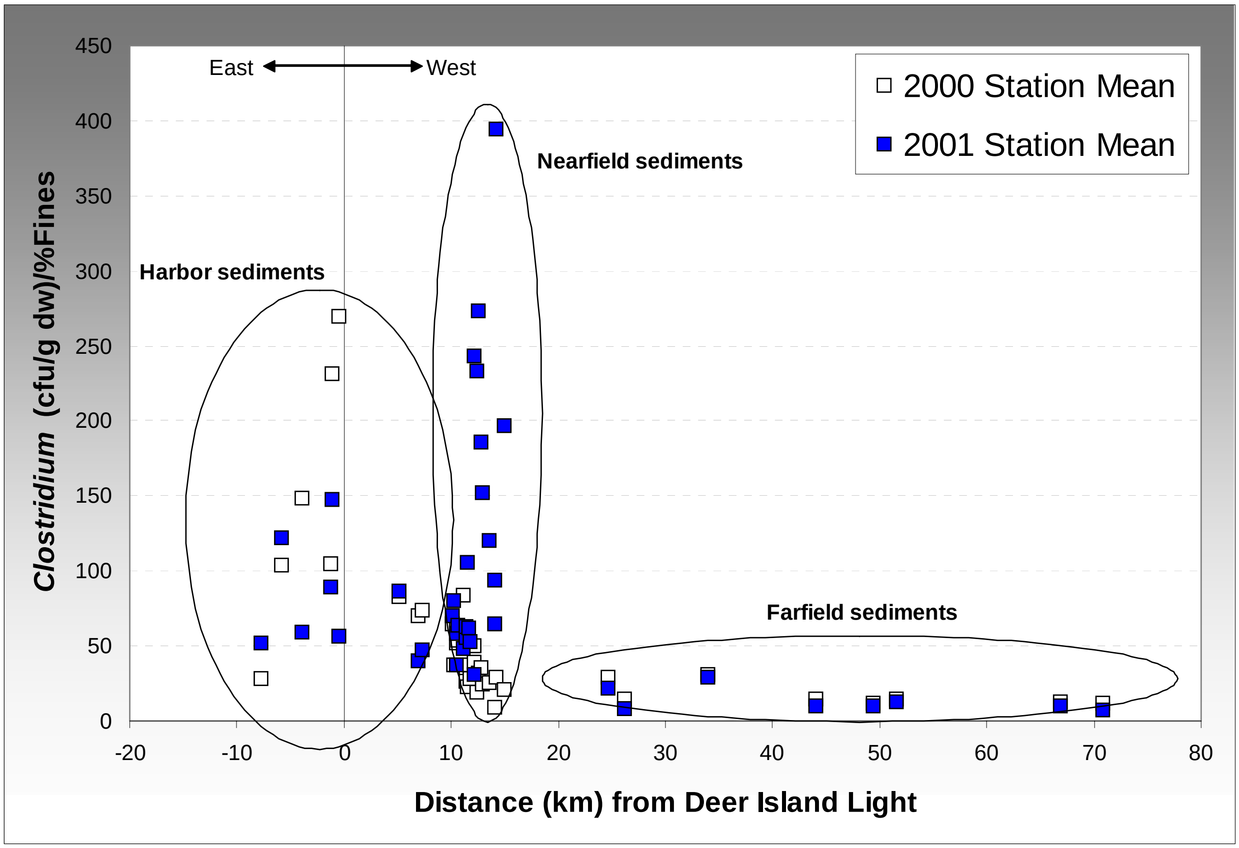
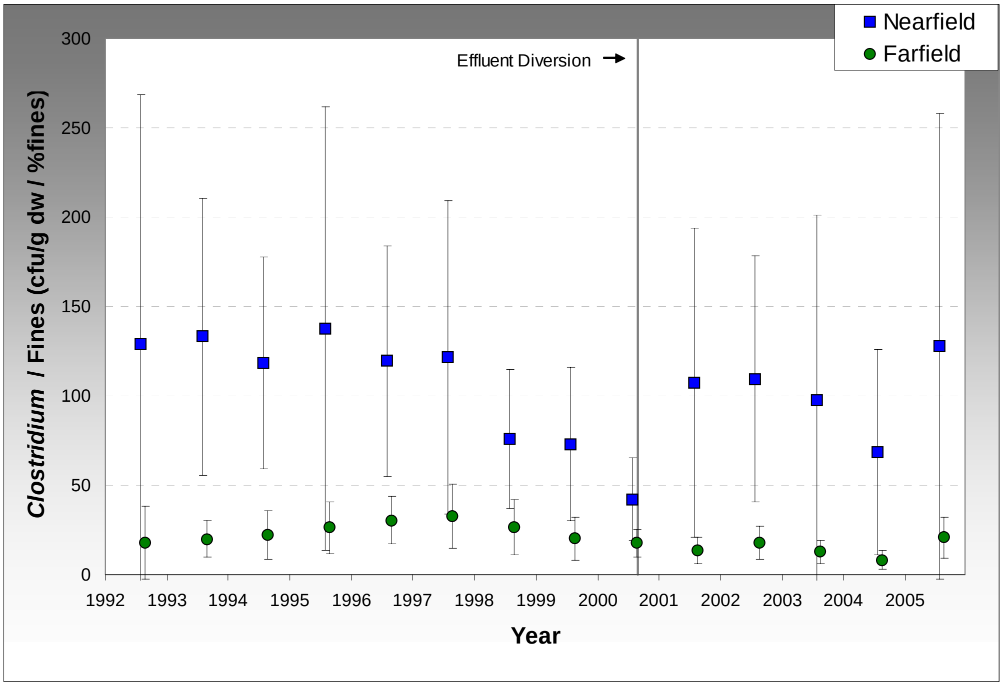


Figure 3-8. Pre-diversion (2000) and post-diversion (2001) station mean abundances of *Clostridium perfringens*, normalized to percent fines, as a function of distance from Deer Island Light at the entrance to Boston Harbor.



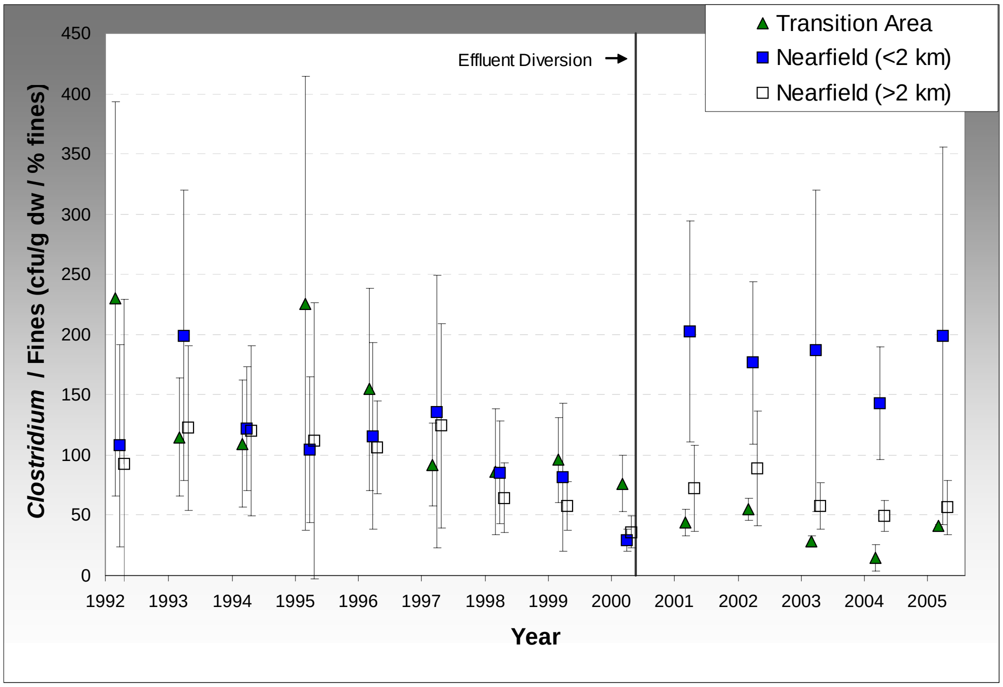


Figure 3-9. Yearly mean abundance of *Clostridium perfringens*, normalized to percent fines, in nearfield and farfield sediments, 1992 to 2005. The top plot illustrates the nearfield and farfield data following effluent diversion in 2000. The bottom plot shows that the nearfield increase is associated 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.

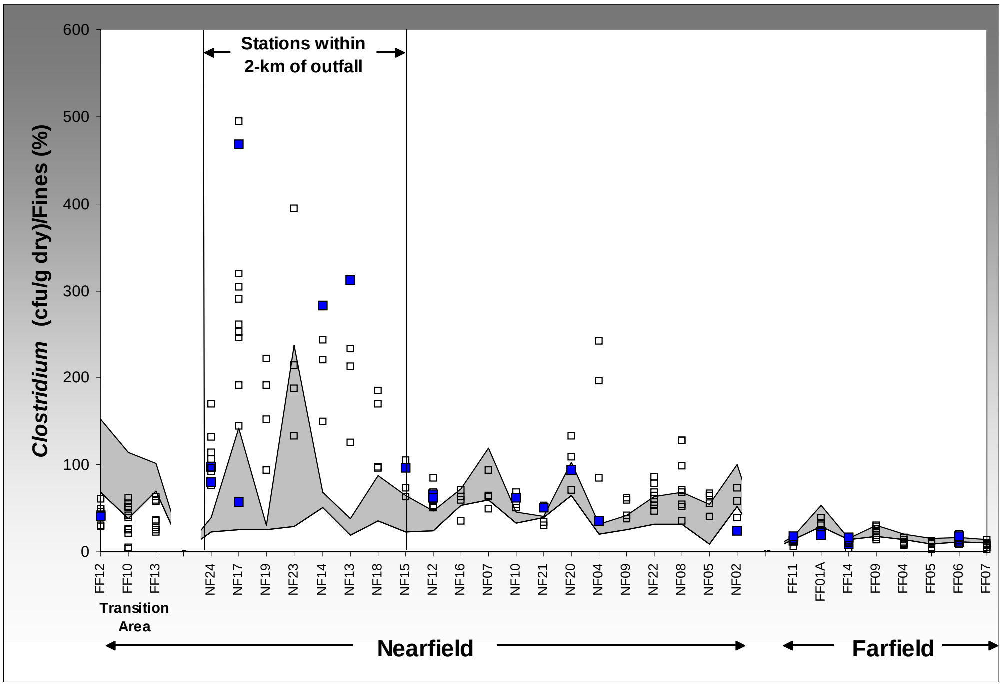
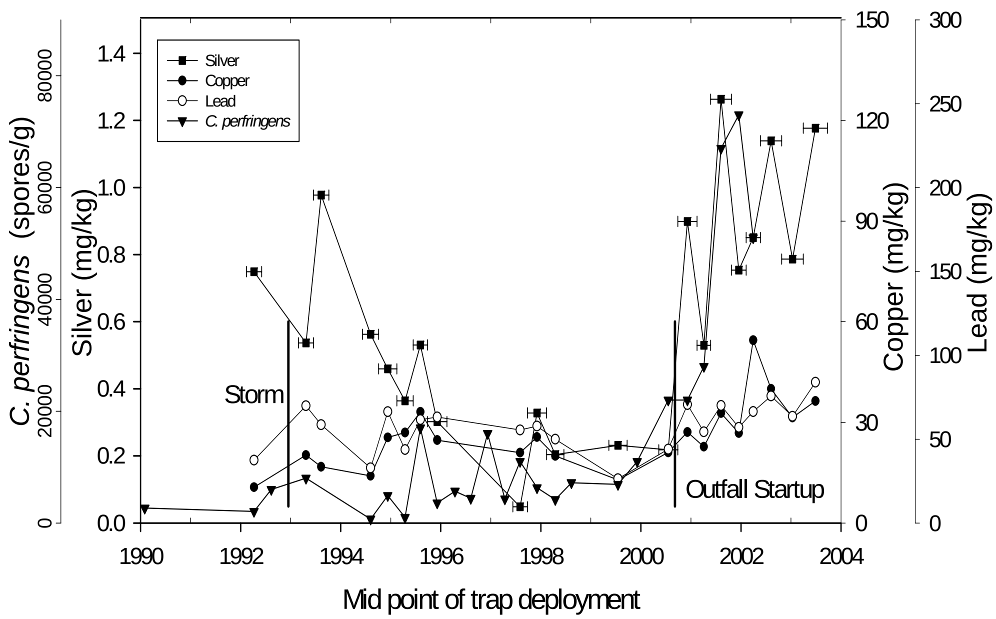


Figure 3-10. Abundances of *Clostridium perfringens* (normalized to percent fines) in nearfield and farfield sediments during baseline (1999–2000 range of values, gray band) and post-diversion (▫ 2001-2004 and the ▪ 2005) periods. Stations FF12, FF10, and FF13 represent the transition area between Boston Harbor and the Massachusetts Bay outfall.

Further evidence of the limited field of influence from the offshore discharge is provided by sediment trap results presented in Bothner and Butman (2005). The USGS program has used sediment traps to collect particles falling through the water column at a location about 1 km south of the Massachusetts Bay outfall since 1992. The USGS data showed that of the parameters measured only *C. perfringens* and silver had statistically higher concentrations (significant increase >95 % level of confidence) in post-diversion samples. *C. perfringens* abundances increased when the outfall started and rose to a maximum of 73,000 spores/gram in the post-outfall data (*i.e.*, 2001 and 2002 data only) from a pre-discharge range of 1,000 and 16,000 spores/g of sediment (Figure 3-11). Silver levels after discharge started were approximately twice those measured before the effluent diversion (Bothner *et al*. in Bothner and Butman, 2005). Bothner and Butman (2005) also calculated that the observed increase in silver concentrations represented a sewage contribution of about 2% in the trapped material. They concluded this was in reasonable agreement with modeled sewage dilutions of about 1% at the trap location. Similar increases in silver were not detected in MWRA nearfield sediments (Figure 3-5 and Appendix B3, Figures B3-23 and B-24).

The temporal patterns in *C. perfringens* abundances in the sediments collected within 2 km of the outfall (Figure 3-9) and the sediment trap data (Figure 3-11) are remarkably similar. Together these 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.



Source: Redrawn from USGS, Bothner and Butman 2005 (http://pubs.usgs.gov/of/2005/1250/html/chapt7.html)

Figure 3-11. Trend in *Clostridium perfringens*, silver, lead and copper in trapped sediment from the USGS mooring in Massachusetts Bay.

3.3.4 Sediment Correlations

Baseline and post-diversion 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. Not all data from the baseline period (1992–2000) were used in the correlation analyses. Rather, only baseline data from 1999 and 2000 were used 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. Consistent with the other data evaluations, post-diversion data included results from the 2001 to 2005 monitoring period. Correlation results for nearfield and farfield sediments are summarized below; detailed results are provided in Appendix B5.

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 0.8 to 0.9 (Appendix B5, Tables B5-1, B5-2, and B5-3), which indicates that 70% to 80% of the variation in the grain size and TOC data (at nearfield and farfield locations) is correlated. The correlation (*r*) between the sewage tracer *C. perfringens* and percent fines or TOC ranged from 0.4 to 0.9 (Appendix B5), which indicates that approximately 20% to 80% 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 which showed that the primary factor associated with the variance in the nearfield and farfield data was sand content, and that secondary factors were associated with fine particles and anthropogenic analytes (Maciolek *et al.* 2003).

The observed decrease in 2005 of crustal elements aluminum, chromium, iron, and nickel (see Section 3.3.2), was mirrored by a loss of fines, and as a result the correlations between these elements and sediment grain size did not change substantially compared to post-diversion correlations without the 2005 data.

There are some subtle differences in the correlations among sediment variables between nearfield and farfield regions. For example, *C. perfringens* and organic contaminants have slightly stronger correlation with bulk sediment characteristics at nearfield locations and many metals have slightly stronger correlations at farfield locations (Figure 3-12). There are also some subtle differences in the correlations among sediment variables between baseline (1999–2000) and post-diversion (2001–2005) periods. For example, the correlation between total DDT and bulk sediment characteristics is stronger in the nearfield following effluent diversion, whereas mercury is weaker (Figure 3-13). Even so, the differences were typically small and are not indicative of an effluent signal. More substantive differences (see for example in Figure 3-13 how the correlation between lead and bulk sediment characteristics degraded in nearfield sediments following effluent diversion) were typically attributed to a few data points with unusually high concentrations that skewed the correlation. The correlation between the sewage tracer *C. perfringens* and bulk sediment characteristics did degrade in farfield sediments following outfall activation. However, the weaker correlation (Figure 3-13) appears to be associated with an observed decrease (approximately 25% on average) in *C. perfringens* abundances with no corresponding change in grain size. Overall, examination of the correlation among sediment variables shows no clear evidence of an effluent signal that may have impacted the relationship among the sediment variables.

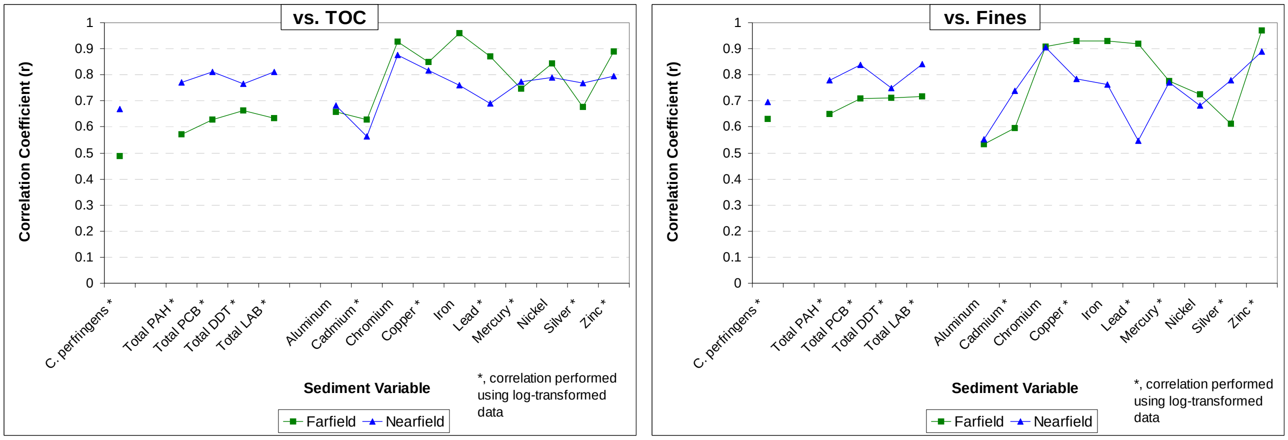


Figure 3-12. Comparison of the linear relationship among sediment variables, measured as the Pearson product-moment correlation coefficients (r), between nearfield and farfield regions of Massachusetts and Cape Cod Bays.

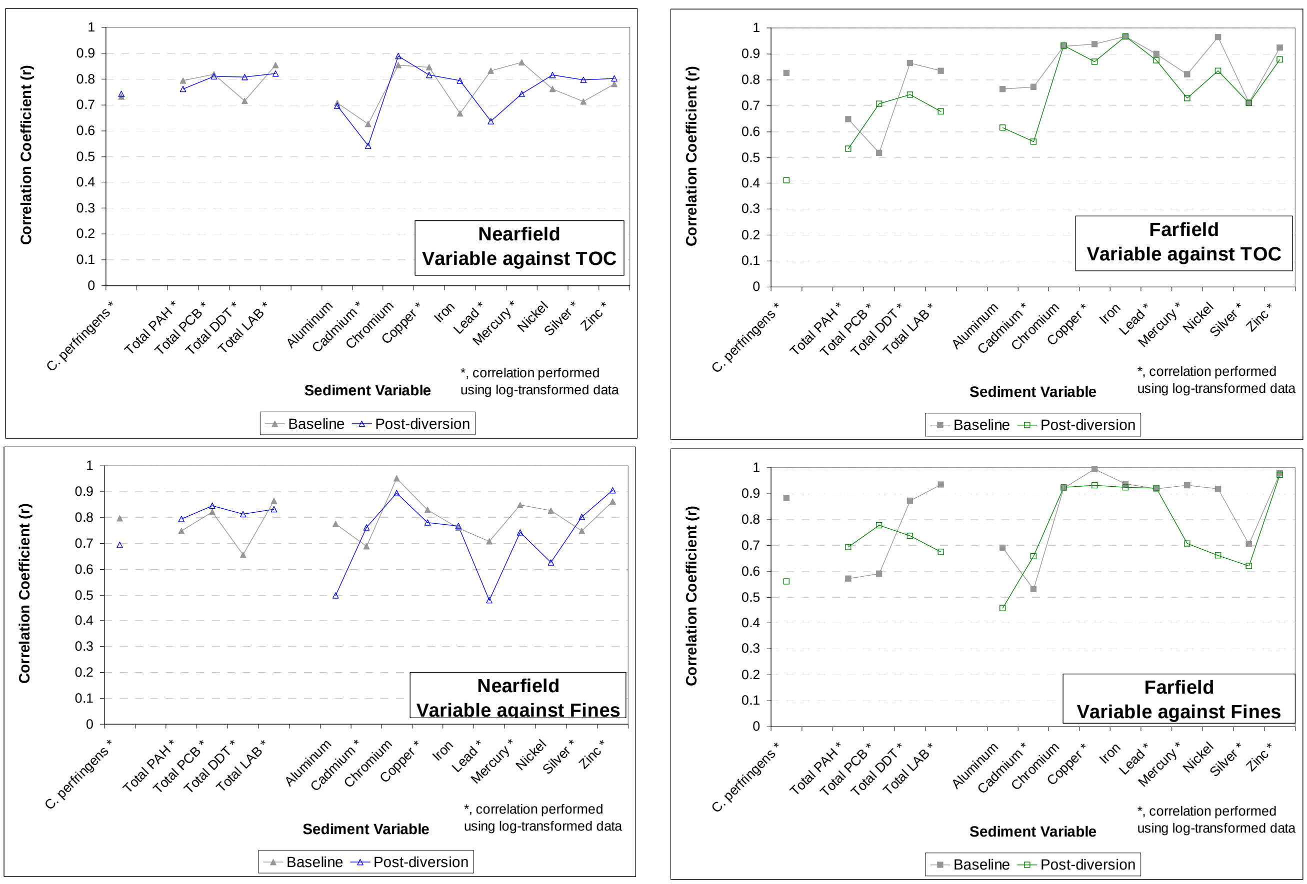
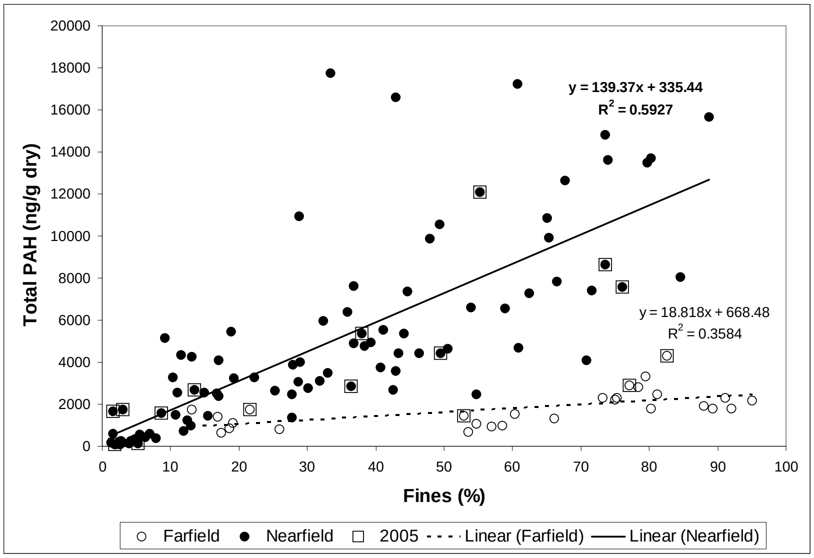


Figure 3-13. Comparison of the linear relationship among sediment variables, measured as the Pearson product-moment correlation coefficients (r), between baseline (1999–2000) and post-diversion (2001–2005) periods in the nearfield (left) and farfield (right) regions of Massachusetts and Cape Cod Bays. The correlation coefficient (r) measures the degree to which two variables have linear relationship if the variables have normal distributions. Station mean values (i.e., average of all replicates, by station and year) were used in the correlation analyses.

Finally, the correlation analyses also showed that the proximity to the primary historic source of contaminants, Boston Harbor, influenced the chemical 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 (see for example total PAH in Figure 3-14; all data in Appendix B5). Anthropogenic concentrations present at levels above the underlying farfield signature are indicative of proximity to a local source (Boston Harbor), as evidenced by a higher slope value from the regression analysis for nearfield data compared with farfield data (see for example total PAH in Figure 3-14; all data in Appendix B5). Anthropogenic concentrations at farfield locations are primarily influenced by widely distributed sources (e.g., atmospheric input, distant rivers). PCA supported this and showed that the composition of sediments at farfield sampling locations is influenced by the analytes associated with fines and may reflect regional inputs that are distinct from Boston Harbor (Maciolek *et al*. 2003).



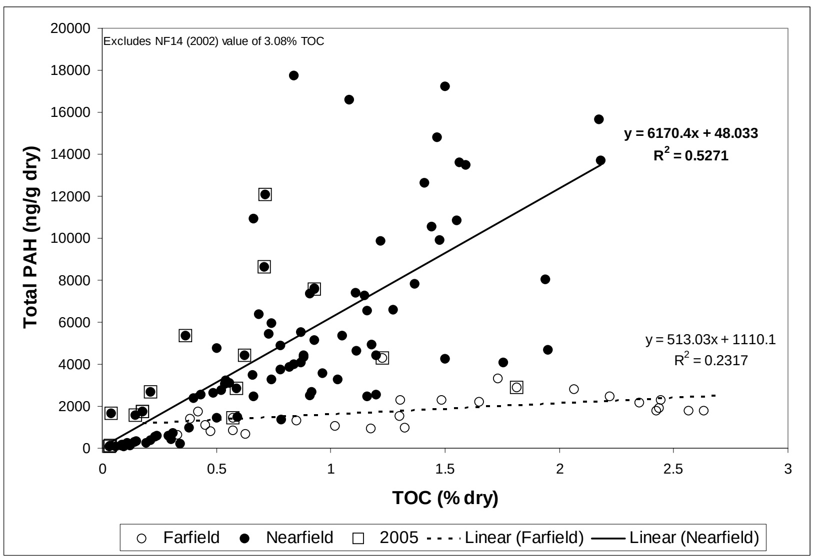


Figure 3-14. Correlation of total PAH against percent fines (top) and TOC content (bottom) in nearfield and farfield sediments, 1999–2005. Station mean values (i.e., average of all replicates, by station and year) were used in the correlation analysis.

3.3.5 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, Hunt *et al.* (2006) used SQG (Long *et al.* 1995) to evaluate whether changes in sediment quality have occurred in the bay system since the early 1990s.

The 2005 Toxics Issue Review (Hunt *et al.* 2006) showed that between 1992 and 1999 improvements in the sediment quality of Massachusetts Bay were clearly evident, demonstrated by a 42 percent decrease (from 1992 to 1999) in the total number of chemicals with concentrations above the Sediment Quality Guidelines (SQGs). In contrast to the 1992 to 1999 period, changes from 1999 to 2002 were generally in the opposite direction, but not at all stations. Overall, the number of chemical concentrations above the SQGs increased 16 percent between 1999 and 2002 (Hunt *et al.* 2006). The changes in sediment quality in the short period following effluent diversion are limited in magnitude and are not spatially consistent with stations shown to have effluent contribution based on the *Clostridium* data. Also, some of the concentration increases observed between 1999 and 2002 may be associated with temporal variability in sediment texture in this dynamic area. For example, station NF02 showed by far the greatest number of increases (12) in the number of contaminants above SQGs between 1999 and 2002. These increases appear to be consistent with changes in bulk sediment at the site, where percent fines (silt + clay) increased from 5% to 61% and TOC increased from less than 0.15% to 1.9% over the same period. Given the large intra- and inter-annual variability observed in the sediment data, year-to-year changes in sediment quality, measured by the number of chemicals with concentrations above the SQGs, must be viewed with caution.

In addition to the annual trends evaluated in Hunt *et al.* (2006), patterns in sediment quality were also evaluated on a station-specific basis within the baseline (1992–2000) and post-diversion (2001–2005) periods. Results indicated that the number of chemicals with concentrations above the SQGs was highly variable during the baseline period, and likely reflected differences in bulk sediment characteristics such as grain-size distribution and TOC content. For example, coarse-grained sediment stations such as NF17, NF09, NF23, NF04, FF01A, and FF09 typically had among the fewest chemicals with concentrations above the SQGs (Figure 3-15). Similarly, fine-grained sediment stations such as NF12 and NF21 typically had more chemicals with concentrations above the SQGs (Figure 3-15). In contrast, farfield stations with fine-grained sediments (*e.g.,* FF11, FF14, FF04, and FF07) had fewer chemicals with concentrations above the SQGs compared to nearfield stations with similar grain size, indicating again that anthropogenic concentrations at farfield locations are less influenced by the historic source of contamination, Boston Harbor. The 2005 data had among the fewest chemicals with concentrations above the SQGs (Figure 3-15). This is consistent with changes in bulk sediment characteristics (*i.e.,* loss of fines and reduced TOC content) which have been attributed to the May 2005 nor'easters.

The sediment quality evaluation also showed that the number of chemicals with concentrations above the SQGs during the post-diversion period is within the general range of the baseline period (Figure 3-15). This indicates 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.

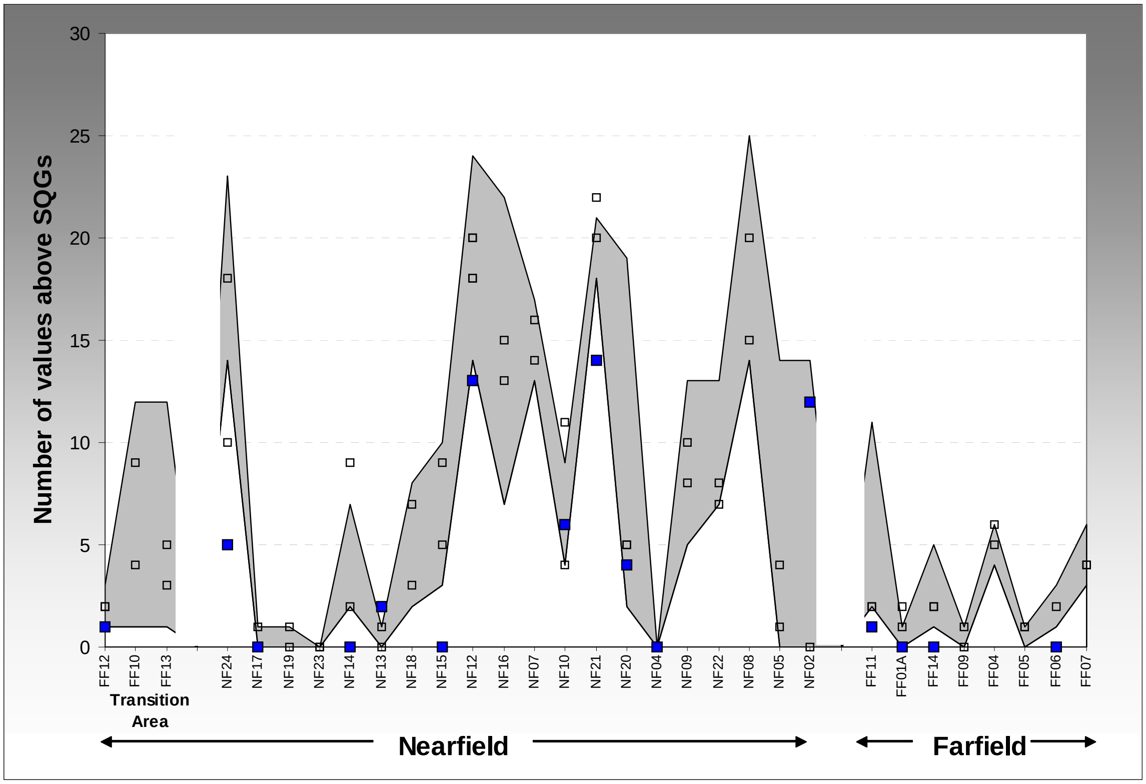


Figure 3-15. Total number of chemicals with concentrations above the SQGs in nearfield and farfield sediments during baseline (1992–2000 range of values, gray band) and post-diversion (▫, 2001-2004 and the ▪ 2005) periods. Stations FF12, FF10, and FF13 represent the transition area between Boston Harbor and the Massachusetts Bay outfall.

3.4 Summary and Conclusions

3.4.1 Monitoring Questions

Relocation of the outfall to Massachusetts Bay raised environmental concerns regarding potential effects of the diverted discharge on the sea floor. 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 (Sea Floor) Monitoring component of the MWRA HOM program was designed to address specific monitoring questions.

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

The monitoring data from 1992 to 2005 show some subtle but localized changes in concentrations of anthropogenic contaminants in Massachusetts and Cape Cod Bays, which appear to reflect differences in bulk sediment characteristics such as grain-size distribution and TOC content, rather than an outfall impact. For example, concentrations of some anthropogenic contaminants (*e.g.,* aluminum, iron and nickel), which are primarily crustal in nature, decreased in 2005 compared to other post-diversion data. The monitoring data also show that the post-diversion mean concentrations of total DDT in the nearfield (excluding the transition area) and farfield have decreased significantly compared to the baseline mean value. A post-diversion decrease in total PCB was also observed in the farfield. These observed decreases may be associated with the banning of DDTs and PCBs in the 1970s and 1980s. Overall, in the first five years following effluent diversion, 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 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?*

The post-diversion data suggest a localized increase in the abundances of *C. perfringens* (normalized to percent fines) at nearfield stations located within two kilometers of the Massachusetts Bay outfall. In contrast, the post-diversion mean abundances of *C. perfringens* (log-transformed) decreased significantly compared to the baseline means in the transition area and farfield. Anthropogenic contaminant data did not show this response.

3.4.2 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. Moreover, although there is a clear signature of effluent discharge on nearby sediments, evidenced by the post-diversion increase in *C. perfringens* abundances, the effluent has not caused substantive changes in the quality of the environment near to or far from the outfall location. Post-diversion abundance of the sewage tracer, *C. perfringens*, has decreased significantly in the transition area and farfield compared to the baseline mean value. The *C. perfringens* data also 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.

4. 2005 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). Ten 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 2005 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 because the RPD layer becomes seasonally shallower in the fall. The largest deepening of the RPD layer between successive samplings was 0.5 cm from 1998 to 1999 and was associated with an increase in the levels of biogenic activity. 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, there were indications that both pioneering Stage I and equilibrium Stage III communities had increased and Stage II had decreased (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 2005, nine stations had measurable RPD layer depths for all years.

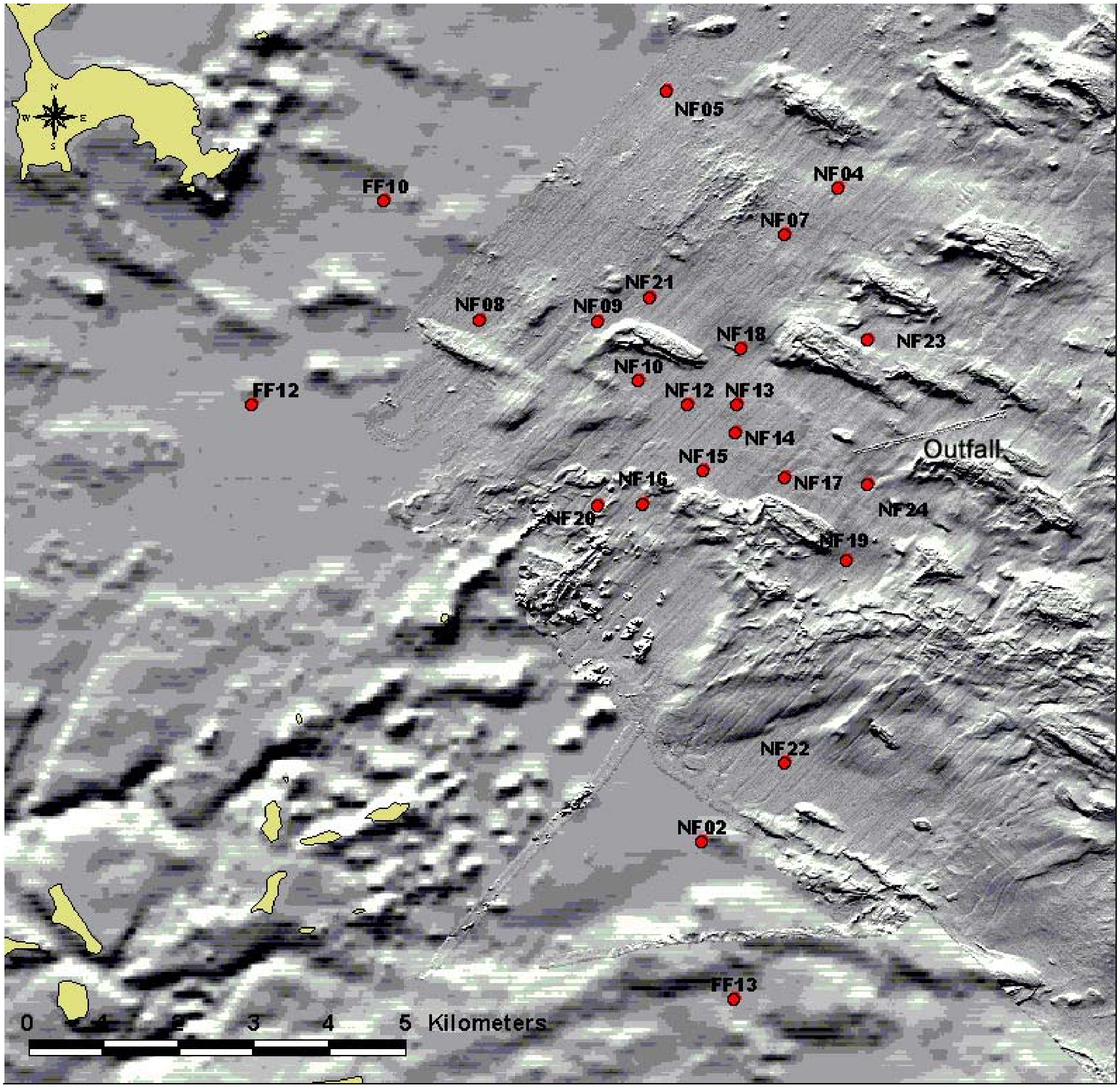


Figure 4-1. Locations of nearfield stations overlaid on multibeam bathymetry of Butman *et al.* (2004).

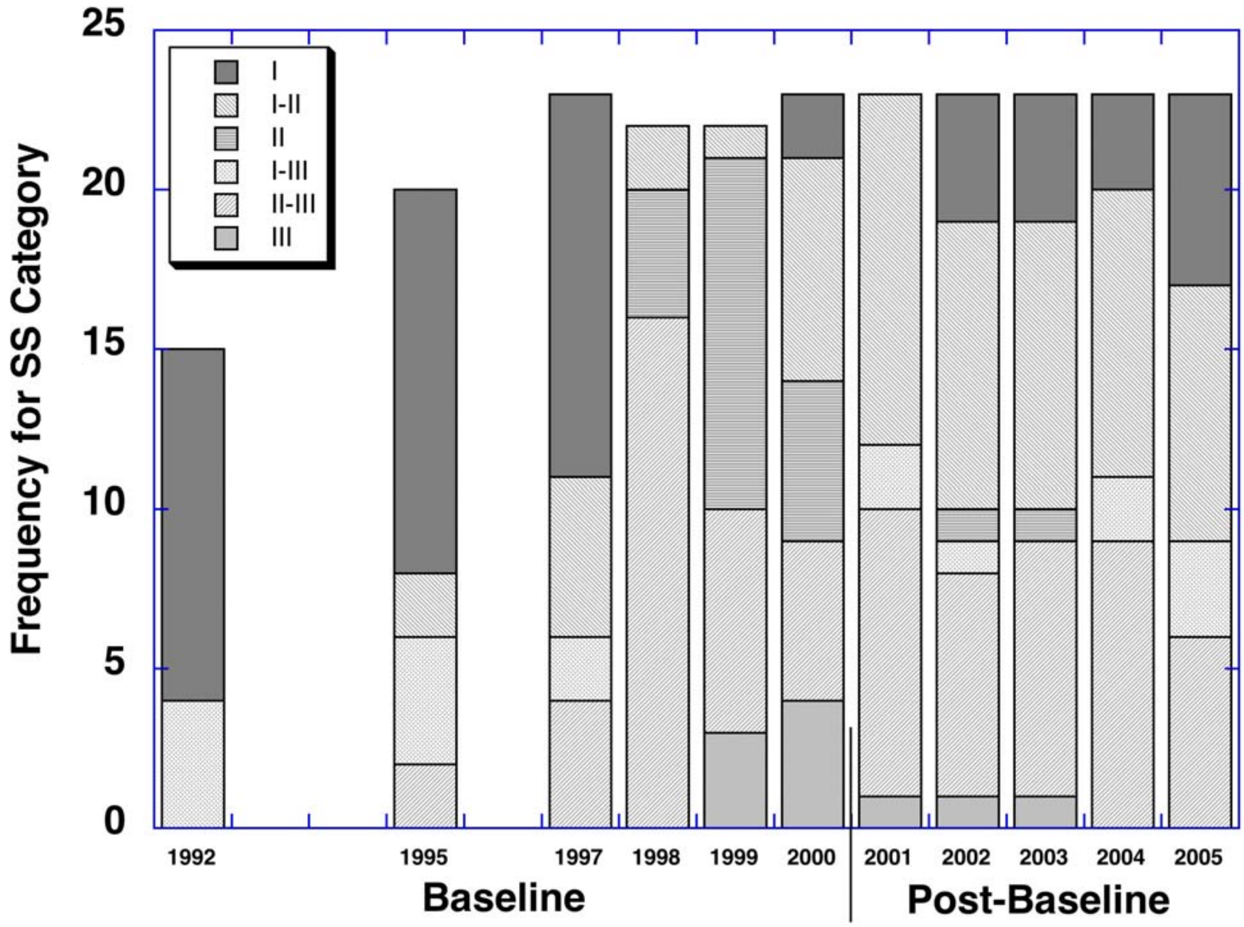


Figure 4-2. Estimated successional stage from nearfield SPI for all years.

There was a general concordance between these nine stations and time with a significant deepening trend from 1997 to 2000 for both the four stations within the topographic feature that contains the outfall (2-way ANOVA without replication, time p = 0.019, station 0.577) and the five stations in other features (2-way ANOVA without replication, time p = 0.001, station 0.950), (Figures 4-1 and 4-3). Post-diversion—from 2001 to 2005—there were no significant trends in RPD layer depth for these nine stations.

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 these 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. Multibeam mapping of the nearfield allowed for the analysis of the complex topography and how it may relate to habitat quality. When stations were grouped by topographic feature (the flat area that contains the outfall and may be more prone to sedimentation verses other areas to the north, west, and east, see Figure 4-1), there was no significant difference in the OSI through time. The stations within the feature that included the outfall did not change in OSI over the baseline period. Post-diversion, from 2001 to 2005, there were also no significant trends in OSI, but the grand mean and median appeared to be increasing since 2003 (Figure 4-4).

There was little difference in the OSI between the baseline mean and post-diversion mean (Figure 4-4). The variation in OSI from year to year was not statistically significant and likely represents annual shifts in the balance between biological and physical processes. However, there were no significant trends in OSI when regressed against year or distance from the outfall. Based on the paradigm used in estimating successional stage from SPI, it is unlikely that the variation in OSI is related to the operation of the outfall, as the only significant trend occurred during the baseline period at stations that were not within the same topographic feature as the outfall, where outfall effects would be most detectable. However, the increase in pioneering Stage I fauna in 2005 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 Preparation). Evidence of change in sediment grain-size (reduction in fines) and TOC (lower %) following the May 2005 storm was also found at seven stations (Chapter 3, this report).

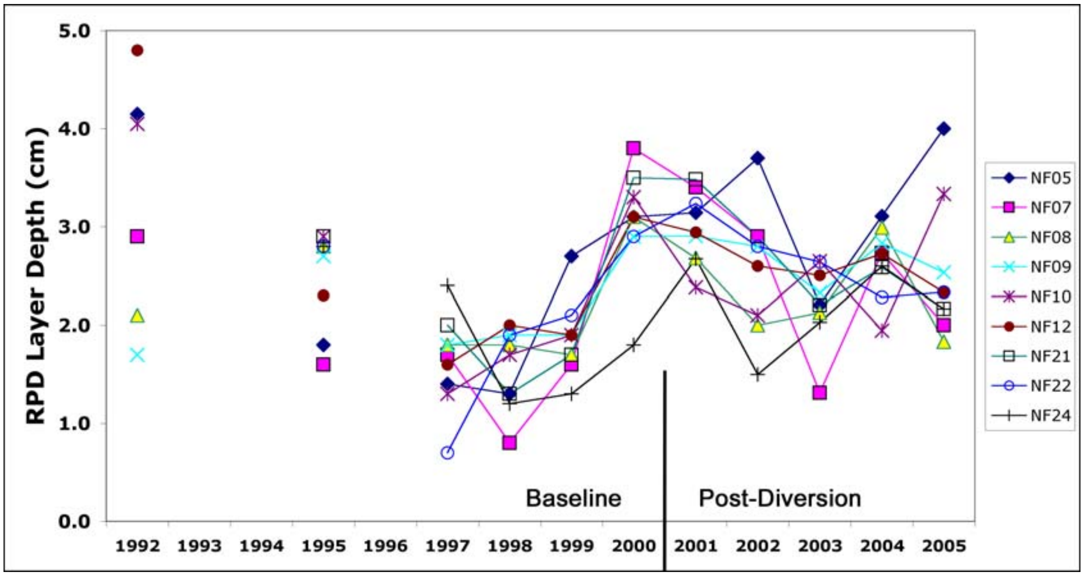


Figure 4-3. Apparent color RPD layer depth (cm) for the nine nearfield stations that had measured values for all years.

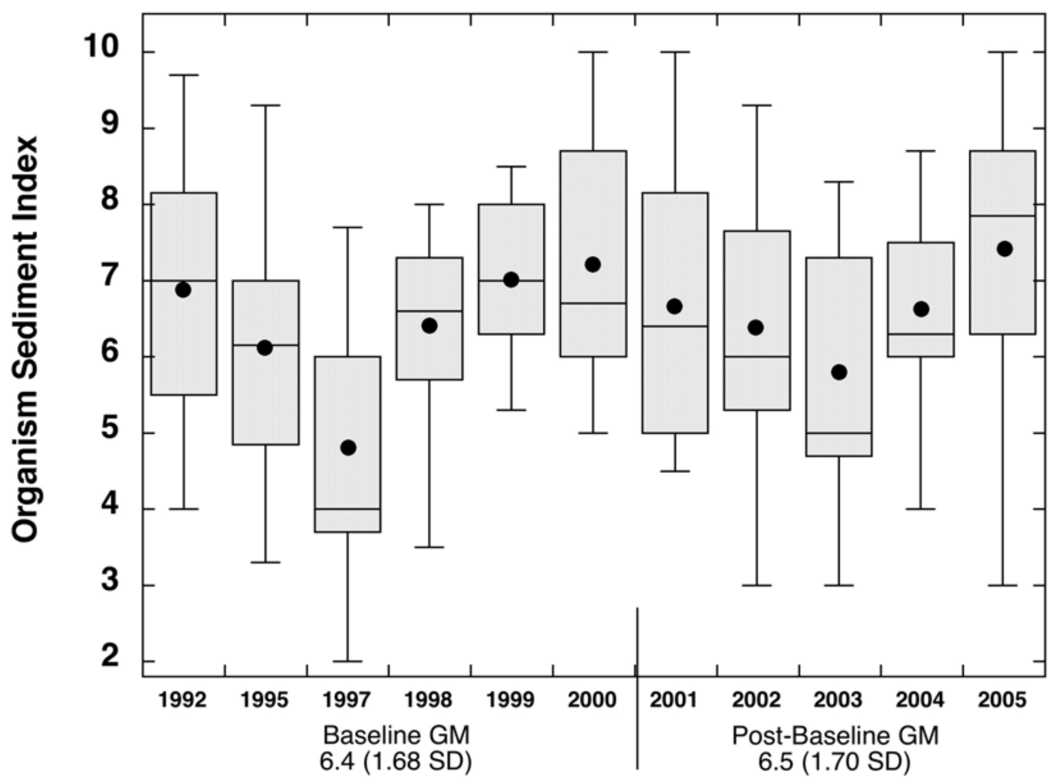


Figure 4-4. Organism Sediment Index (OSI) summarized by year for all data from nearfield stations. Box is interquartile range, short bar is median, dot is mean, and whiskers are data range.

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 4-1 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 histogram equalized with Adobe Photoshop®.

4.3 Results and Discussion

4.3.1 Summary of 2005 SPI Data

Physical Processes and Sediments—Sediment grain size in 2005 continued to be heterogeneous and ranged from pebble to fine-sand-silt-clay (Figures 4-5 and 4-6). Stations FF10 and FF13, which had only fine sediments in 2004, reverted to having coarse pebble/cobble sediments in 2005. The only station in 2005 to coarsen in sediments since the start of sampling was NF07, which for the first time had pebble (Table 4-2). The year-to-year variation within some stations in grain-size appeared due to small-scale patchiness of coarser sediments and location of sampling points within the 30-m radius station target. For example, at FF13, sediments to the northwest of the target coordinates were finer sands and silty while near and to the south of the target, sediments were more heterogeneous with gravel and coarser grains (Figure 4-7). In years when samples were located within 10 m or south of target coordinates, sediments tended to be heterogeneous and coarser. Overall, a total of 11 stations had coarser (gravel and larger grains) and 12 stations had primarily finer (silt and clay) sediments. Sandy sediments that ranged from very-fine-sand to fine-medium-sand occurred at the same three stations (FF12, NF04, and NF17) as in previous years. Prism penetration in 2005 was similar to 2004 (paired t-test, $p = 0.546$) with lowest penetration occurring at sand to pebble stations and the highest at mixed muddy stations. Penetration was shallowest (1.9 cm) at Station NF13, which had fine-medium-sand-gravel sediments and deepest (16.3 cm) at Station NF08, which had fine-sand-silt-clay (Figure 4-5 and Table 4-3).

Relative to the baseline years, sediment grain sizes in 2005 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 that 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 4-2). Images from 1992 were not available for reanalysis. Sediment grain-size analysis in 2005 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 did not change but the range in grain-size increased to include pebbles at stations NF14, NF15, and NF20 (Table 4-2). A similar pattern of increased coarse grains was observed at stations FF10, FF13, NF07, NF19, and NF23. The coarsening of sediments in 2005 was likely related to bottom disturbance from the May 2005 storms, which were associated with the second highest bottom stress winter on record (Butman *et al*. In Preparation). At station NF05 there appeared to be a fine-sand layer over fine-sand-silty that could be a result of storm-induced winnowing of surface sediments.

Table 4-1. 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	—	V	Identify
Pelletal Layer	cm	V	Measure thickness, area
Bacterial Mats	—	V	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

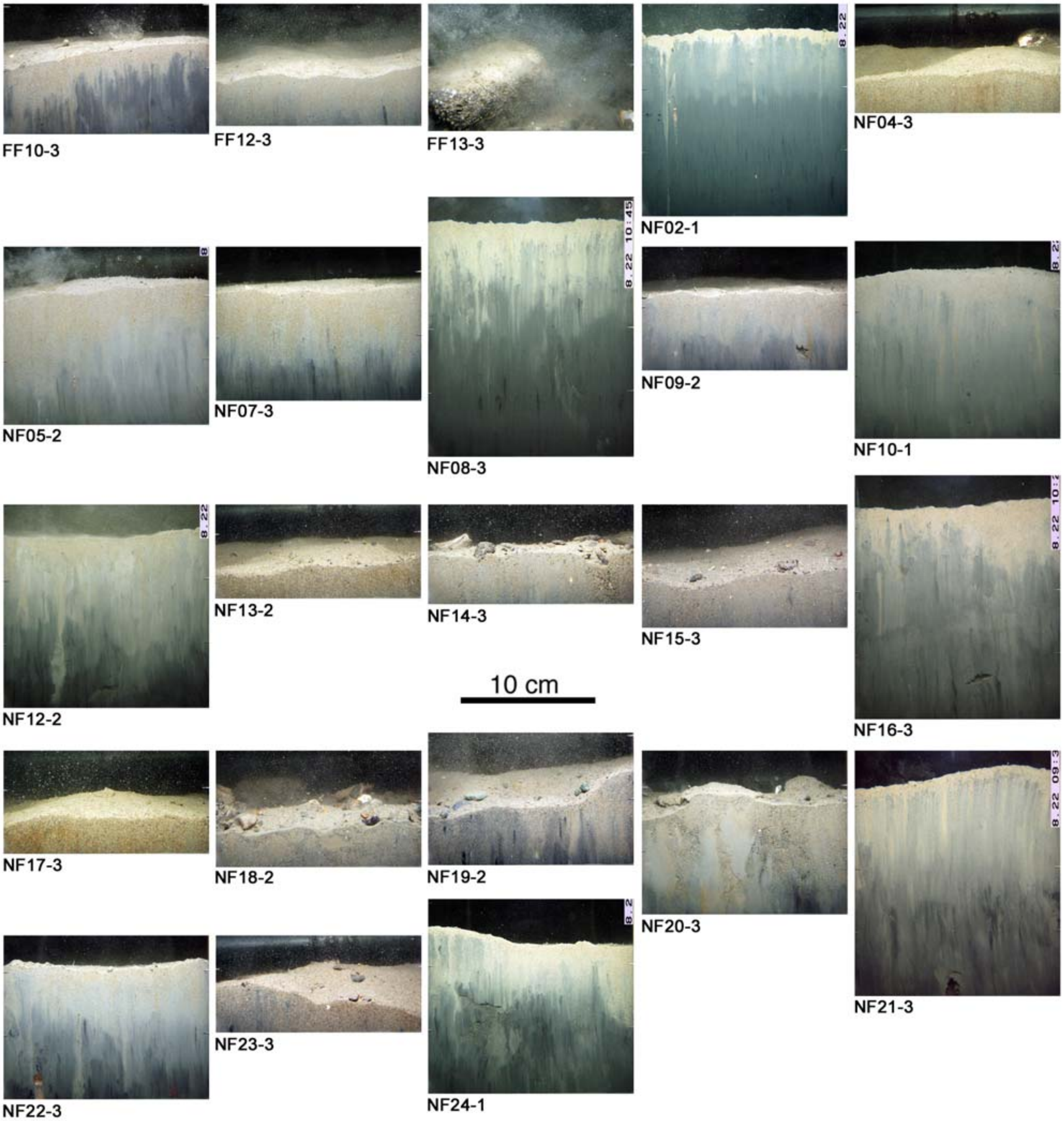


Figure 4-5. Example SPI for 2005 nearfield stations. Number following station is replicate image number. Image color was enhanced to emphasize the difference between oxic and anaerobic sediments.

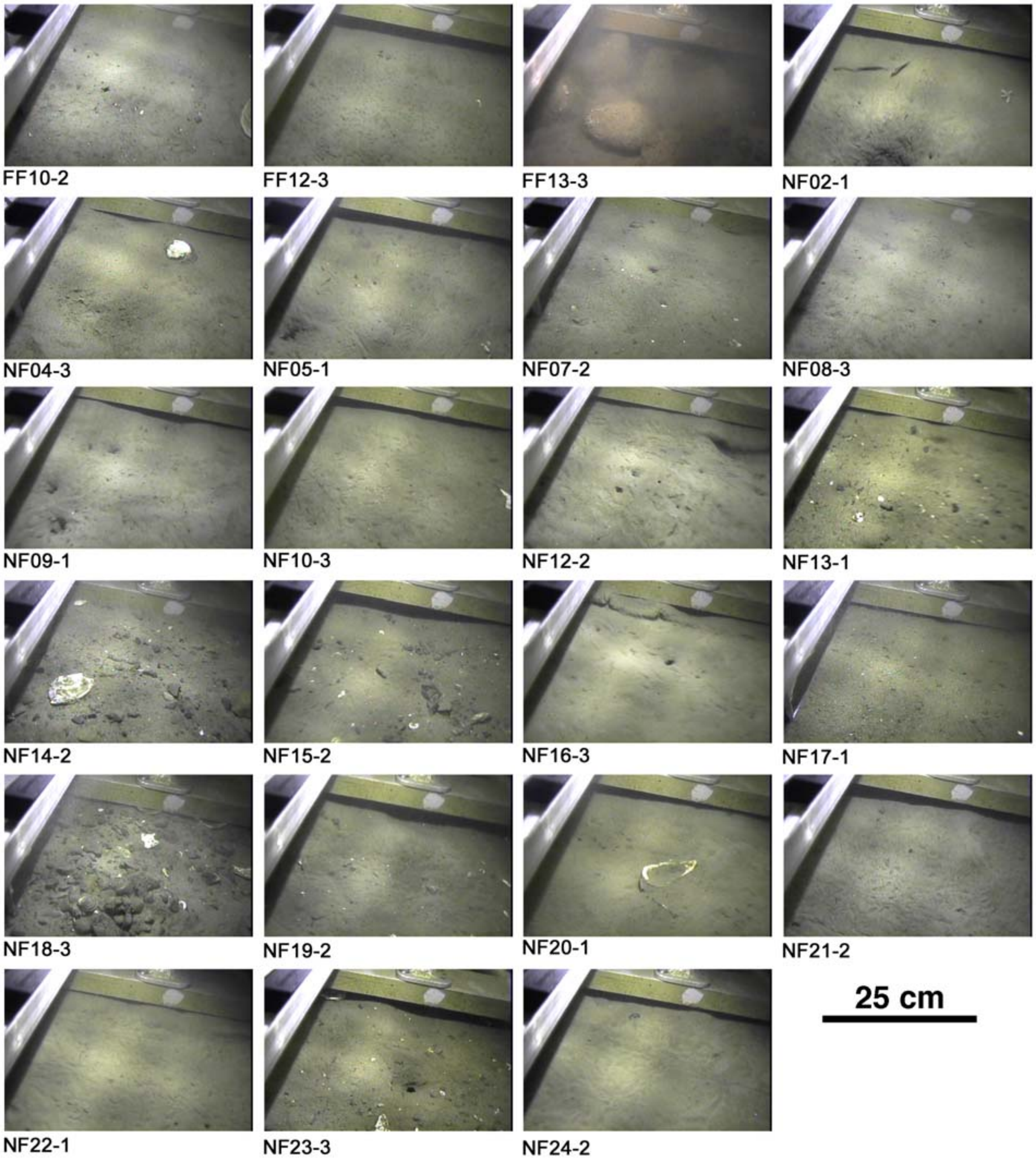


Figure 4-6. Example sediment surfaces for 2005 nearfield stations. Number following station is replicate image number. Images were contrast enhanced and edge sharpened.

Table 4.2 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**
FF10	VFS	.	PB to VFS	VFS	CB to SIFS	PB to GR	CB to FS	PB to FSSICL	VFS	FSSICL	PB to FSSI
FF12	.	.	VFS	FS	FS	VFS	VFS	VFS	VFS	VFS	VFS
FF13	.	.	SIFS	SIFS	CB to FSSI	CB to SI	FSSI	CB to FSGR	CB to FSSI	FSSI	CB to PB
NF02	VFS	PB to CS	SIFS	PB to GR	CB to FSSI	CB to MSCS	FSSI	FSSI	FSMS/FSSI	FSSICL	SIFS
NF04	FS	FS	PB to VFS	FS	GR to FS	FS	PB to FSMS	PB to FS	FS	FS	FSMS
NF05	FS	VFS	VFS	VFS	FS/SICL	FS/SICL	FSSICL	FSSICL	FSSICL	FSSICL	FS/FSSI
NF07	VFS	VFS	VFS	VFS	SIFS	SIFS/CL	FSSICL	FSSICL	FSSICL	FSSICL	PB to FSSICL
NF08	VFS	SIFS	VFS	VFS	SIFS	SIFS	SIFS	FSSICL	SIFS	FSSICL	FSSICL
NF09	VFS	VFS	VFS	VFS	FSSI	FSSI	FSSICL	FSSI	FSSICL	FSSICL	FSSICL
NF10	VFS	VFS	VFS	VFS	FSSICL	FSSICL	FSSICL	FSSICL	FSSICL	FSSICL	FSSICL
NF12	VFS	SI	SIFS	SIFS	FSSICL	FSSICL	FSSICL	FSSI	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	FSMSGR	FSMSGR
NF14	FS	PB to VFS	PB to FS	PB to VFS	PB to SIFS	PB to FSSICL	PB to FSSI	PB to FSSI	PB to FSSIGR	FSMSSIGR	PB to FSMSSI
NF15	FS	PB to VFS	GR to FS	GR to FS	PB to FSSI	PB to FSSI	PB to FSSI	GR to VFS	PB to FSSIGR	FSMSSIGR	PB to FSMSSI
NF16	VFS	SIFS	SIFS	SIFS	FSSICL	PB to FSSI	CB to FSSICL	FSSICL	CBPB	PB to FSSICL	PB to SICL
NF17	FS	CS to FS	FS	FS	GR to FSMS	PB to 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
NF19	.	PB to VFS	GR to VFS	FSSICL	FSSICL	CB to FSSICL	GR to FSSI	VFS	CB to FSSI	FSSIGR	PB to FSSI
NF20	VFS	PB to VFS	GR to FSMS	GR to SICL	PB to SIFS	PB to SIFS	PB to FSSI	FSSI	CB to FSSIGR	FSSIGR	PB to FSSI
NF21	.	SIFS	VFS	SIFS	SIFS	SIFS	SIFS	FSSICL	FSSICL	FSSICL	FSSICL
NF22	.	SIFS	SIFS	SIFS	SIFS	SIFS	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	FSMSGR	PB to FSMS
NF24	.	SI	SIFS	FSSICL	PB to FSSICL	FSSICL	FSSICL	FSSICL	FSSICL	FSSICL	FSSICL

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

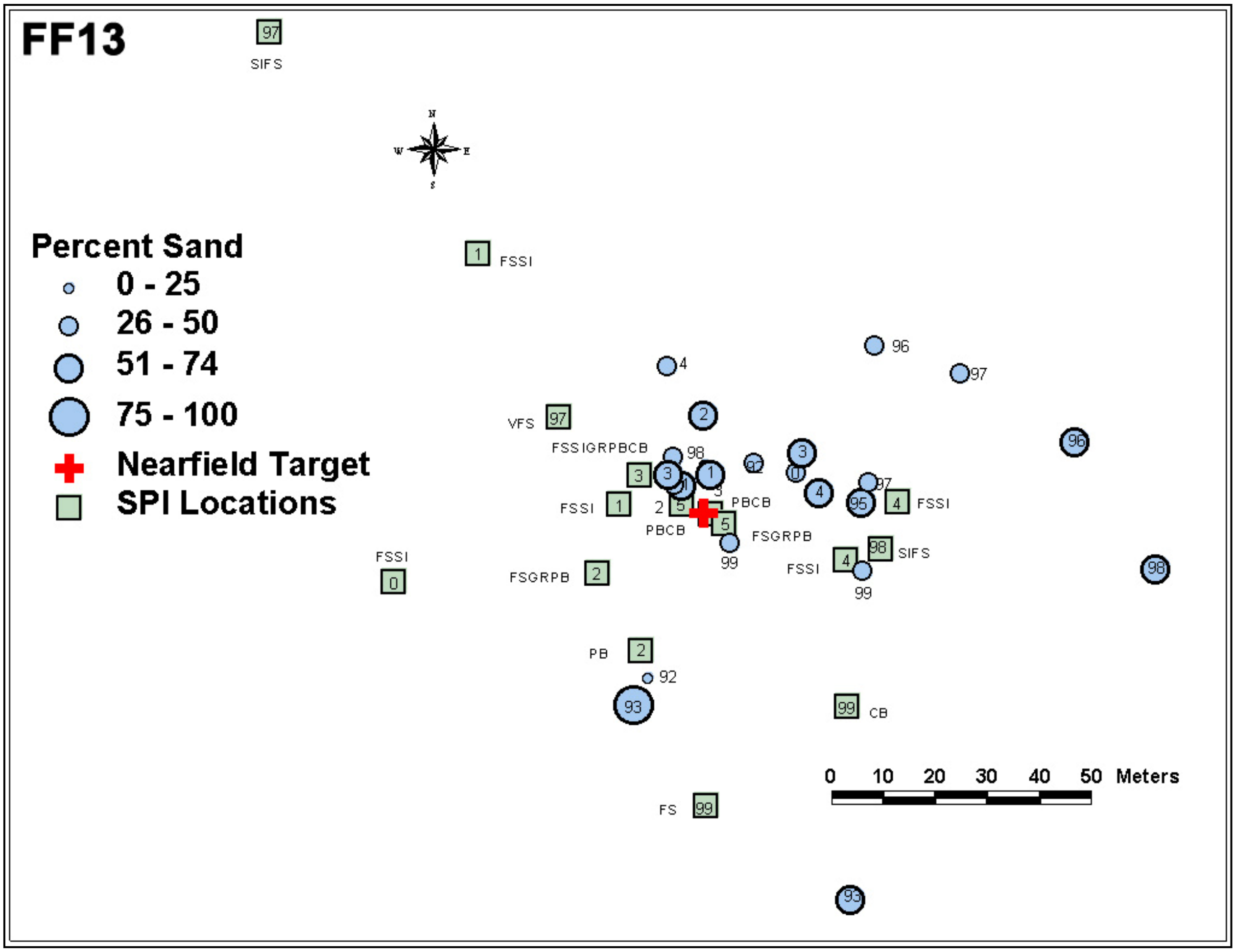


Figure 4-7. Spatial plot of individual replicate sediment and SPI data for station FF13. Cross is at the target coordinates for the station. Numbers inside symbols represent year of sampling.

Table 4-3. Summary of SPI parameters for nearfield stations, August 2005. 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	6.2	2.1	2.4	FSSI	PB	BIO/PHY	NONE	FEW	3.7	0.7	0.3	I-II	6.3
FF12	2.1	0.9	2.1	VFS	FS	BIO/PHY	NONE	SOME	1.7	1.7	0.0	I-II	5.5
FF13	2.0	4.0	IND*	PB	CB	PHY	NONE	MANY	IND	IND	IND	I	IND
NF02	9.7	0.8	0.9	SIFS	FS	BIO/PHY	NONE	FEW	4.0	3.3	1.0	I-III	6.0
NF04	3.1	1.3	>3.1**	FSMS	MS	PHY	NONE	SOME	0.0	0.0	0.0	I	7.0
NF05	8.3	1.2	4.4	FS/FSSI	FS	BIO/PHY	NONE	MANY	3.0	2.0	0.3	I-II	8.3
NF07	7.9	0.9	3.4	FSSICL	PB	BIO/PHY	NONE	SOME	1.7	1.3	0.7	I-II	7.7
NF08	16.3	0.8	2.2	FSSICL	FS	BIO/PHY	NONE	FEW	2.3	3.7	1.0	II-III	8.3
NF09	7.0	0.8	2.6	FSSICL	FS	BIO/PHY	FEW	SOME	6.7	5.3	0.7	I-III	8.0
NF10	9.5	1.0	3.5	FSSICL	FS	BIO/PHY	NONE	MANY	5.3	3.7	0.7	II-III	10.0
NF12	13.5	0.7	2.3	FSSICL	FS	BIO/PHY	NONE	SOME	2.0	4.7	1.3	II-III	8.7
NF13	1.9	1.0	>1.9	FSMS	GR	PHY	NONE	MANY	0.0	0.0	0.0	I-II	IND
NF14	3.3	1.5	2.5	FSMSSI	PB	PHY	NONE	FEW	0.3	0.3	0.0	I	5.0
NF15	3.9	2.1	>3.9	FSMSSI	PB	PHY	FEW	SOME	0.3	1.3	0.3	I-II	9.5
NF16	15.7	0.9	1.5	SICL	PB	PHY	NONE	FEW	3.3	4.3	0.7	I-III	6.7
NF17	2.5	1.3	>2.5	FSMS	MS	PHY	NONE	SOME	0.0	0.0	0.0	I	IND
NF18	2.9	1.4	>2.9	FSSI	PB	PHY	NONE	MANY	0.0	0.0	0.0	I	IND
NF19	3.2	3.1	1.2	FSSI	PB	PHY	NONE	SOME	0.7	1.7	0.0	I	3.0
NF20	7.6	1.5	4.6	FSSI	PB	PHY	FEW	SOME	1.0	2.3	0.0	I-II	7.3
NF21	13.3	1.4	2.5	FSSICL	FS	BIO/PHY	NONE	SOME	4.7	5.3	1.7	II-III	8.7
NF22	9.0	1.3	2.6	FSSICL	FS	BIO/PHY	NONE	SOME	3.3	4.7	1.0	II-III	8.0
NF23	2.4	1.2	>2.4	FSMS	PB	PHY	NONE	SOME	0.0	0.0	0.0	I-II	IND
NF24	9.9	1.1	2.4	FSSICL	FS	BIO/PHY	NONE	SOME	3.3	3.3	2.0	II-III	9.0

*IND = Indeterminate **> = Actual values is deeper than prism penetration,

Apparent color RPD Depth—At five porous, coarse-sediment stations (NF04, NF13, NF15, NF17, and NF23) and one finer-sediment station (NF18), 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 2005. At stations FF12 and NF14, one 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 2005 was similar to both the baseline and previous post-diversion years (Figure 4-3). In 2005, the average apparent color RPD layer depth ranged from 0.9 cm (NF02) to 4.6 cm (NF20), with a grand mean of 2.6 cm (SD = 0.92 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 2005), found that there was no significant difference in the depth of the apparent color RPD layer depth between baseline years and 2005 ($F = 2.04$, $p = 0.164$). The fact that there was no statistical difference between 2005 and the baseline would also indicate that the RPD threshold was not exceeded. The difference between 2005 and the baseline was a deepening of the RPD by 13%. When the six baseline years were compared to the five discharge years for mean, median, and range of RPD layer depth, there were no significant differences.

There is evidence that for the nearfield the apparent color RPD layer depth from SPI images is a conservative estimate of the boundary between oxic and reduced sediments, which is operationally defined as an Eh of 0 to 100 mV (see Diaz and Trefry In Press). Oxidation-reduction potential of sediments measured as Eh between stations NF10 and NF12 (MB01 of Tucker *et al*. 2005), and NF21 and NF22 (MB02 and MB03) were indicative of highly oxic conditions (Tucker *et al.* 2005). At station MB01 and MB03 in August 2005, the Eh profile did not drop below 100 mV with the lowest Eh of 123 mV at 5 cm for station NF10 and 193 mV at 5 cm for station NF22 (Tucker *et al.* In Preparation), which was close to the 3.5 cm (0.7 SD) SPI-estimated RPD layer depth for NF10 and deeper than the 2.6 cm (0.7 SD) RPD for NF22 in 2005. At both stations, biogenic structures convoluted the RPD layer and extended its depth into the sediments (Figure 4-5). On average, the maximum extent of the RPD layer was 7.1 cm (1.2 SD) at NF10 and 6.4 cm (2.9 SD) at NF22. For station MB02, the August 2005 Eh profile dropped to 89 mV at 5 cm and was 103 mV at 3 cm, which was close to the 2.6 cm (0.7 SD) RPD layer depth for 2005 but shallower than the maximum extent of 6.4 cm (2.9 SD) for NF21. For coastal sediments with low TOC content, it appears that the apparent color RPD layer depth is more representative of the thickness of highly oxic sediments than the actual boundary between oxic and anaerobic sediments. For low TOC deep sea sediments, Diaz and Trefry (In Press) found SPI-estimated RPD layer depths to have a higher correlation with dissolved oxygen profiles than Eh profiles.

Biogenic Activity—The importance of biogenic structures and organism activity in structuring surface sediment seemed to decline in 2005 relative to 2004. For example, while tubes were observed at all 23 stations, their overall density declined. In 2004, ten stations had many tubes (>24 tubes/image); in 2005 there were five stations with many tubes. 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 NF09, NF15, and NF20 had larger amphipod-like tubes. Mobile epifauna were not common: small shrimp were seen at stations NF02 and NF22, and a starfish (*Asterias*) and crab (*Cancer*) were seen at stations NF20.

Sediment surfaces at 12 of the 23 stations in 2005 appeared structured by a combination of biological and physical processes (e.g., NF09). At 11 stations (e.g., FF13), physical processes dominated. No station was classified as having a biologically structured sediment surface in 2005 (Table 4-3). Most of the pebble-size sediments were not covered with tubes as they were in 2004, which may indicate that weather was more severe over the 2004/2005 winter, imparting more stress on the bottom. The one station that had cobble (FF13) did have tubes covering the cobble surface, but only one of nine stations with pebbles had tubes on the pebbles (NF18).

The number of subsurface biogenic structures, primarily burrows and oxic voids, was not significantly different between 2005 and 2004, but mean structures per image all trended down. However, free-burrowing infaunal worms declined from a grand average in 2004 of 4.8 (SE = 0.90) to 2.2 (SE = 0.42) worms/image in 2005 (Welch ANOVA, F = 7.3, p = 0.011). Station NF09 had the highest average number of worms with 6.7 per image (SD = 3.8), but the maximum worms per image in 2005 was 12 at an image from NF21. The number of worms in 2005 was also significantly lower than the last three years of the baseline period (ANOVA, F = 9.2, p = 0.004). 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 2004 to 2005 (See Chapter 5).

Biogenic structures associated with activities of successional Stage II and III fauna were the most common evidence of biological processes in 2005 and were similar to those found during the baseline period. Included were what appeared to be *Haploops* spp. tubes (NF09), biogenic whips or sticks of *Dyopedos* spp. (FF12), and biogenic mounds (NF09). Subsurface biogenic structures associated with infaunal organisms included active oxic burrows (NF21) and water-filled oxic voids (NF24). Cerianthid anemones were observed at stations NF02 and NF22.

Successional Stage and Organism Sediment Index—The distribution of estimated successional stages of the infaunal communities in 2005 was about evenly split between pioneering (Stage I) and a combination of pioneering and intermediate (Stage I to II), and a combination of intermediate and equilibrium (Stage II to III) (Figure 4-2). About three-fourths of the stations (17 of 23) classified as a mixture of successional stages (Table 4-3). Stage I appeared to dominate at the other six stations. 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 communities also dominated six stations. Stage II and III successional designations were made based on the degree of biogenic sediment reworking and presence of larger fauna. Relative to 2004, the pioneering Stage I classification increased in 2005 for the second time post-baseline, the first time being 2002 (Figure 4-2). Over the 14-year period of sampling the nearfield, the largest shift in successional stage occurred during the baseline period between 1997 and 1998 when the Stage I classification declined and 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 2005 Stage II and III classifications dominated.

These changes in successional stage classification correspond closely to the water quality periods defined by Taylor (2005). In period A, from 1991 to 1997, which included cessation of sludge dumping within the harbor and improvements in treatment, the successional stage in the nearfield was dominated by Stage I. During period B (1998 to 1999), which included transfer of all sewage effluent to Deer Island, Stages II and III dominated. In period C, which started with the operation of the offshore outfall in 2000, all three successional stages were present, with Stage I and III predominating (Figure 4-2). Given the distance between the harbor and nearfield it is hard to imagine how events in Boston Harbor could be so tightly coupled with the nearfield.

In 2005, the mean Organism Sediment Index (OSI) was 7.4 (SE = 0.40), 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 2005, three stations had OSI values <6 (FF12, NF14, and NF19). At these stations, the stressor appeared to be physical processes with no sign of stress from organic loading (Table 4-3). Sediments at NF14 did appear to coarsen in 2005. At another five stations, which were also physically dominated, the OSI could not be calculated because of shallow prism penetration. The lowest station-averaged OSI value was 3.0 at station NF19, which had coarse heterogeneous sediments with little evidence of biological activity. In 2004, NF19 also had the lowest average OSI value. The highest average OSI in 2005 was 10.0 at station NF10, which had finer sediments and a well-developed infaunal community.

4.3.2 Comparison of Pre-and Post-Diversion Results

If the outfall is considered a point source of stress to the nearfield, then local outfall effects would be expected to be related with distance from and time since start-up of the outfall. To test this hypothesis we used analysis of covariance with distance measured as a straight line from all 23 stations to the nearest diffuser on the outfall and year as covariates, and baseline/post diversion as the factor with SPI, infaunal community, and sediment parameters as the dependent variables. None of the infaunal parameters was different between baseline and postdiversion periods, but total abundance and total species were lower with increasing distance from the outfall and evenness was lower with time (Table 4-4). For sediment parameters, percent gravel decreased postdiversion and *Clostridium perfringens* spores normalized to percent fines increased. Relative to distance from the outfall, both percent gravel, and *C. perfringens* spores and TOC, both normalized to percent fines, declined with distance from the offshore outfall. For SPI parameters, anaerobic voids per image declined postdiversion. There were no relationships with distance from the outfall, but OSI increased with time (Table 4-4).

There were no significant relationships between RPD layer depth for baseline vs. postdiversion or distance from the outfall or time. For 2005, the mean apparent color RPD layer depth of 2.6 cm (SD = 0.20) was statistically the same as the baseline period RPD of 2.3 cm (SD = 0.88) (Welch ANOVA, F = 2.04, p = 0.164). The fact that there was no statistical difference between 2005 and the baseline would also indicate that the RPD threshold was not exceeded. There did not appear to be any relationship between RPD layer depth and outfall operation, which started in September 2000 (Figure 4-8). There were no significant differences baseline/postdiversion for the four stations with measured RPD depths from 1997 to 2005 and within the topographic feature that contained the outfall (NF10, NF12, NF21, and NF22). At stations NF05 and NF07 within the same depth stratum (30 to 35 m) as the outfall but to the northwest and NF22 to the south, only NF05 had a significantly deeper RPD layer postdiversion (t-Test, t = 2.48, p = 0.038 and Figure 4-3). For stations NF08 and NF09 in a shallower depth stratum (25 to 30 m) northwest of the outfall, there were no differences in RPD between baseline and postdiversion.

From the SPI for 2005, there was little change in the sedimentary environment relative to baseline or other postdiversion years. Within a station, there did not appear to be any change in the sediment color or fabric, which would indicate there has not been an accumulation of organic matter in surface sediments of the nearfield stations. Similar conclusions were drawn from the TOC analysis and sediment flux studies (Chapter 3 and Tucker *et al*. In Preparation). Sediment grain-size did indicate that sediments at seven nearfield stations were coarser in 2005, possibly related to winter storms, and flux measurements for the last several years have remained low indicating there has been little change in sediment quality.

Table 4-4. Analysis of covariance summary comparing baseline and postdiversion periods with distance from outfall.

Parameter	Baseline Mean		Post-diversion Mean	p	Baseline N	Post-diversion N	Distance as Covariate	p	Year as Covariate	p
Sediment:										
Percent Fines	30.6	=	32.4	0.382	128	94	No relationship	0.341	No relationship	0.636
Percent Gravel	6.4	>	5.3	0.042	128	94	Less with distance	0.039	No relationship	0.124
C. perfringens normalized to % Fines	86.5	<	102.5	0.008	127	94	Less with distance	0.005	Less with time	0.016
TOC normalized to % Fines	0.04	=	0.03	0.458	126	94	Less with distance	<0.001	No relationship	0.93
Infauna:										
Total Abundance	2460	=	2626	0.495	128	93	Lower with distance	<0.001	No relationship	0.916
Total Species	71.3	=	73.6	0.552	128	93	Lower with distance	0.012	No relationship	0.495
H'	3.8	=	3.8	0.128	128	93	No relationship	0.312	No relationship	0.105
J'	0.6	=	0.6	0.052	128	93	No relationship	0.070	Lower with time	0.039
LSA	14.3	=	14.7	0.565	128	93	No relationship	0.341	No relationship	0.757
SPI:										
Modal Phi	4.1	=	4.4	0.869	128	115	No relationship	0.097	No relationship	0.05
OSI	6.4	=	6.5	0.150	123	108	No relationship	0.748	Increase with time	0.014
RPD	2.2	=	2.5	0.079	92	82	No relationship	0.885	No relationship	0.852
Successional Stage*	1.78	<	1.83	0.002	126	115	No relationship	0.764	Increase with time	0.001
Infauna/Image	3.5	=	3.2	0.232	99	112	No relationship	0.421	No relationship	0.421
Burrows/Image	2.3	=	3.2	0.874	99	112	No relationship	0.623	No relationship	0.053
Oxic Voids/Image	0.7	=	0.6	0.177	99	112	No relationship	0.277	No relationship	0.174
Anaerobic Voids/Image	0.09	>	0.01	0.026	99	112	No relationship	0.954	No relationship	0.585

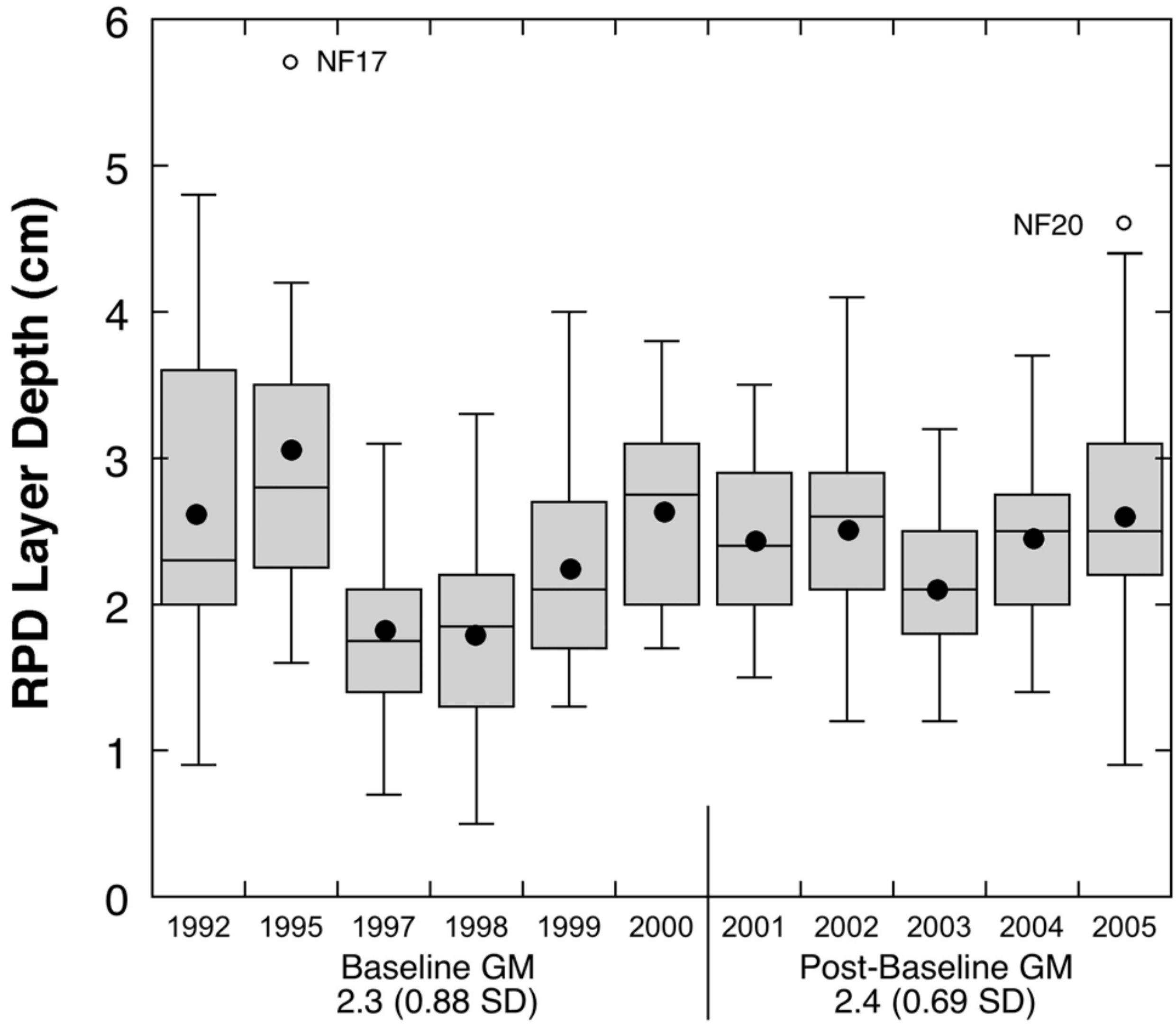


Figure 4-8. Apparent color RPD layer depth (cm) summarized by year for all data from nearfield stations. Box is interquartile range (IR), bar is median, circle is mean, and whiskers are data range. Outliers are >(2*IR).

Biogenic structures on the sediment surface and organism activity in 2005 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. In 2005, stations NF09, NF15, and NF20 appeared to have amphipod tubes. Station NF05, which had amphipod tubes in 1995 (based on a reanalysis of 1995 images), did not appear to have amphipod tubes in 2005. Overall, in 2005 it appeared that physical processes predominated over biological processes in structuring surface sediments. However, in 2005 the OSI continued to trend upward with a grand average of 7.4 (Figure 4-4). The increase in the OSI appears counter to the increase in physical stress the bottom received over the winter of 2004–2005 (Butman *et al.* In Preparation). While there was an increase in stress to surficial sediments, which disrupted small surface- and near-surface-dwelling infauna that were mostly pioneering successional Stage I fauna, the deeper dwelling fauna responsible for much of the subsurface biogenic activity and higher successional Stage were unaffected. This, combined with deeper RPD layer depths, led to higher OSI values even with the increased predominance of physical processes. In contrast, the increasing trend in OSI that started in 1998 was a representation of the increasing importance of biological processes in structuring surface sediments throughout the nearfield.

The sediments at many stations in 2005 continued to be heterogeneous, with a mixture of grain sizes ranging from sandy-silts-clays to pebbles (Table 4-3). Relative to 2004, 2005 sediments were coarser with the difference between years being related to higher bottom stress in 2005 (Butman *et al.* In Preparation). 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 reflected the importance of physical processes in structuring benthic habitats.

While the general appearance of the sediments and benthic habitat conditions at the nearfield stations in 2004 was similar to that of the other post-diversion and baseline years, the overall dominance of surface sediments by biogenic structures and organism activity in 2005 appeared to be less relative to the last three years of the baseline period. 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 m2), but tube mats have not been observed since 2002. Also, the medium-size twisted tube that was widespread at nearfield stations in 2001 occurred at only two stations in 2005. Three stations did have low densities of amphipod tubes in 2005 but they were not the same three stations as in 2004. While biogenic activity at the sediment surface appeared to be reduced in 2005 relative to the last portion of the baseline period, the level of subsurface biogenic activity appeared similar.

4.3.3 Spatial and Temporal Patterns

From 1992 to 2005 the nearfield was sampled 11 times with SPI. Over this 14-year period there was variation within a station through time that appeared to be related to both regional trends and small-scale, on the order of 10s of m, spatial variation. Examples of SPI from 1995 to 2005 are in Figures 4-9 and 4-10. Images from 1992 were not available.

Based on the modal grain-size of the SPI and the median grain-size from grabs from 1997 to 2005, the 23 stations divided into two groups using cluster analysis (normalized Euclidean distance with complete linkage sorting) based on temporal trends in grain-size. Data from 1992 and 1995 were not included in the analysis because not all 23 stations were sampled, but 1995 was added to the comparison of means as only FF10, FF12, and FF13 were not sampled (Table 4-5). Both estimates of grain-size produced similar station groupings with Group A being coarser than Group B. For all years, median Phi was significantly lower for Group A stations (Table 4-5). Differences between groups for modal grain-size tended to be not as large, with 1998, 1999, 2000, and 2003 not being significant. The largest difference between groups was in 2005 when Groups A and B were over 2.5 Phi apart for both modal and median grain-size. It appeared that Group A coarsened from 2004 to 2005 but Group B remained essentially the same.

Table 4-5. Temporal comparison of SPI modal grain-size with sediment median phi from 1995 to 2005. Groups A and B were determined from cluster analysis of grain-size (normalized Euclidean distance with complete linkage sorting).

Sediment Median Phi						
		Group A			Group B	
		NF04	NF17		FF10	NF09
		NF13	NF18		FF12	NF10
		NF14	NF19		FF13	NF12
		NF15	NF20		NF02	NF16
			NF23		NF05	NF21
					NF07	NF22
					NF08	NF24
Year Groups			Mean		Mean	p
	1995*		2.2	<	4.6	0.007
2	1997		2.3	<	3.7	0.001
2	1998		1.5	<	3.4	0.004
2	1999		1.9	<	3.6	0.002
1	2000		1.5	<	3.7	<0.0001
2	2001		1.9	<	3.7	<0.0001
3	2002		2.0	<	3.9	<0.0001
3	2003		2.1	<	3.8	<0.0001
3	2004		2.1	<	4.3	0.001
3	2005		1.6	<	4.3	0.002
SPI Modal Phi						
		Group A			Group B	
		FF12	NF15		FF10	NF10
		FF13	NF17		NF02	NF12
		NF04	NF18		NF05	NF16
		NF13	NF19		NF07	NF21
		NF14	NF20		NF08	NF22
			NF23		NF09	NF24
Year Groups			Mean		Mean	p
	1995*		2.6	<	4.3	0.009
1	1997		3.4	<	4.0	0.050
1	1998		4.0	=	3.8	0.791
2	1999		4.2	=	5.0	0.053
2	2000		4.1	=	4.2	0.913
3	2001		3.8	<	5.1	0.003
3	2002		3.5	<	5.3	<0.0001
3	2003		3.4	=	4.4	0.146
3	2004		3.1	<	5.5	<0.0001
3	2005		2.8	<	5.3	<0.0001

* FF10, FF12, and FF13 were not sampled in 1995.

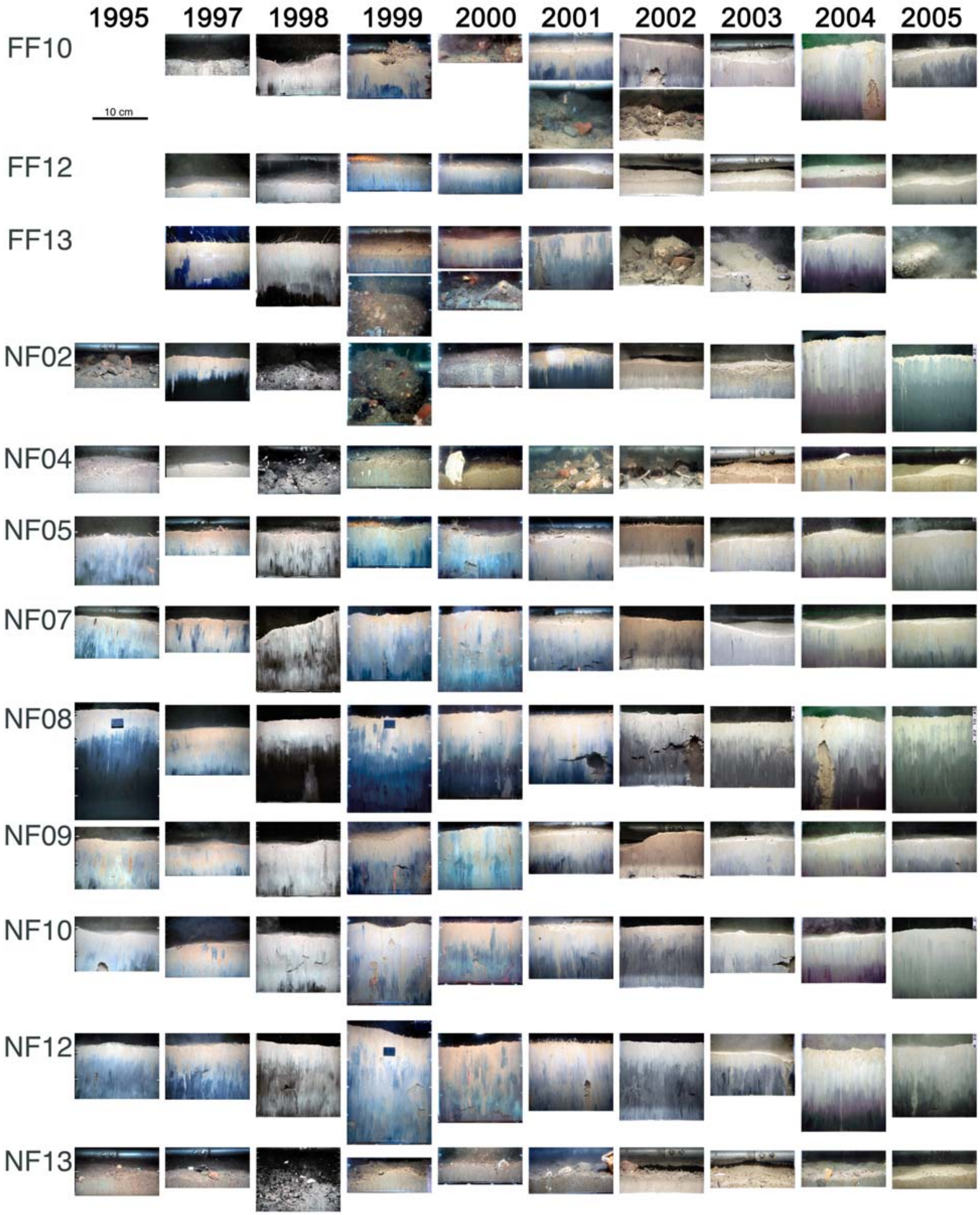


Figure 4-9. Example SPI images from nearfield stations FF10 to NF13. For some stations two images were used to show the range of variation in sediment type between replicates. Color of all images was enhanced to emphasize the difference between oxic and anaerobic conditions. Black rectangle in some images is a reflection guard and the light band at the bottom of the 2002 images is an artifact.

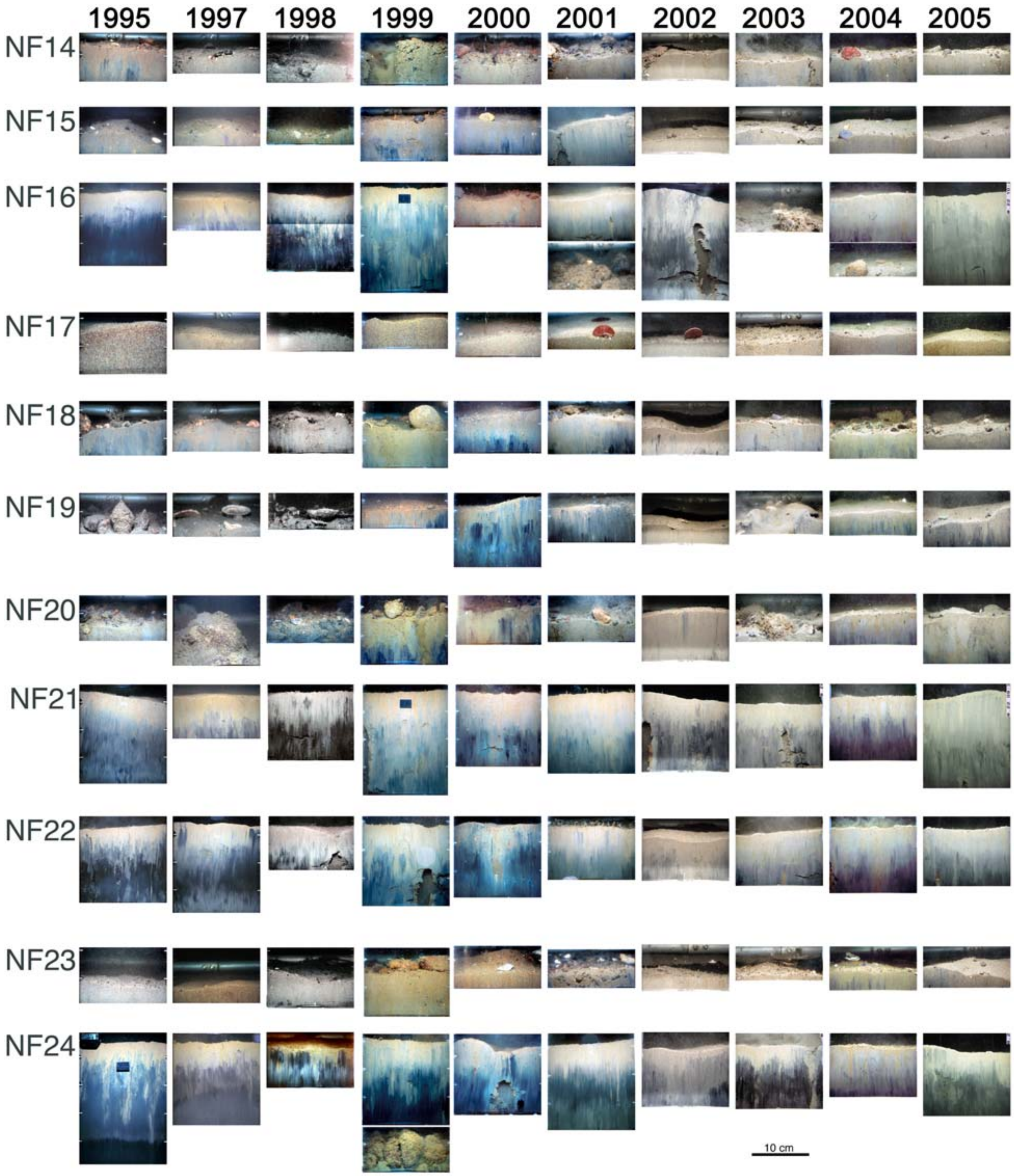


Figure 4-10. Example SPI images from nearfield stations NF14 to NF24. For some stations two images were used to show the range of variation in sediment type between replicates. Color of all images was enhanced to emphasize the difference between oxic and anaerobic conditions. Black rectangle in some images is a reflection guard and the light band at the bottom of the 2002 images is an artifact.

The difference was not due to station depth as there was no significant difference between groups in depth. From SPI it appeared that pebbles were more numerous in 2005 relative to 2004 at Group A stations (Figures 4-9 and 4-10). 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 2005 for Group A is consistent with the higher bottom stress in 2005 from winter storms (Butman *et al.* In Preparation). Possible hypotheses as to why Group B stations did not coarsen in 2005 is 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 2005 (Tables 4-2 and 4-5).

There were many significant differences between other SPI and infaunal parameters when averaged by sediment derived Group A and B (Table 4-6). All sedimentary parameters were significant and pointed to Group A being coarser grained with lower TOC and *Clostridium perfringens* spore concentrations. While infaunal abundance was higher in Group A, other community structure parameters were either the same or lower. SPI parameters, which are measures of infaunal activity such as bioturbation, were lower for Group A. The exception was the depth of the RPD layer, which was the same for both groups. Through time there were significant increases in SPI parameters that would be indicative of increased biogenic activity, much of which occurred at Group B stations.

At many nearfield stations, small-scale spatial variation on the order of 10s of meters appeared to contribute to long-term variation in sediments and likely biological parameters. Variation in sediments could be related to both sediment dynamics (movement, erosion, or deposition) and true spatial pattern. Examples of stations with spatial gradients in sediments are NF02 and FF13; whereas NF17 and NF24 had homogeneous sediments. At NF02, there was a patch of coarse sediment to the north of the target coordinates. Whenever SPI samples were located to the north of the target coordinates, sediments ranged from medium sand to cobbles. Closer to the target and east/west sediments were finer (Figures 4-9 and 4-11). Sediments samples were consistently 75% to 100% sand, except 1992, 2002, and 2005 when sand was <50%. Declines in percent sand in 1992 and 2005 were concordant with stormy winter conditions. At FF13, sediments to the northwest of target coordinates were finer sands and silty, while near and to the south sediments were more heterogeneous with gravel to cobble sediments (Figure 4-7). Sand content at FF13 was variable with little spatial pattern, but in 1992 there was <25% sand. FF13 was not sampled in 2005. At NF17 and NF24, stations closest to the outfall, sediments were more uniform. At NF24, sediments were fine-sand-silt-clay for all years with one occurrence of pebble in 1999. Sand content tended to be <50% with no spatial pattern (Figures 4-10 and 4-12). Station NF17 was consistently fine-medium-sand with >75% sand, and gravel and pebble occurring only in 1999 and 2000, respectively (Figures 4-10 and 4-13).

Table 4-6. Temporal comparison of SPI and infaunal parameters from 1995 to 2005 by sediment- derived station groups (see Table 4-5) using analysis of covariance.

Parameter	Group A		Group B	p	Year as Covariate	p
Sediment:						
Percent Fines	13.8	<	47.4	<0.0001	No relationship	0.549
Percent Gravel	10.1	>	1.5	<0.0001	No relationship	0.756
Clostridium perfringens	1530	<	2860	<0.0001	No relationship	0.167
TOC	0.6	<	1.0	<0.0001	No relationship	0.841
Infauna:						
Total Abundance	2959	>	2567	0.036	No relationship	0.283
Total Species	75.6	=	74.2	0.569	No relationship	0.808
Shannon diversity index H'	3.5	<	3.8	0.002	No relationship	0.601
Pielou's Evenness J'	0.57	<	0.62	0.001	No relationship	0.505
Log-series *alpha* LSA	14.7	=	14.9	0.492	No relationship	0.732
SPI:						
OSI	5.6	<	7.2	<0.0001	Increase with time	0.004
RPD	2.1	=	2.3	0.061	Increase with time	0.001
Successional Stage*	1.5	<	2.2	<0.0001	Increase with time	0.004
Infauna/Image	2.5	<	5.6	<0.0001	No relationship	0.767
Burrows/Image	1.8	<	4.5	<0.0001	Increase with time	<0.0001
Oxic Voids/Image	0.2	<	1.2	<0.0001	No relationship	0.538
Anaerobic Voids/Image	0.01	<	0.10	0.028	Decline with time	0.014

* Successional Stage coded as: I = 1, II = 2, and III = 3

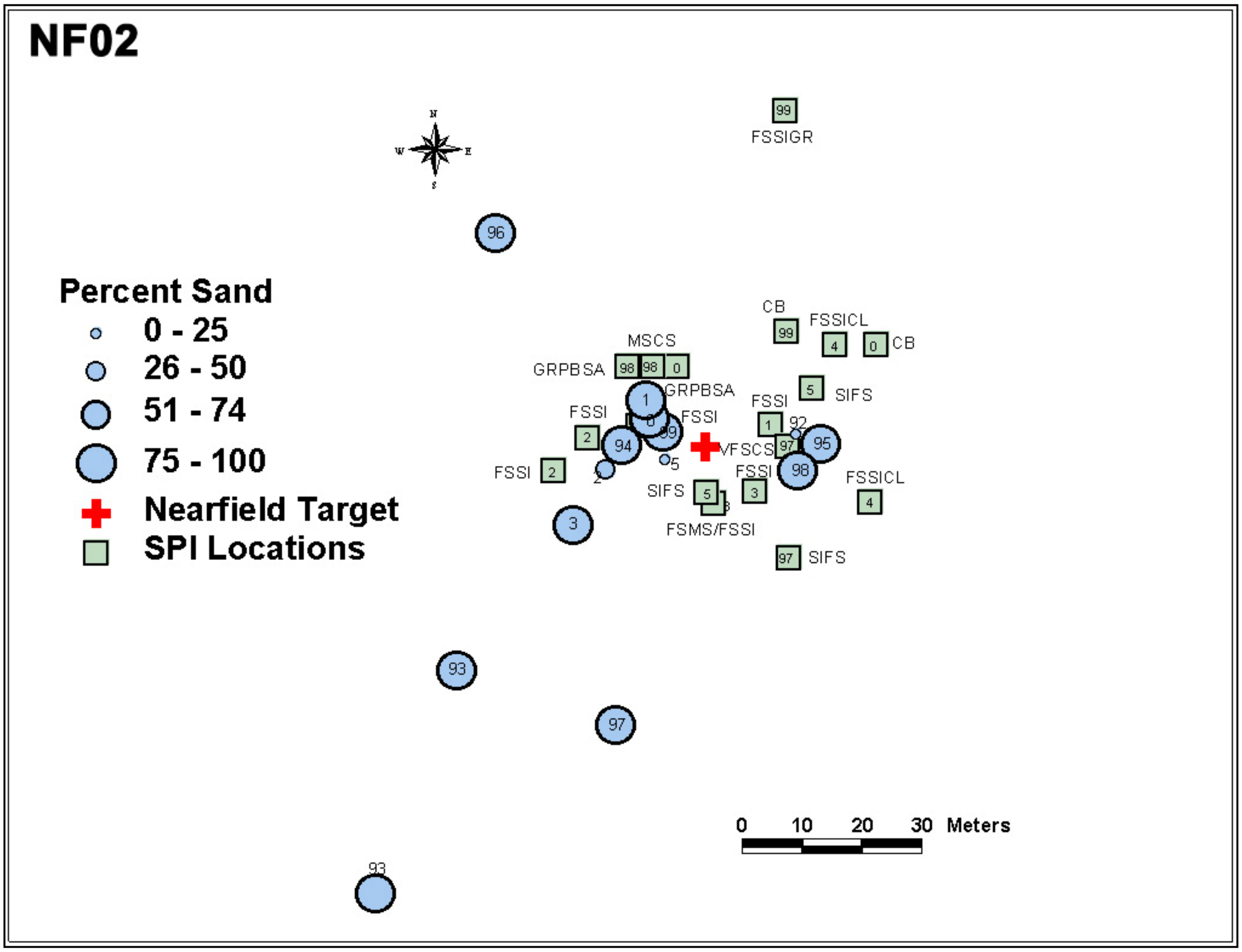


Figure 4-11. Spatial plot of individual replicate sediment and SPI data for station NF02. Cross is at the target coordinates for the station. Numbers inside symbols represent year of sampling.

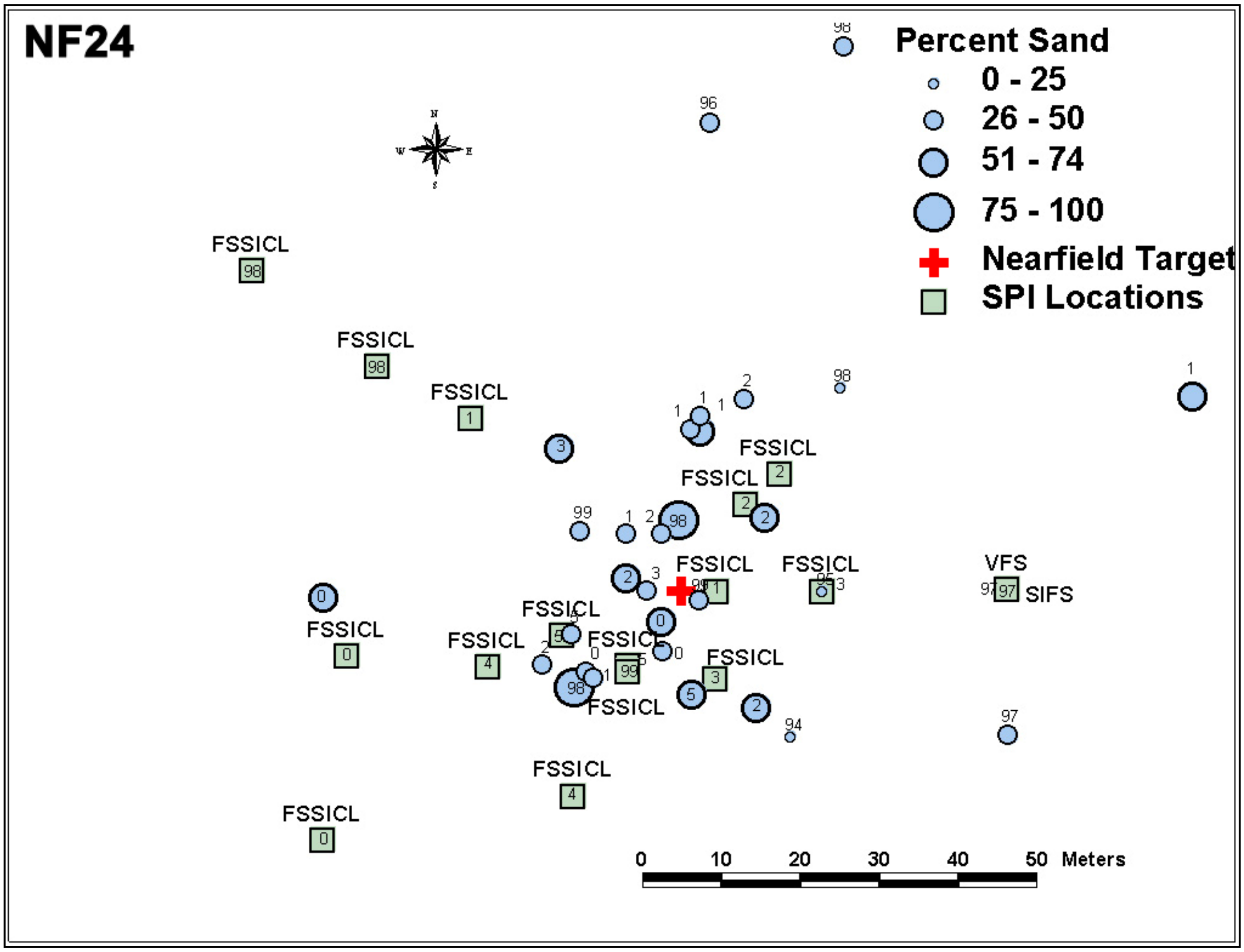


Figure 4-12. Spatial plot of individual replicate sediment and SPI data for station NF24. Cross is at the target coordinates for the station. Numbers inside symbols represent year of sampling.

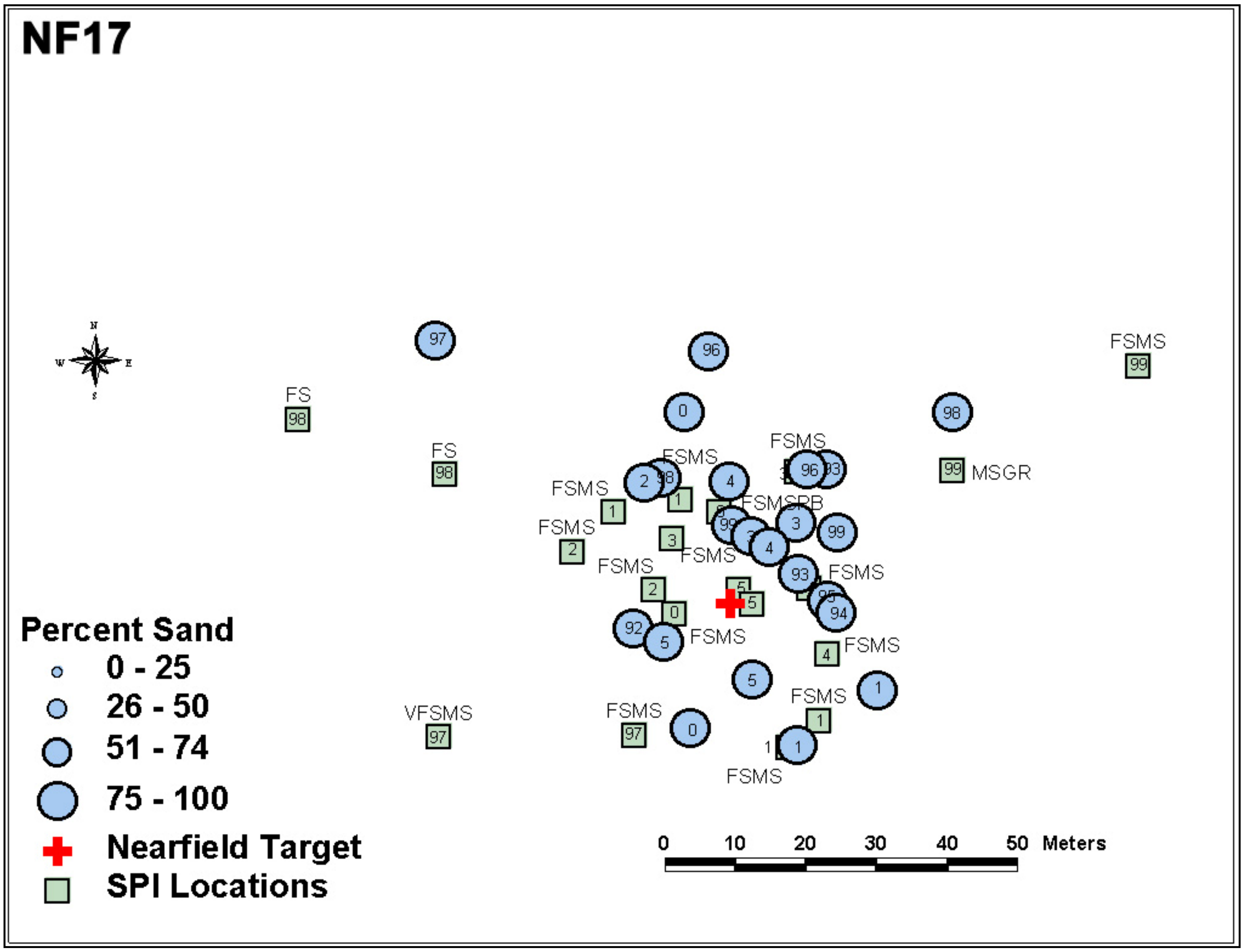


Figure 4-13. Spatial plot of individual replicate sediment and SPI data for station NF17. Cross is at the target coordinates for the station. Numbers inside symbols represent year of sampling.

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?*

There do not appear to be any regional trends between RPD layer depth and the outfall, which started operation in September 2000. 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 2005 of 2.6 cm was not significantly different from the baseline RPD of 2.3 cm. A 50% shallowing in RPD layer depth would require the mean RPD for a year to be 1.2 cm or less. The average RPD for 2005 was well within the range of annual RPDs, with 1998 being the shallowest year at 1.6 cm and 1995 the deepest year at 3.0 cm (Figure 4-8).

Based on the color and texture of sediments in the 2005 SPI images, it does not appear that the amount of deposited organic matter has changed relative to the operation of the outfall, postdiversion, or the baseline for the nearfield SPI stations. TOC was also not different between baseline and postdiversion years (Chapter 3). The percentage of TOC in sediments in 2005 tended to be at the low end of the range of all values from 1992 to 2004 for the 12 nearfield stations sampled. Only FF12 and NF02 were above the long-term mean TOC (Chapter 3).

5. 2005 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 2005, a different subset of stations were sampled than 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 2001–2004, after the outfall went online, did not indicate any discernable impact of the discharge on the infauna (Kropp *et al.* 2002, Maciolek *et al.* 2003, 2004, 2005). 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 (1992–2005) 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,

$$I_{10}(\text{station}) = \begin{cases} 1 & \text{if station is less than 10 km from outfall.} \\ 0 & \text{otherwise.} \end{cases}$$

and

$$I_2(\text{station}) = \begin{cases} 1 & \text{if station is less than 2 km from outfall.} \\ 0 & \text{otherwise.} \end{cases}$$

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

$$\begin{aligned} \log\left(\mu_{ij}\right) = \mu + \alpha_{si} + \alpha_{yj} + \beta_1 x_{ij} + \alpha_{10D} I_{10}(station_i) I_D(y_j) \\ + \alpha_{2D} I_{10}(station_i) I_D(y_j) \end{aligned} \qquad (0.1)$$

where α_{10D} and α_{2D} 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,"

$$\text{Relative change associated within 10 km after 2000} = e^{\alpha_{10D}}$$
$$\text{Relative change associated within 2 km after 2000} = e^{\alpha_{2D}}$$

Note that for stations within 2 km of the diffuser these effects are nested and multiplicative. For these stations the change relative to the far field is $e^{\alpha_{10D}} e^{\alpha_{2D}}$.

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 square-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 2005 Samples

Species Composition—A list of all species collected as part of the Outfall Monitoring Program is included in Appendix C2. Three taxa were newly reported from the 2005 samples, which comprised 232 valid species. Two of these, a spionid polychaete, *Malacoceros* sp. 1, and an amphipod, *Aonyx sarsi* Steele and Brunel, 1968, were new to the MWRA database. Another amphipod, *Microdeutopus anomalus* (Rathke, 1843), was new to the Massachusetts Bay species list, but had been identified in Boston Harbor in previous years. The number of valid taxa in the Massachusetts Bay database, which includes both nearfield and farfield samples, and also includes all of the stations sampled in the program, now stands at 467 species. Over the course of the program, 358 species have been found at the nearfield stations sampled in 2005, and 307 species at the farfield stations.

5.3.2 Benthic Community Analysis for 2005: Nearfield

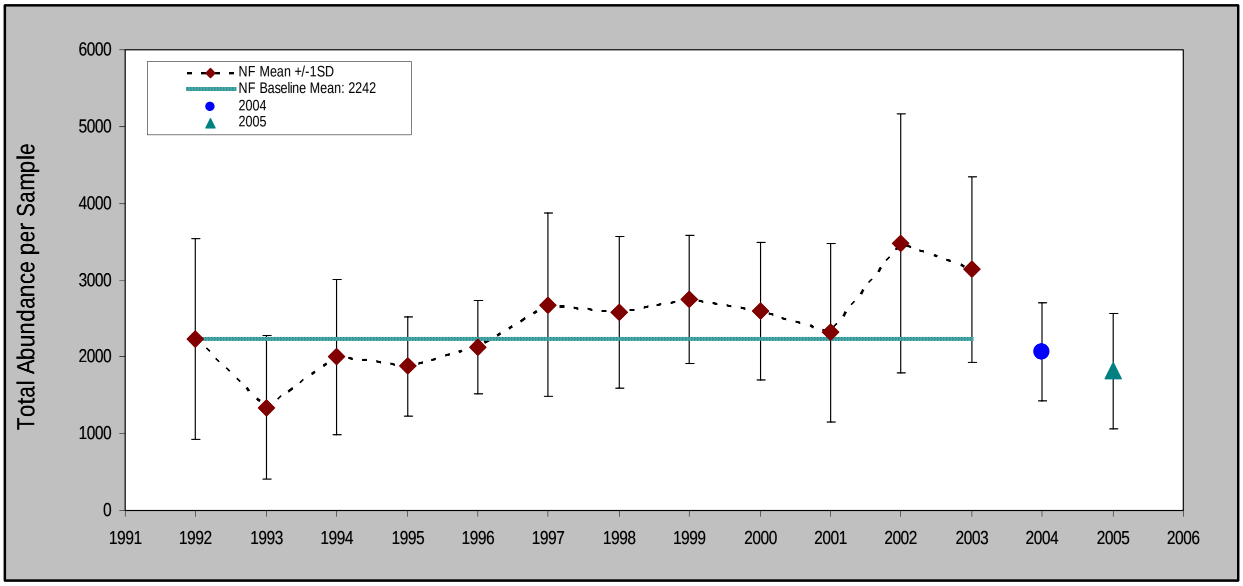
Several benthic community parameters, including the number of organisms and species in each sample, and the calculated measures of diversity (Shannon H′) and evenness (Pielou's J′), and Fisher's log-series *alpha,* were calculated for each sample. All nearfield samples collected prior to the outfall 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 2004 and 2005 each indicated by a different symbol since these represent two different subsets 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 mean for all five parameters was lower in 2005 than in 2004, and slightly lower than the baseline average.

***Density*—**The highest mean infaunal density per sample was recorded in 2002 (3,475 organisms per sample), and was only slightly lower in 2003 (3,138 organisms per sample). In 2004, the mean density for the reduced station set was 2,061.8 ± 641 SD, and even lower at 1,821.3 ± 753.2 SD organisms per sample for the alternate station set sampled in 2005 (Figure 5-1A). The 2005 value is lower than the baseline mean for all nearfield stations, but within the range of values recorded during the pre-operational years: it is similar to 1995 when the mean was 1,880.6 ± 648.4 SD. 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 as well as occasional scouring of the bottom by storms both contribute to the overall invertebrate densities recorded in the benthic grab samples.

Inspection of the abundance data for individual nearfield stations (Figure 5-1B; Appendix C3, Table C3-2, Figure C3-1) indicated that total densities had declined at eight of the 10 nearfield stations last sampled in 2003, and at both of the stations (NF12 and NF17) that were last sampled in 2004. Only two stations, NF13 and FF12, had higher abundances in 2005 than in 2003: at NF13, abundance increased from 1,479 to 2,190 organisms per sample, which was comparable to densities recorded in 1998, 2000,

A



B

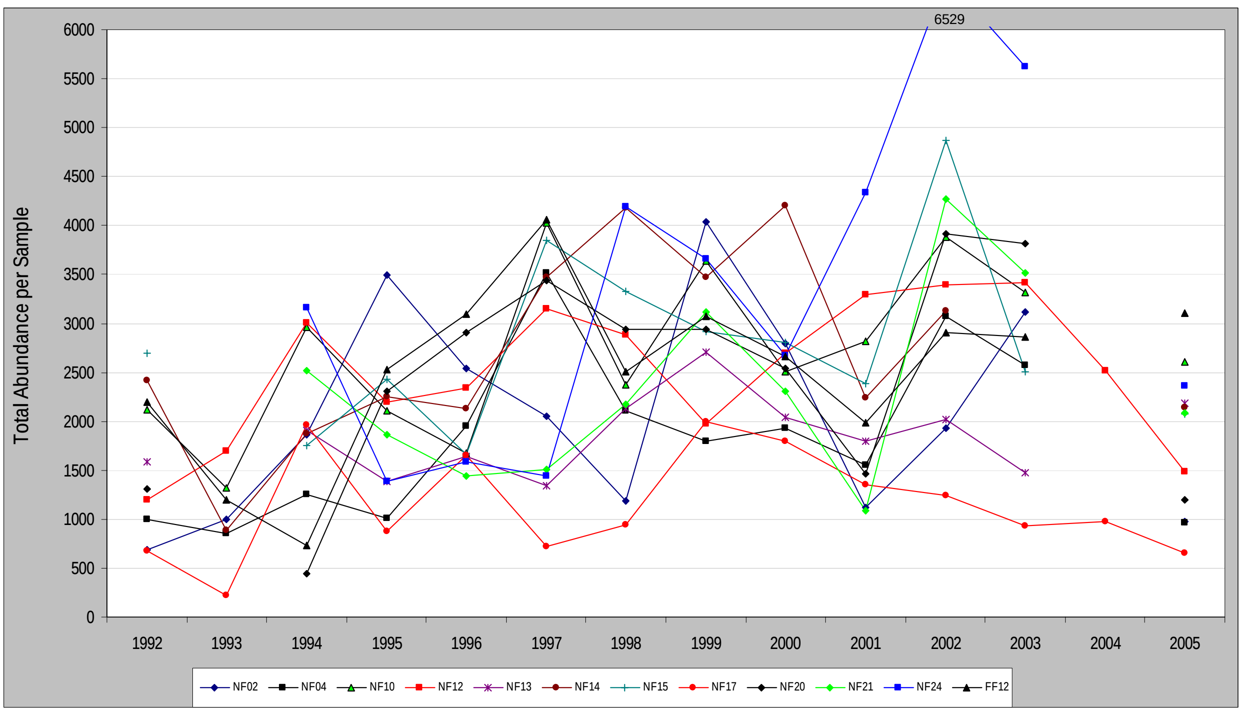


Figure 5-1. (A) Mean abundance per sample for nearfield stations. The means for the two subsets of stations, one sampled in 2004 and the other in 2005, are indicated by different symbols. (B) Abundance each year for individual nearfield stations.

and 2002 (when 2,126, 2,041, and 2,022 organisms per sample, respectively, were recorded). At FF12, average density was 3,109 organisms per sample, the highest recorded since 1992, although only slightly higher than 1996 and 1999, when densities were 3,089 and 3,077 organisms per sample, respectively.

At the 10 stations where densities had decreased, the decline ranged from 17.1 percent and 21.7 percent at NF15 and NF10, respectively, to 68.5 percent at NF02 and NF20. The lowest abundances were found at NF17 (650.3 organisms per sample) and NF02 (977 organisms per sample), and the highest were at NF24 and FF12 (2,364 and 3,109 organisms per sample, respectively).

Species Richness—In 2005, 179 species occurred in the 20 nearfield samples, with a mean of 61.1 species per sample (Figure 5-2A). The average number of species per sample had been increasing from 2001 through 2004, when it was well above the baseline average of 65 species per sample. In 2005, the number of species per sample decreased at all stations, except FF12. At FF12, one of the two stations where abundance values increased between 2003 and 2005, the species richness values were similar to those recorded in 2003 (60.7 species per sample in 2005, compared with 60.0 species per sample in 2003).

At the remaining stations, the species richness values were 64.0 to 90.0 % of the 2003 values. The largest decreases were at NF04 (a 36% decrease from 86 to 55 species), NF02 (a 29.3% decrease from 75 to 53 species), and NF24 (a 28.4% decrease from 82.0 to 58.7 species) (Appendix C3, Figure C3-2).

Diversity and Evenness—In 2005, all three measures indicated a decrease in diversity compared with the past several years (Figure 5-2B-D). Both Shannon diversity (H′) and Pielou's evenness (J′) were comparable to the baseline means of 3.68 (H′) and 0.62 (J′) (Figure 5-2B,C; Appendix C3, Figures C3-3 and C3-4). Mean Shannon diversity for the nearfield stations sampled in 2005 was 3.63. The values at individual stations were comparable to those measured in 2003 (or 2004 for NF12 and NF17). Shannon diversity was 2.82 in both years at NF24, and small increases ranging from 1.1% to 10.8% were recorded at six stations (NF10, NF12, NF15, NF20, NF21, and FF12); *e.g.*, the greatest increase was recorded at NF20, where H' increased from 3.35 in 2003 to 3.71 in 2005). Decreases in Shannon diversity were recorded at five stations: NF02, NF04, NF13, NF14, and NF17. At NF17, H′ has declined every year since reaching a high of 4.29 in 2002 (Appendix C3, Figure C3-3). NF14 was last measured in 2002 (part of the sample taken in 2003 was accidentally lost); H' in 2002 was 4.24; in 2005, diversity at this station was 3.47, a decline of 18.2%.

Similarly, mean evenness in 2005 was 0.61, a decline from the mean of 0.67 recorded in 2004. Most of the individual stations showed values similar to those last recorded for these stations in 2003 or 2004. The largest changes were seen at NF02 (decrease from 0.56 in 2003 to 0.51 in 2005) and NF20 (increase from 0.53 in 2003 to 0.63 in 2005) (Appendix C3, Figure C3-4).

The diversity measure log-series *alpha* reversed the trend of a higher mean value compared with the three years previous (Figure 5-2D, Appendix C3, Figure C3-5). The mean value in 2005 was 12.58, just slightly lower than the baseline value of 13.06. When individual stations were considered (Appendix C3, Figure C3-5), *alpha* was lower in 2005 compared with the previous sampling year at all stations except NF12. The largest decrease was at NF13, where alpha was 16.49 in 2003 and 10.57 in 2005. Compared with 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 abundances, appears to provide a better discrimination among subtly different sites and thus is more reliable in reflecting the actual environmental trend.

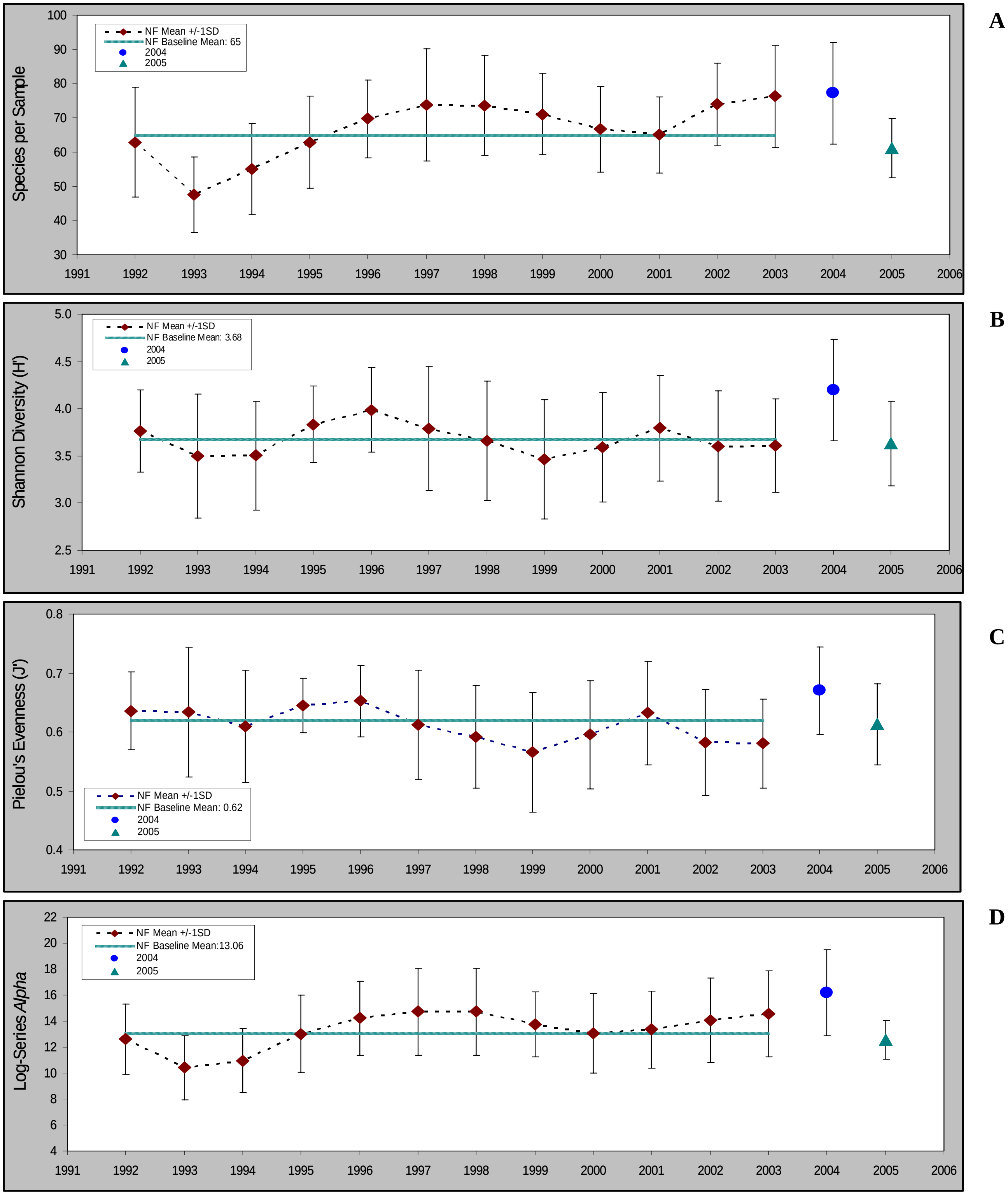


Figure 5-2. (A) Mean number of species per sample, (B) Mean Shannon diversity, (C) Mean evenness, and (D) Mean log-series *alpha* at nearfield stations from 1992–2005. The means for the two subsets of stations, one sampled in 2004 and the other in 2005, are indicated by different symbols.

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 spionid polychaete *Prionospio steenstrupi* has been the numerical dominant in Massachusetts Bay for the past several years; in 2003 it was the most numerous species recorded and was the numerical dominant at 18 of the 23 nearfield stations, while ranking second at another two stations. In 2004, the population level of this species had declined substantially at all except one of the stations that were sampled, but in spite of the reduced densities, *P. steenstrupi* remained the numerical dominant at six of the 13 nearfield stations sampled that year. In 2005, although the abundance of *P. steenstrupi* at individual stations was sometimes only 50% of the 2003 values (Figure 5-3), it was the numerical dominant at nine of the 12 nearfield stations, and ranked second or third at another two stations (NF04 and NF21). At the sandy station NF17, where *Molgula manhattensis* was the numerical dominant, *P. steenstrupi* was the fourth most abundant species. At those stations where *P. steenstrupi* was the numerical dominant, it usually accounted for as much as a third of the organisms in the sample, and up to 54% at NF02 and 59% at NF24.

Ten of the 2005 stations were last sampled in 2003, and the dominants at most were similar to those recorded in 2003. However, a distinct faunal change was evident at NF02: while *P. steenstrupi* was the numerical dominant in both years, the next two, *Tharyx acutus* and *Aricidea catherinae*, with 592 and 483 individuals, respectively, in 2003, were represented in 2005 by only nine and two individuals, respectively. This faunal shift is most likely associated with the change in sediment composition at this site. Sediments at NF02 were coarse (<10% silt-plus-clay) in all years except 1992 and 2002, when 77% and 61% silt-plus-clay, respectively, were measured. In 2005, 76% fine sediments were again recorded at this station (Chapter 3, Appendix B2, Figure B2-12). A large faunal change was associated with the shift from 76% silt-plus-clay in 1992 to 3% in 1993, but there was little indication of a faunal change that might have been associated with the change in grain size between 2001 and 2002; in 2005, the fauna was only 40% similar (based on a Bray-Curtis percent similarity analysis of square-root-transformed abundances, Appendix C5) to samples taken at that station over the previous decade. In addition, when tested against other samples taken in 2005, NF02 was an outlier to the group containing the muddier stations NF 10, NF12, NF21, and NF24.

When within-station similarity was examined for each of the stations (Appendix C5), the majority (*e.g.*, NF10) exhibited a dichotomy between the early years (1992–1996) and subsequent years. In many cases, samples from 2005 were most similar to samples from 2001–2003 (*e.g.*, FF12, NF13, NF15, NF21), although on occasion, the greatest similarity was to samples from 1995–1997 (*e.g.*, NF14, NF24).

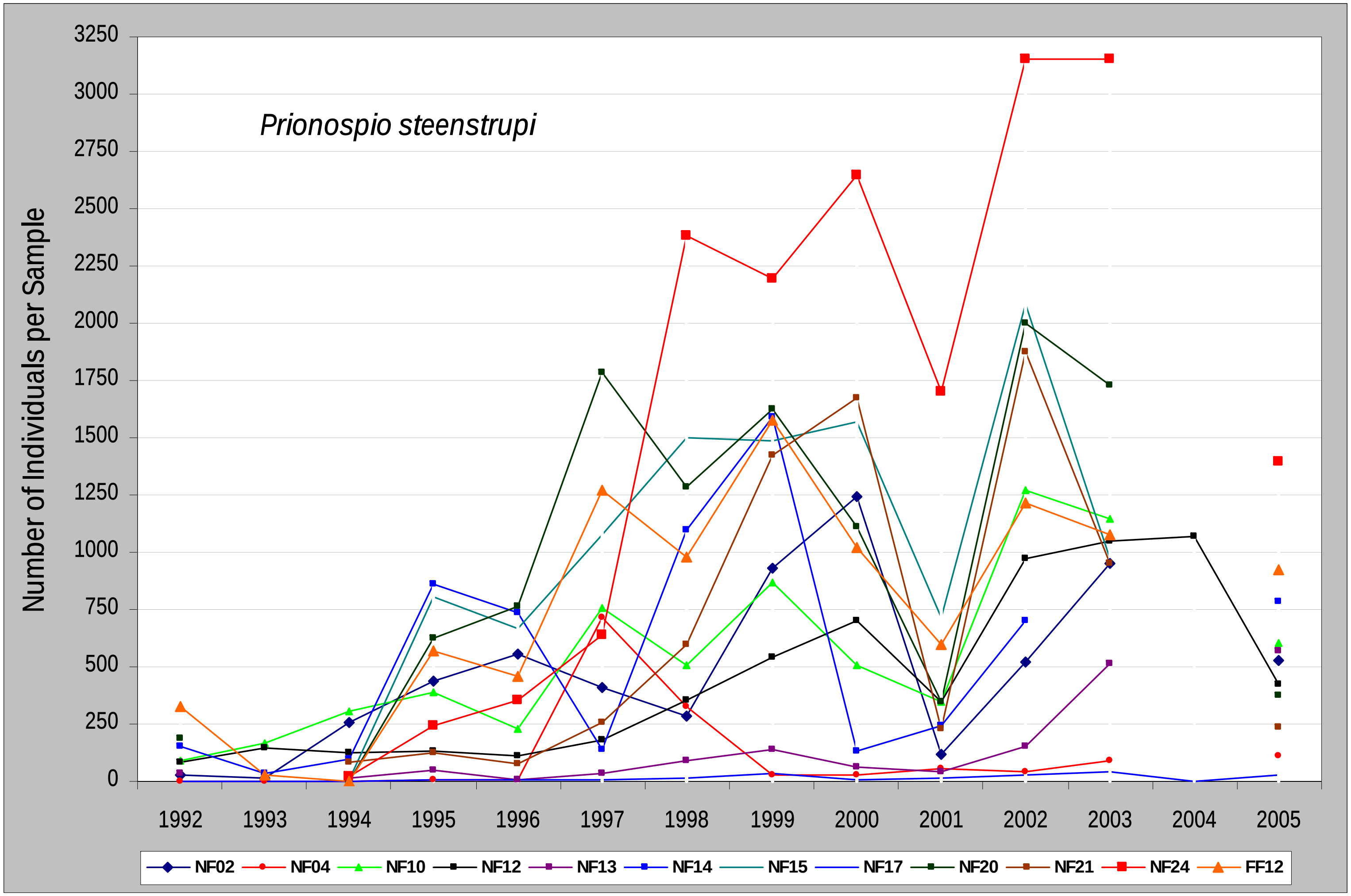


Figure 5-3. Abundance (or mean abundance) of *Prionospio steenstrupi* at nearfield stations sampled in 2005.

5.3.3 Benthic Community Analysis for 2005: 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*, have been 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 1992–2005 are plotted below, with the means for 2004 and 2005 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. FF01A and FF06 are both at about 35 m depth, but FF01A is to the north, off Cape Ann, while FF06 is in Cape Cod Bay. FF11 is the northernmost of the stations, in 88 m water depth. FF14, near Stellwagen Bank, is also a deep station, at about 73 m water depth (see Figure 2-2, Table 2-1).

Density—Densities at the farfield stations rose dramatically in 2003, when the mean density increased to 3249 organisms per sample, nearly twice that recorded in 2002 and more than twice the baseline average of 1615 organisms per sample (Figure 5-4A). In 2004, the mean density at farfield stations remained well above the baseline mean of 1615 organisms per sample; albeit with a large standard deviation around the mean (Figure 5-4A). The subset of farfield stations sampled in 2005 also had a mean density well above the baseline average, although this mean was lower than that recorded in 2004 (Figure 5-4A). Abundance declined at all four farfield stations compared with abundances recorded in 2003, the last time these stations were sampled (Figure 5-4B).

The change in abundance at each farfield station was due to different species at each location:

- At FF01A, changes were associated with a reduction in the density of *Prionospio steenstrupi*, and to a lesser extent, *Aricidea catherinae* and *Euchone incolor*. Because *E. incolor* is associated with *Molpadia*, a deep-burrowing holothurian, it is possible that the reduction in the density of this species was due only to the likelihood of the sampling grab hitting or missing a *Molpadia* location.

- At FF06, the Cape Cod Bay station, the density of *Euchone incolor* dropped from an average of 2216 to 322 individuals per grab, and as stated above, this reduction was most likely due to whether or not the grab sampled a location where *Molpadia* was present. Other species, including *Mediomastus californiensis*, *Spio limicola*, *Tharyx acutus*, *Aricidea catherinae*, and *Ninoe nigripes* increased in abundance at this station, but not in sufficient numbers to offset the reduction in *E. incolor*.

- At FF11, *Prionospio steenstrupi*, *Aricidea quadrilobata*, and *Anobothrus gracilis*, all declined in density to roughly 50% of the 2003 levels. However, *Spio limicola* increased from 314 to 1012 per individuals per sample, but this was not sufficient to offset the overall decline in density at this station.

- At FF14, the numerical dominant, *Spio limicola*, was present in roughly equal abundance in both 2003 and 2005, but the subdominants, *Prionospio steenstrupi*, *Chaetozone setosa*, and *Aricidea quadrilobata* occurred in greatly reduced numbers, resulting in an overall decline in density.

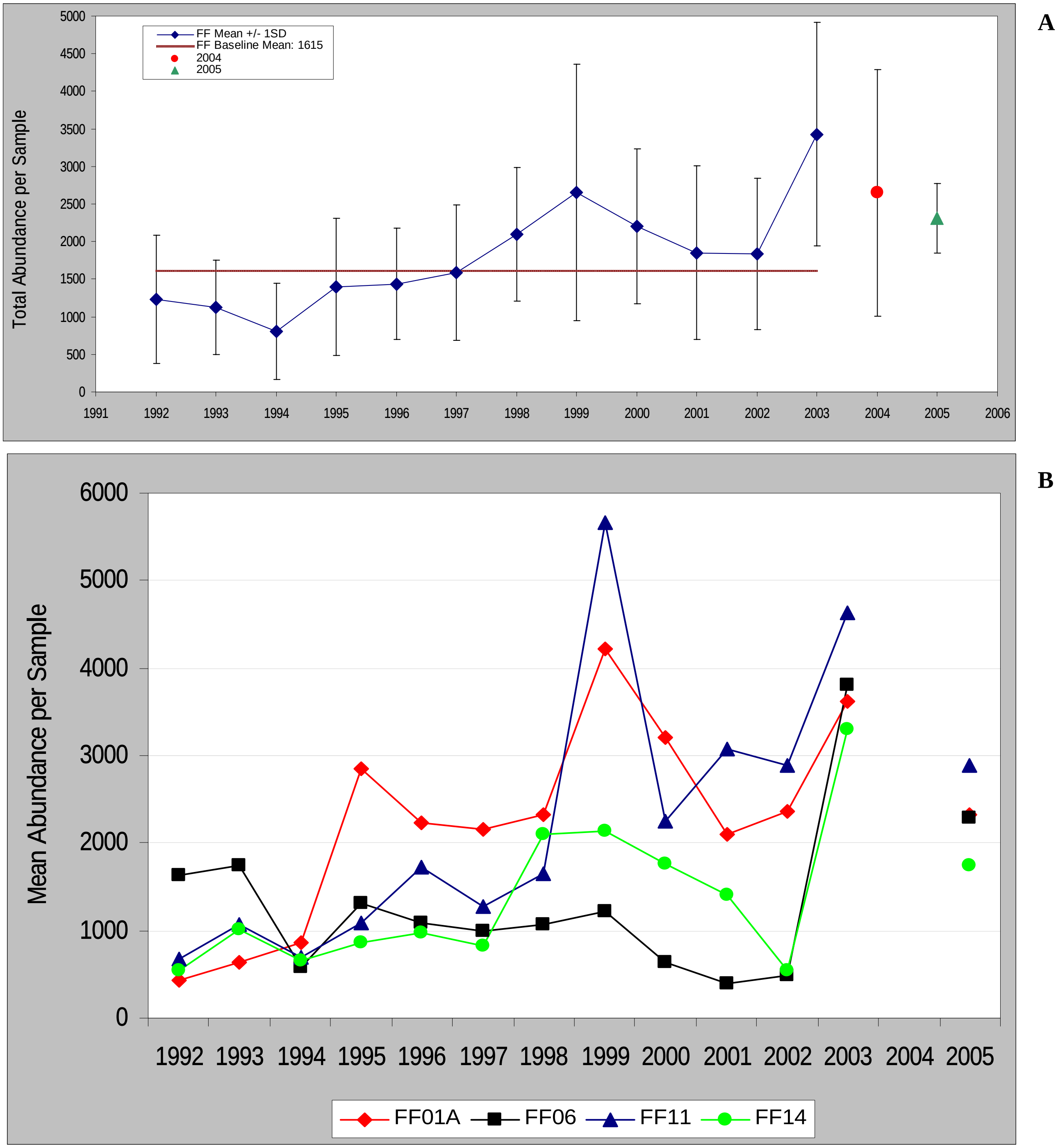


Figure 5-4. (A) Mean abundance per sample for farfield stations. The values for 2004 and 2005 represent different subsets of four stations each. (B) Mean abundance by year for farfield stations sampled in 2005.

Species Richness—In 2005, 172 species were identified from the 12 farfield samples taken at four locations. In 2004, the average for four stations was 79.8 species per sample (range 57.7–104.3 species, Maciolek *et al*. 2004). In 2005, the average for a different subset of stations was 73.1±2.38 SD (Figure 5-5A) with a range from 69.7 at FF06 to 75.0 at FF14. This mean, when compared with the 2003 mean of 88 species per sample for the same subset of stations, indicated a real decline in the number of species at these stations. Although the mean number of species per sample declined at three of the four farfield stations (Figure 5-6A, Appendix C3, Figure C3-2), the overall mean remained well above the baseline value of 61 species.

***Diversity and Evenness*—**In 2005, mean Shannon diversity (H′) at the farfield stations was 3.79 (compared with the baseline mean of 3.74, (Figure 5-5B). Each of the four stations sampled had a different pattern of change compared with H′ values recorded in 2003 (Figure 5-6B, Appendix C3, Figure C3-3): FF01A remained essentially the same, with a minor increase from 2.91 in 2003 to 2.98 in 2005; FF06 showed the greatest increase, from 2.9 to 4.5; FF11 increased slightly, from 3.3 to 3.6; and FF14 decreased from 4.4 to 4.1. The overall result was an increase in mean diversity from 3.37 in 2003 to 3.79 in 2005; however, mean farfield H′ declined compared with the 2004 mean diversity of 4.0 (Figure 5-5B).

Mean Pielou's evenness (J′) (0.61) was also lower in 2005 compared with the 2004 mean value of 0.64, and slightly lower than the baseline value of 0.64 (Figure 5-5C). However, when stations were examined individually and compared with the values obtained when last sampled in 2003 (Figure 5-6C, Appendix C3: Figure C3-4), evenness declined only at FF14 (from 0.68 to 0.66). The other three stations showed increases in evenness: FF01A, from 0.44 to 0.48; FF11, from 0.50 to 0.58; and FF06, from 0.47 to 0.73.

Mean log-series *alpha* declined from 16.75 in 2004 to 14.63 in 2005, but was still well above the baseline mean of 13.4 (Figure 5-5D). The four 2005 stations had a mean *alpha* value of 16.35 when last sampled in 2003. *Alpha* declined at three of the four farfield stations, the exception being FF06, where *alpha* increased from 12.31 in 2003 to 13.78 in 2005 (Figure 5-6D).

With the possible exception of the change at FF06, the changes in these parameters were so small as to be trivial. Compared with values obtained for 2004, all five measures examined here declined (Figure 5-5), but this decline was not significant. However, when only the same four stations are compared with parameters last measured in 2003, *alpha* reflects the decline in species richness, whereas Shannon diversity and evenness show the opposite trend.

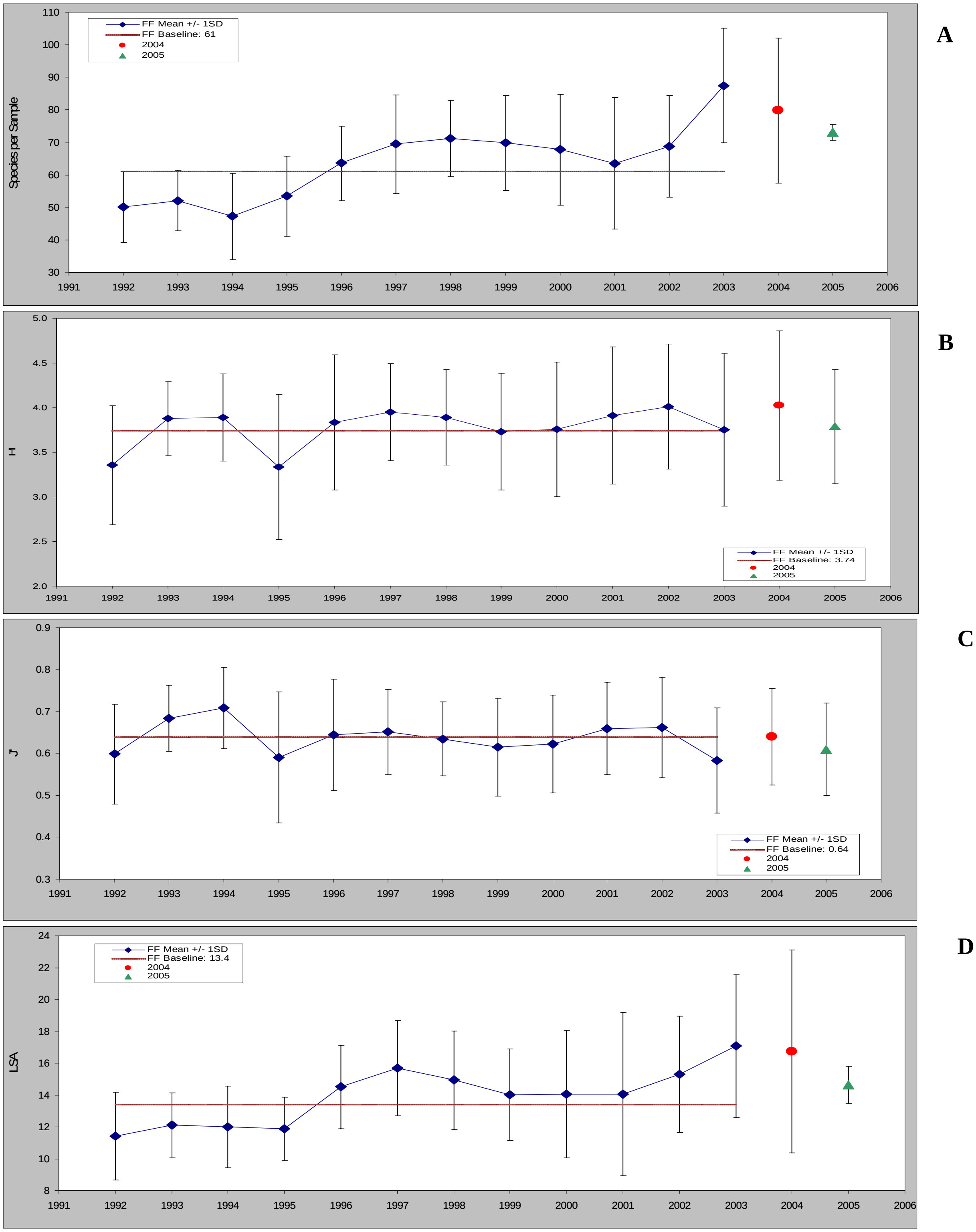


Figure 5-5. Annual mean parameters for farfield benthic infaunal stations. (A) Mean number of species per sample, (B) Mean Shannon diversity, (C) Mean evenness, and (D) Mean log-series *alpha* at farfield stations from 1992–2005. The means for the two subsets of stations sampled in 2004 and 2005 are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

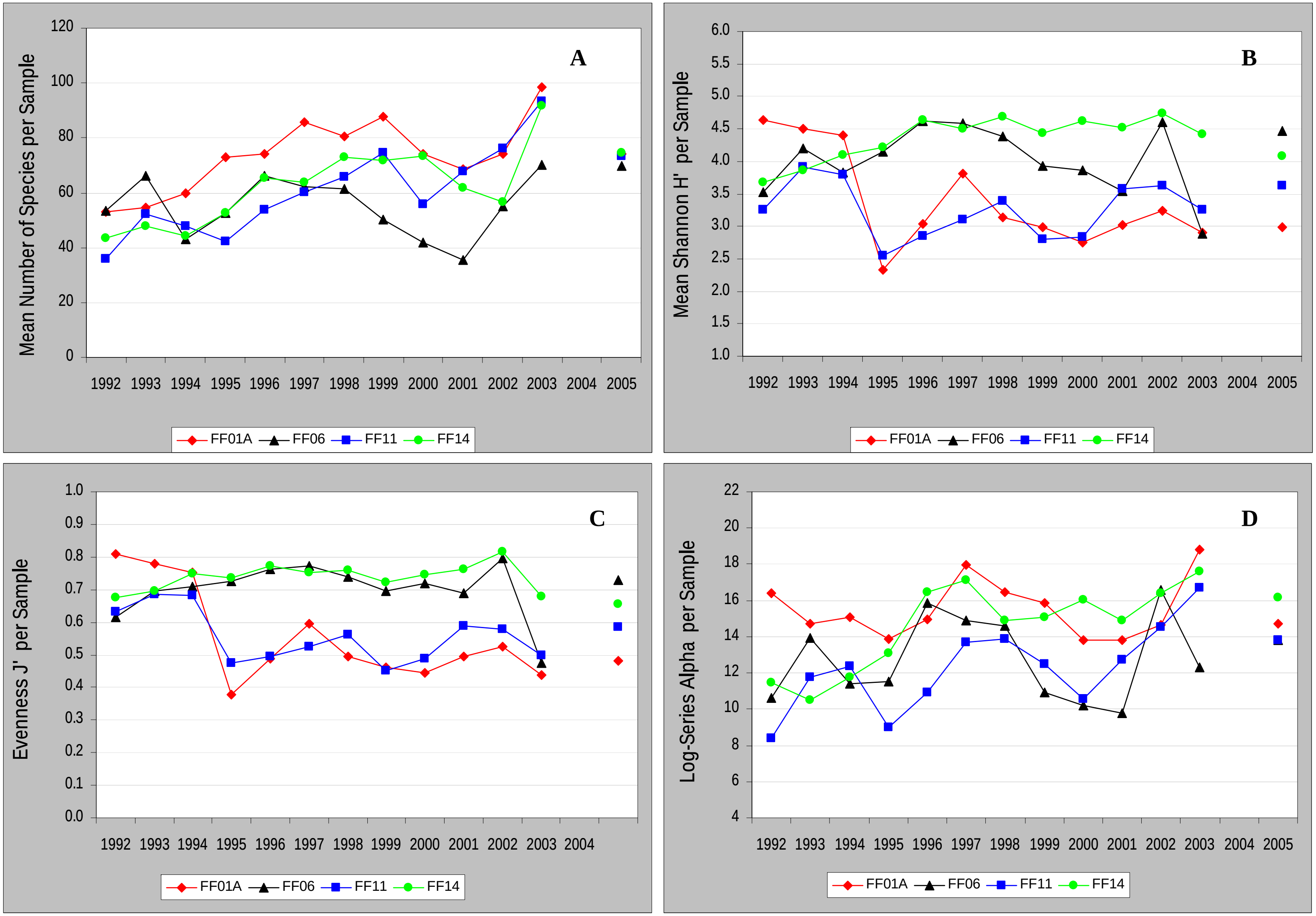


Figure 5-6. Annual parameters for individual farfield benthic infaunal stations sampled in 2005. (A) Mean number of species per sample, (B) Mean Shannon diversity, (C) Mean evenness, and (D) Mean log-series *alpha*.

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 four of the dominant species are shown in Figure 5-7. The species composition at FF01A and FF11 has remained fairly stable over the past several years, whereas greater changes have been seen at F06 and to a lesser extent, at FF14.

- FF01A—*Prionospio steenstrupi* has been the numerical dominant for the last several years, and, in 2005, accounted for over 58% of the organisms collected at that station even though overall densities were reduced. The bivalve *Nucula delphinodonta* and the polychaetes *Tharyx acutus*, *Levinsenia gracilis*, *Aricidea catherinae*, and *Mediomastus californiensis* were among the ten most numerous species, as they were in 2003.

- FF06—Although the density of *Euchone incolor* in 2005 at the Cape Cod Bay station was greatly reduced compared with 2003 (see above), it was, however, the numerical dominant at that station, accounting for over 14% of the organisms collected. Prior to 2003, *Euchone. incolor* was rarely encountered at this station. Similarly, *P. steenstrupi* and *Spio limicola* occurred only in low numbers for several years, but in 2005 accounted for nearly 10% and 9 % of the infauna, respectively, and were the second and fourth most numerous species.

- FF11—*Prionospio steenstrupi* has been the numerical dominant at this station for the past several years. In 2005, this species accounted for nearly 34% of the infauna, although abundances were reduced at this station as at FF01A. Other numerical dominants at this stations have remained stable for the past several years; these species include the polychaetes *Aricidea quadrilobata, S. limicola, Anobothrus gracilis, L. gracilis, E. incolor,* and *Chaetozone setosa* mb*,* and the oligochaete *Tubificoides apectinatus*.

- FF14—*Spio limicola* dominated this station in 2002, 2003, and again in 2005, comprising over 33% of the organisms collected. Other common species include *Anobothrus gracilis*, *P. steenstrupi*, *N. delphinodonta*, and a recent addition to the dominants, the bivalve *Crenella decussata*.

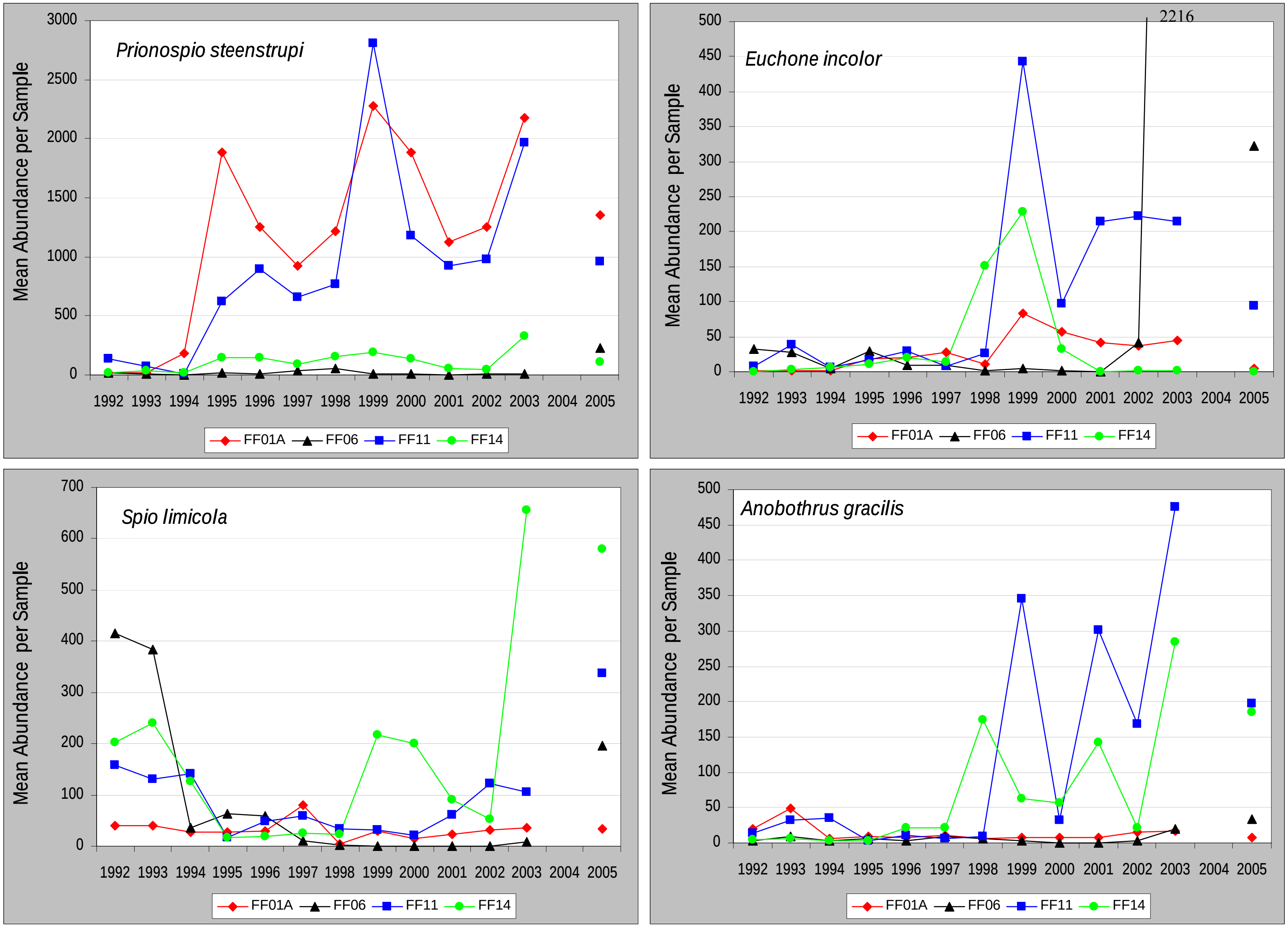


Figure 5-7. Mean density per 0.04-m^2 sample of four species common at the farfield stations.

5.3.4 Multivariate Analysis of 2005 Samples

***Similarity Analysis*—**The CNESS (*m* =15) similarities of the 32 samples taken in 2005 were clustered using group average sorting (Figure 5-8). The samples form three major groups or clusters, with one station (NF02) forming a single-station outlier to group 1. The four groups comprise (1) a mix of nearfield stations and FF01A, with sediment types ranging from 3.0 to 73.5% silt+clay, (2) fine-grained station NF02 (outlier to group 1), (3) fine-grained farfield stations FF11, FF14, and Cape Cod Bay station FF06, and (4) nearfield sandy stations NF04, NF13, and NF17. 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 NF04 (group 4) have a very low level of similarity to the remaining stations. NF04 and NF17 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 FF06, FF11, and FF14 and the remaining nearfield samples most likely reflects the higher densities of *Spio limicola*, *Euchone incolor*, and *Anobothrus gracilis* at these stations. The sample from NF02 differs from the rest due to >100 individuals of *Pholoe minuta/tecta*/spp. in the sample.

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, with only NF13 clustering with a different grouping of stations (Figure 5-9). Specific similarities among the nearfield stations differ to a small degree between the two analyses, but replicates from single stations always cluster together, as in previous years (Maciolek *et al.* 2004, 2005). The major difference between the Bray-Curtis and CNESS results is that the cluster including farfield stations FF06, FF11, and FF14 has the lowest similarity to the remainder of the samples, whereas with CNESS, the group comprising NF04, NF13, and NF17 is the most dissimilar.

***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 5-10A). 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. The CNESS clusters are distinct in this two-dimensional presentation, with the Cape Cod Bay station FF06 appearing well separated from the other stations (FF11 and FF14) in cluster group 3. NF02, the outlier to cluster group 1, is positioned on axis 3, which is not represented in this diagram; it therefore appears to be closer to NF14 and NF15 than it actually is in multidimensional hypergeometric space. With CNESS (*m*=15), 37 of the 232 species recorded in 2005 accounted for 91% of the variation in the community structure, and contributed at least 1% to the PCA-H axes (Table 5-1).

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 5-10B) and are detailed for Axes 1–3 in Table 5-2. The majority of nearfield stations are structured by the surface-deposit- (and sometimes filter-) feeder *Prionospio steenstrupi*, and the subsurface deposit feeders *Mediomastus californiensis*, *Levinsenia gracilis*, *Monticellina baptisteae*, and *Tharyx acutus*. The sandy nearfield stations (NF17, NF13, and NF04) are characterized by the syllid polychaete *Exogone hebes* (an omnivore), the ascidian *Molgula manhattensis*, the amphipod *Crassicorophium crassicorne*, and a bivalve, *Ensis directus.* At farfield stations FF11 and FF14, the important species comprise a suite of polychaetes including *Anobothrus gracilis, Spio limicola*, *Aricidea quadrilobata*, and the oligochaete *Tubificoides apectinatus*.

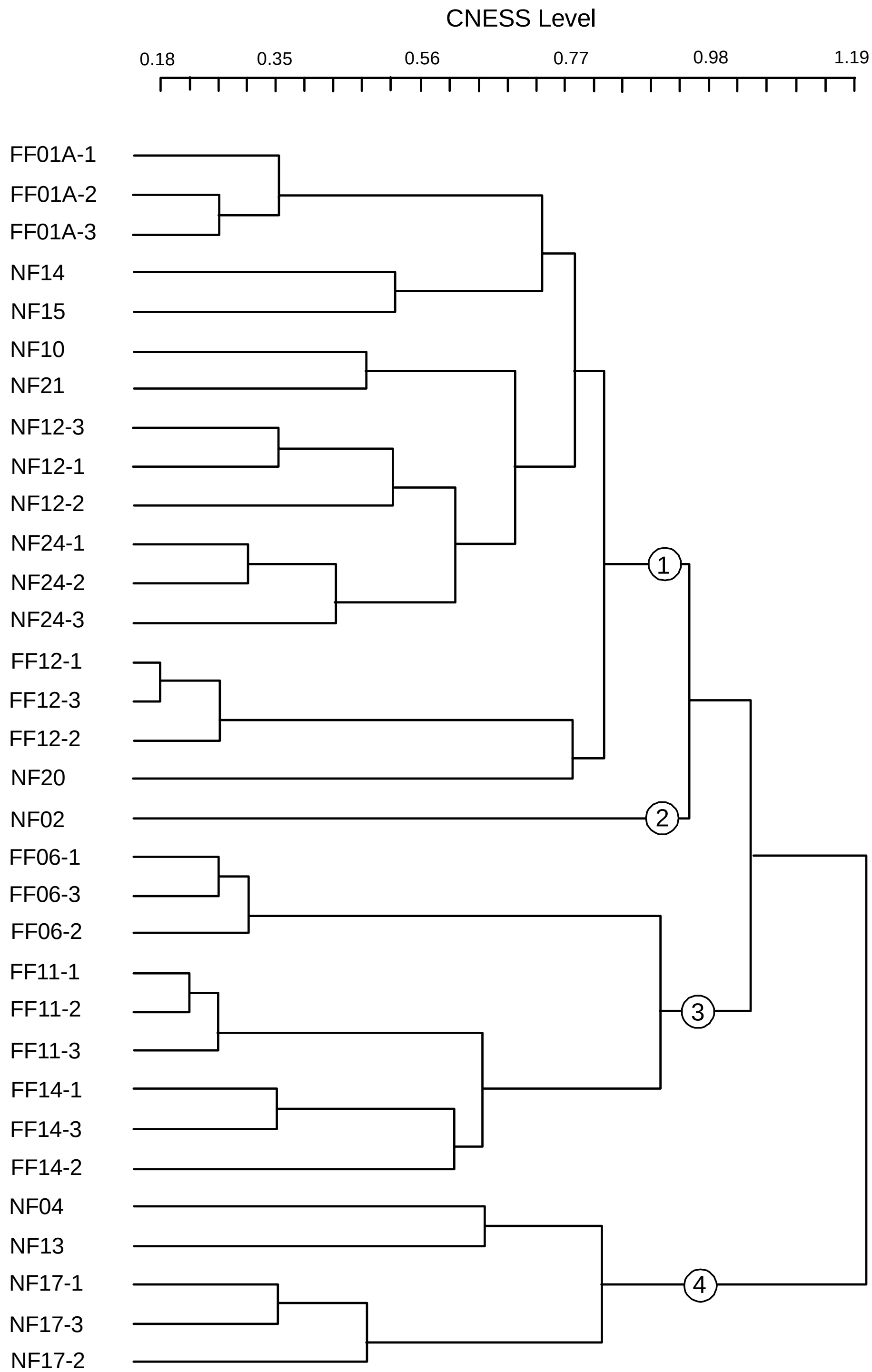


Figure 5-8. Relationship of 2005 samples based on CNESS similarity (*m*=15) and group average clustering.

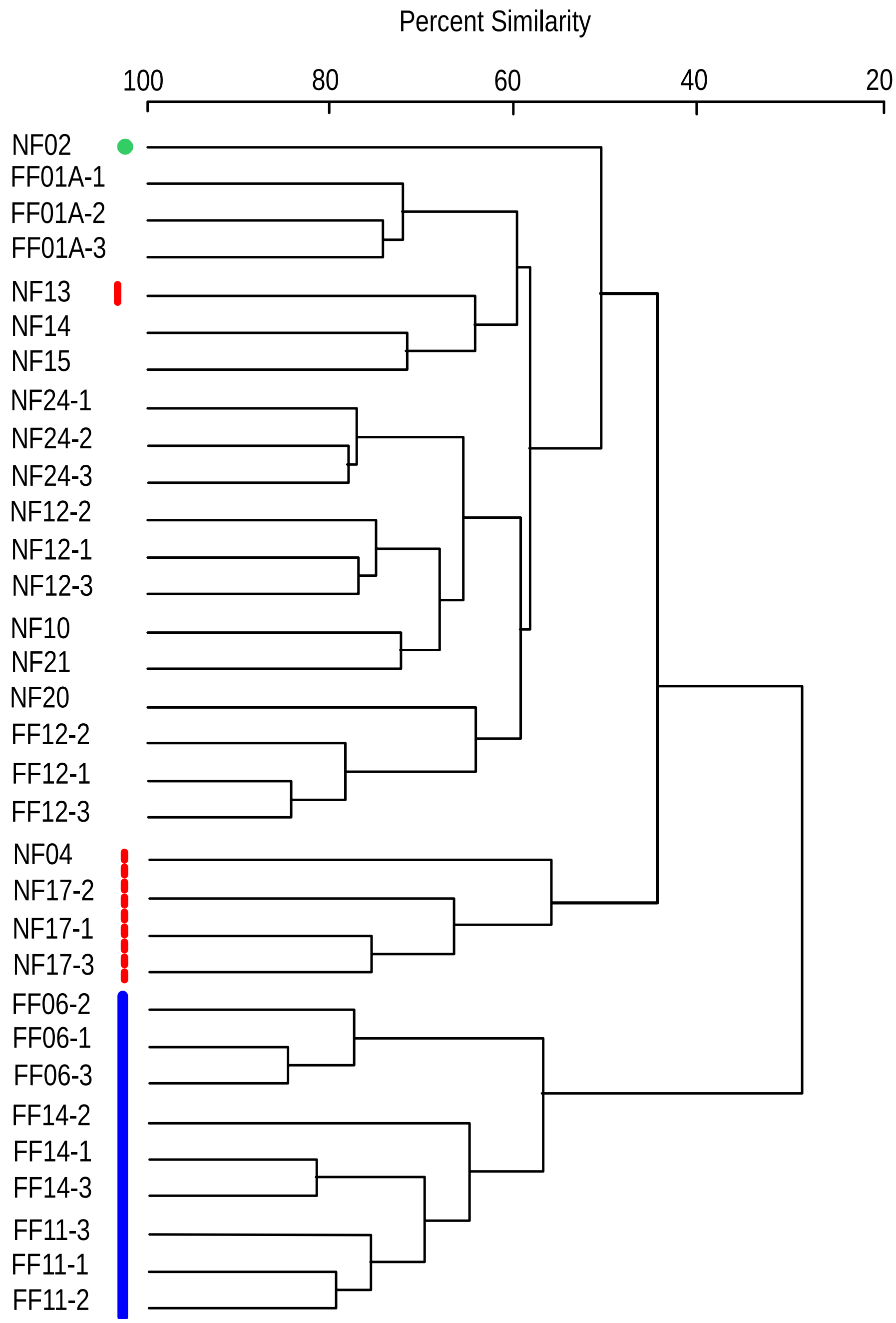
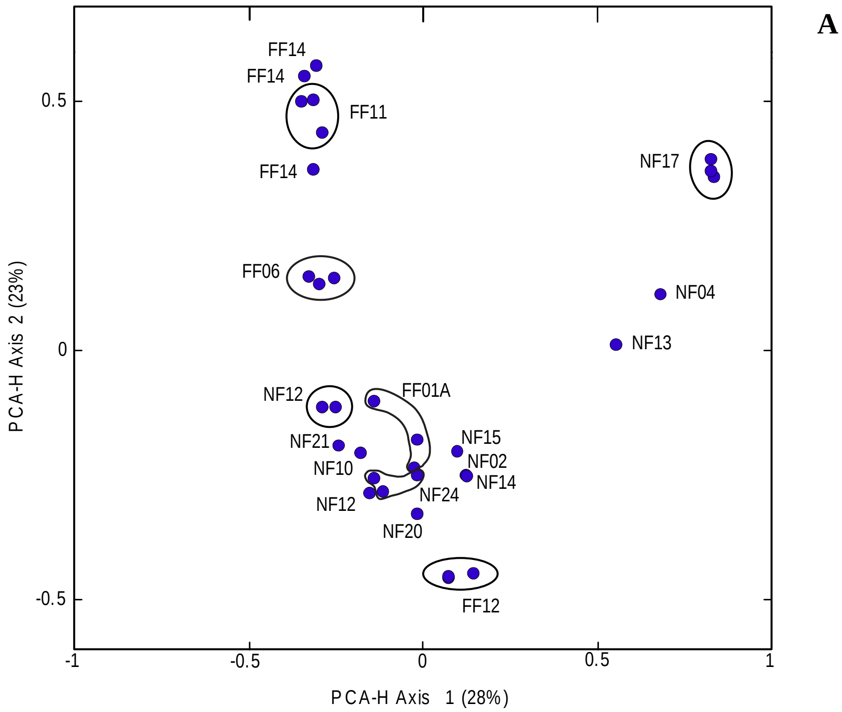


Figure 5-9. Relationship of 2005 samples based on Bray-Curtis similarity after fourth-root transformation of the data and group average clustering. Samples corresponding to CNESS groups are identified by no line (group 1), green circle (group 2), solid blue line (group 3), and dashed red line (group 4).



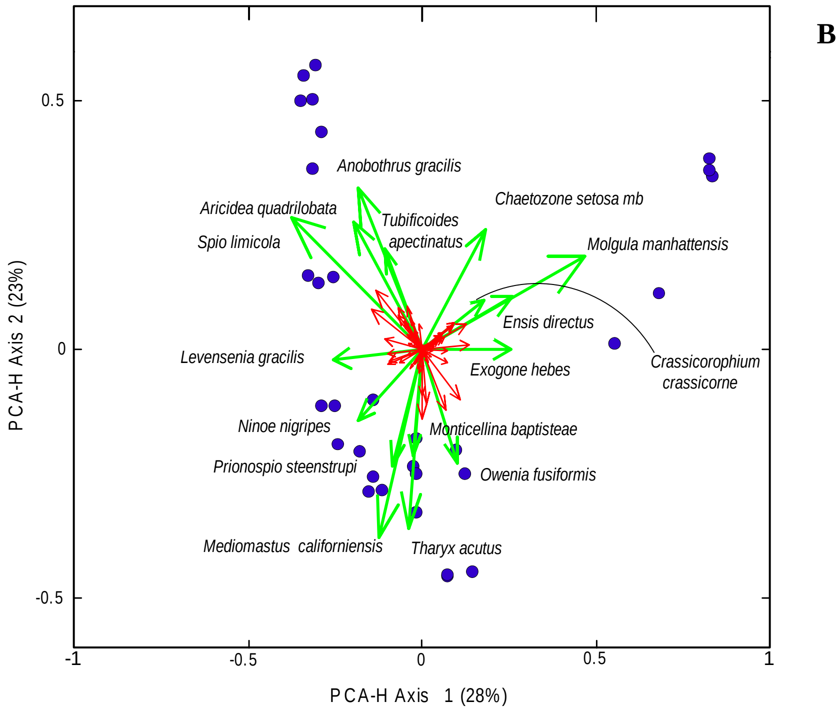


Figure 5-10. Metric scaling on PCA-H axes 1 and 2 of the 2005 benthic infaunal samples (A) and the Euclidean distance biplot showing the species responsible for at least 2% of the variation (B).

Table 5-1. Contribution of the 37 species in the 2005 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	*Molgula manhattensis*	7	7	22	4	2	1	0	0	1
2	*Spio limicola*	7	15	14	7	0	1	10	11	0
3	*Owenia fusiformis*	5	20	1	5	12	14	3	11	0
4	*Mediomastus californiensis*	5	25	2	14	3	2	1	4	2
5	*Tharyx acutus*	5	29	0	13	0	4	13	1	1
6	*Exogone hebes*	4	34	7	0	1	0	21	0	19
7	*Anobothrus gracilis*	4	38	3	10	5	0	0	1	1
8	*Aricidea quadrilobata*	4	42	4	7	0	6	0	3	2
9	*Prionospio steenstrupi*	4	45	1	5	3	1	0	24	4
10	*Levinsenia gracilis*	3	49	7	0	1	5	3	2	1
11	*Nucula delphinodonta*	3	52	1	0	8	1	12	3	25
12	*Euchone incolor*	3	55	2	1	10	17	0	1	0
13	*Chaetozone setosa* mb	3	57	3	6	0	0	0	0	1
14	*Arctica islandica*	3	60	0	2	2	12	0	0	0
15	*Ensis directus*	3	63	7	1	1	0	0	0	1
16	*Aricidea catherinae*	3	65	1	1	4	4	11	4	0
17	*Ninoe nigripes*	3	68	3	22	5	0	1	1	3
18	*Cossura longocirrata*	2	70	2	1	6	9	0	0	2
19	*Pholoe minuta/tecta/spp.*	2	72	0	2	4	2	5	6	1
20	*Tubificoides apectinatus*	2	74	1	4	3	0	0	0	7
21	*Monticellina baptisteae*	2	76	0	5	1	0	0	7	0
22	*Crassicorophium crassicorne*	2	78	3	1	0	1	2	0	4
23	*Parougia caeca*	2	80	1	0	10	0	0	0	0
24	*Aphelochaeta marioni*	1	81	1	0	2	2	0	0	1
25	*Nephtys incisa*	1	82	1	0	3	2	1	0	0
26	*Scoletoma hebes*	1	83	0	1	2	2	2	5	0
27	Tubificidae sp. 2	1	84	0	0	0	0	0	1	2
28	*Spiophanes bombyx*	1	85	2	0	0	0	0	0	2
29	*Terebellides atlantis*	1	86	0	0	2	4	0	0	1
30	*Crenella decussata*	1	86	0	0	2	1	2	0	2
31	Nemertea sp. 12	1	87	0	1	0	2	0	0	1
32	*Monticellina dorsobranchialis*	1	88	0	1	0	0	0	2	1
33	*Ampharete acutifrons/baltica*	1	88	0	0	0	0	1	0	1
34	*Cerastoderma pinnulatum*	1	89	2	0	0	0	0	0	0
35	*Leitoscoloplos acutus*	1	90	0	0	1	1	0	2	1
36	*Metopella angusta*	1	90	0	0	0	0	0	1	0
37	*Pectinaria granulata*	1	91	0	0	0	0	1	2	0

Table 5-2. Contributions to PCA-H axes by species accounting for at least 2% of the CNESS variation among the infaunal samples collected in 2005 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	*Molgula manhattensis*	14	14	22	4
2	*Spio limicola*	11	25	14	7
3	*Mediomastus californiensis*	7	32	2	14
4	*Anobothrus gracilis*	7	38	3	10
5	*Tharyx acutus*	6	44	0	13
6	*Aricidea quadrilobata*	5	49	4	7
7	*Chaetozone setosa* mb	4	54	3	6
8	*Ensis directus*	4	58	7	1
9	*Levinsenia gracilis*	4	62	7	0
10	*Exogone hebes*	4	65	7	0
11	*Owenia fusiformis*	3	68	1	5
12	*Prionospio steenstrupi*	3	71	1	5
13	*Ninoe nigripes*	3	74	3	2
14	*Tubificoides apectinatus*	2	76	1	4
15	*Crassicorophium crassicorne*	2	79	3	1
16	*Monticellina baptisteae*	2	81	0	5
Important species: Axis 1 vs. 3					
PCA-H Rank	**Species**	**Contr.**	**Total Contr.**	**Axis 1**	**Axis 3**
1	*Molgula manhattensis*	17	17	22	2
2	*Spio limicola*	10	28	14	0
3	*Ensis directus*	5	33	7	1
4	*Exogone hebes*	5	38	7	1
5	*Levinsenia gracilis*	5	43	7	1
6	*Euchone incolor*	4	47	2	10
7	*Anobothrus gracilis*	4	51	3	5
8	*Owenia fusiformis*	4	55	1	12
9	*Ninoe nigripes*	4	58	3	5
10	*Parougia caeca*	3	62	1	10
11	*Aricidea quadrilobata*	3	65	4	0
12	*Cossura longocirrata*	3	67	2	6
13	*Nucula delphinodonta*	3	70	1	8
14	*Crassicorophium crassicorne*	3	73	3	0
15	*Chaetozone setosa* mb	2	75	3	0
Important species: Axis 2 vs. 3					
PCA-H Rank	**Species**	**Contr.**	**Total Contr.**	**Axis 2**	**Axis 3**
1	*Mediomastus californiensis*	11	11	14	3
2	*Tharyx acutus*	9	20	13	0
3	*Anobothrus gracilis*	9	29	10	5
4	*Owenia fusiformis*	7	36	5	12
5	*Spio limicola*	5	41	7	0
6	*Prionospio steenstrupi*	5	46	5	3
7	*Aricidea quadrilobata*	5	51	7	0
8	*Chaetozone setosa* mb	4	55	6	0
9	*Tubificoides apectinatus*	4	59	4	3
10	*Monticellina baptisteae*	3	62	5	1
11	*Euchone incolor*	3	66	1	10
12	*Molgula manhattensis*	3	69	4	2
13	*Parougia caeca*	3	72	0	10
14	*Cossura longocirrata*	3	75	1	6
15	*Ninoe nigripes*	3	78	2	5
16	*Pholoe minuta/tecta/*spp.	2	80	2	4

5.3.5 Multivariate Analysis of the 1992-2005 Nearfield Samples

CNESS Analysis— A multivariate analysis of all nearfield replicates collected from the 2005 subset of stations between 1992 and 2005 indicated two major groups of samples (Figure 5-11). As seen in the analysis of the 2004 samples (Maciolek *et al*. 2005), the major division into two groups separates the sandy stations from the finer-grained ones. These two major clusters were similar to each other at a level of 1.28 (with 1.41 being the lowest similarity by the CNESS measure).

The sand station samples are further subdivided into three groups that have a low level of similarity (1.12) The first contains five replicates from NF17, from the years 1995, 1996, 2001, and 2002. These replicates have a low similarity to each other, and also to the remainder of the samples in group 1. Thirty-five replicates from NF17 formed the second cluster, and although replicates from 2004 and 2005 formed clusters with high within-year similarity, groupings of years such as 1994 and 1996 with 2003, and 1998 with 2001, were also seen, indicating that there is no clear separation of earlier monitoring years from later ones. The third subgroup consists of samples from NF04, NF13, and NF14. Although the sediment composition at NF04 did not differ noticeably from year to year at this station, higher numbers of *Crassicorophium crassicorne*, *Unciola* spp., and species of *Exogone* were found in the samples that were clustered in this first major group. This is true for NF13 and NF14 as well: sediments did not differ greatly between years, but the numbers of *Crassicorophium crassicorne* and *Unciola* spp. were higher in the years represented in group 1.

The second major group includes five subgroupings plus one outlier to the largest subgroup, which contains the majority of samples (160) (Figure 5-11). The least similar of the smaller groups comprises the three replicates from FF12 in 1994. The remainder of the FF12 replicates are not individually indicated in Figure 5-11, but they form a highly self-similar unit within the large group of nearfield replicates. The samples from 1994 differ from the others by lacking *Prionospio steenstrupi*.

Samples from NF02 were found in three separate clusters, including a unique subgroup that comprised eight samples from 1993 and 1997–2001; a single sample from 2005 that had low similarity to the largest group of nearfield samples; and the remainder scattered through the large nearfield group. Sediments at NF02 differed considerably over the course of the monitoring program: when first sampled in 1992, sediments were comprised of 77.2% silt+clay, but in subsequent years (1993–2001), fines ranged from 2.9 to 10.6%. Sediments were also coarse in 2003 (10% fines), but in 2002 and 2005 the amount of silt plus clay was 60.9 and 76.1 %, respectively. A PCA-H analysis of the NF02 data (not presented here) indicated that the reason for the low similarity of the 2005 sample to earlier years is due to the presence of 113 individuals of *Pholoe minuta/tecta*/spp., compared with 0–26 individuals per sample in other years. Samples taken in 1993 and 1997–2001, which clustered together, were characterized by sediments with 2.9–8.5% fines, and by *Hiatella arctica*, *Ophiura robusta*, *Cerastoderma pinnulatum, Phyllodoce mucosa,* and *Aricidea catherinae*. Remaining samples had higher numbers of *Prionospio steenstrupi* and *Mediomastus californiensis*.

The third subgroup of major group 1 is comprised of 14 samples from 1992–1994 and 1997 from stations NF04, NF13, NF14, NF15, and NF24. The fourth subgroup includes six samples from NF14, and two each from NF04 and NF13. These samples are either from the late 1990s or after 2002. The early 1990s were characterized by higher numbers of the polychaetes *Spio limicola* and *Dipolydora socialis,* and later years by increased number of *Prionospio steenstrupi*, as well as *Molgula manhattensis*, and *Owenia fusiformis*. At many stations, samples from years 1992–1999 were dissimilar to those from later years, but the overall within-station similarity levels were such that no before- and after-discharge effects were identified.

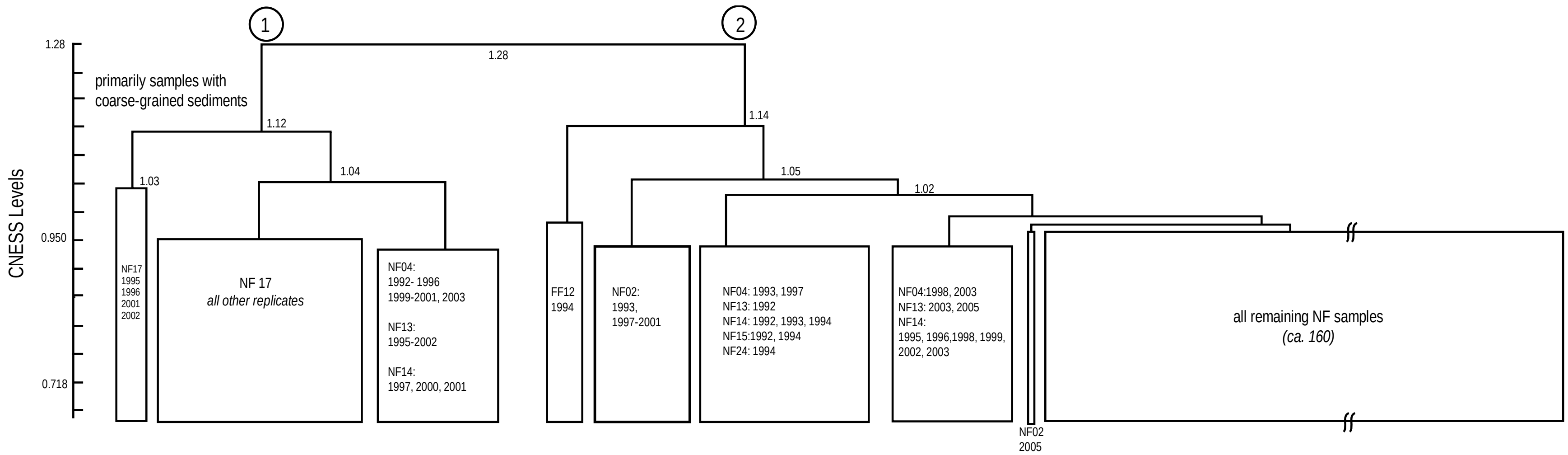


Figure 5-11. Summary CNESS dendrogram of nearfield replicates collected 1992–2005.

PCAH Analysis—This analysis was based on 258 samples taken at nearfield stations between 1992 and 2004; these samples are all from the subset of stations sampled in 2005.

With CNESS (*m*=15), 40 of the 359 species recorded in the 258 nearfield samples in 1992–2004 accounted for 90% of the variation in community structure, and contributed at least 1% to the PCA-H axes (Table 5-3). Of these 40 species, 32 were identified as important in a similar analysis of stations sampled in 2004 (Maciolek *et al*. 2005). In turn, the 2004 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 versus FF12 in 2005.

Axes 1 and 2 of this multidimensional analysis accounted for 44% 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.* 2005) (Figure 5-12A). The majority of nearfield samples separated only along axis 2; in particular, FF12, which has a slightly different species composition, separated from the remaining nearfield stations along this axis, similar to the alignment seen for FF11 and FF13 in 2004. Stations with intermediate positions on this diagram most likely reflect a gradient of species composition and sediment texture. Samples collected in 2005 are indicated by red star symbols (Figure 5-12A). While the majority are found within the cloud of points associated with the majority of samples, some, such as NF04 and NF13 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 5-12B) and detailed in Table 5-4. 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 *Aphelochaeta marioni*, *Aricidea catherinae*, *Levinsenia gracilis*. *Mediomastus californiensis*, and *Tharyx acutus*. The sandy nearfield stations (NF17) are influenced by the polychaetes *Exogone hebes*, *Spiophanes bombyx*, *Polygordius* sp. A, the amphipod *Crassicorophium crassicorne,* and the ascidian *Molgula manhattensis*. 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 5-3. Contribution of the 40 species in the 1992–2005 Massachusetts Bay nearfield samples identified by PCA-H analysis as important in structuring the infaunal communities, and their loadings on each of seven PCS-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*	7	7	13	7	2	0	29	3	1
2	*Spio limicola*	6	14	6	29	3	5	0	3	1
3	*Mediomastus californiensis*	6	19	15	0	0	0	0	1	4
4	*Crassicorophium crassicorne*	5	25	12	0	4	1	0	7	4
5	*Exogone hebes*	5	30	8	2	17	0	5	0	10
6	*Tharyx acutus*	5	34	5	7	2	2	4	0	15
7	*Aricidea catherinae*	5	39	3	0	0	42	7	1	21
8	*Owenia fusiformis*	4	43	0	22	4	19	3	0	1
9	*Dipolydora socialis*	4	47	1	8	10	11	11	8	1
10	*Molgula manhattensis*	3	50	3	0	0	1	3	32	1
11	*Aphelochaeta marioni*	3	53	2	6	2	1	1	1	3
12	*Polygordius* sp. A	3	56	3	0	3	0	0	0	5
13	*Spiophanes bombyx*	3	58	3	4	4	1	0	3	3
14	*Pseudunciola obliquua*	2	60	2	0	11	0	0	2	2
15	*Exogone verugera*	2	63	1	4	13	0	2	5	0
16	*Ninoe nigripes*	2	65	3	0	0	1	0	3	1
17	*Monticellina baptisteae*	2	67	2	0	0	2	5	2	0
18	*Hiatella arctica*	2	69	0	0	1	4	6	1	8
19	*Levinsenia gracilis*	2	71	3	0	3	0	1	2	0
20	*Euchone incolor*	2	73	1	0	0	1	4	0	1
21	*Cerastoderma pinnulatum*	2	75	2	0	0	1	0	0	1
22	*Unciola inermis*	2	76	1	0	1	0	1	8	4
23	Enchytraeidae sp. 1	1	78	1	0	2	0	2	2	1
24	*Scoletoma hebes*	1	79	0	5	0	1	5	1	0
25	*Phyllodoce mucosa*	1	80	0	1	0	1	0	2	0
26	*Leitoscoloplos acutus*	1	81	1	0	1	0	0	0	0
27	*Echinarachnius parma*	1	82	1	0	1	0	0	0	1
28	*Phoronis architecta*	1	83	0	0	0	0	0	1	1
29	*Chiridotea tuftsi*	1	83	1	0	3	0	0	0	1
30	*Pholoe minuta/tecta/spp.*	1	84	0	0	0	0	1	0	1
31	*Crenella decussata*	1	85	0	0	2	0	0	0	0
32	*Ensis directus*	1	85	0	0	0	0	0	3	0
33	*Arctica islandica*	1	86	0	0	0	0	0	0	0
34	*Chaetozone setosa* mb	1	87	1	0	0	0	0	1	0
35	*Asabellides oculata*	1	87	0	0	1	0	1	0	0
36	*Dipolydora quadrilobata*	1	88	0	0	0	0	0	0	0
37	*Nucula delphinodonta*	1	88	0	0	0	0	0	0	0
38	*Aglaophamus circinata*	1	89	1	0	0	0	0	0	0
39	*Euclymene collaris*	1	89	0	0	1	0	0	1	2
40	*Parougia caeca*	1	90	0	0	0	0	1	0	0

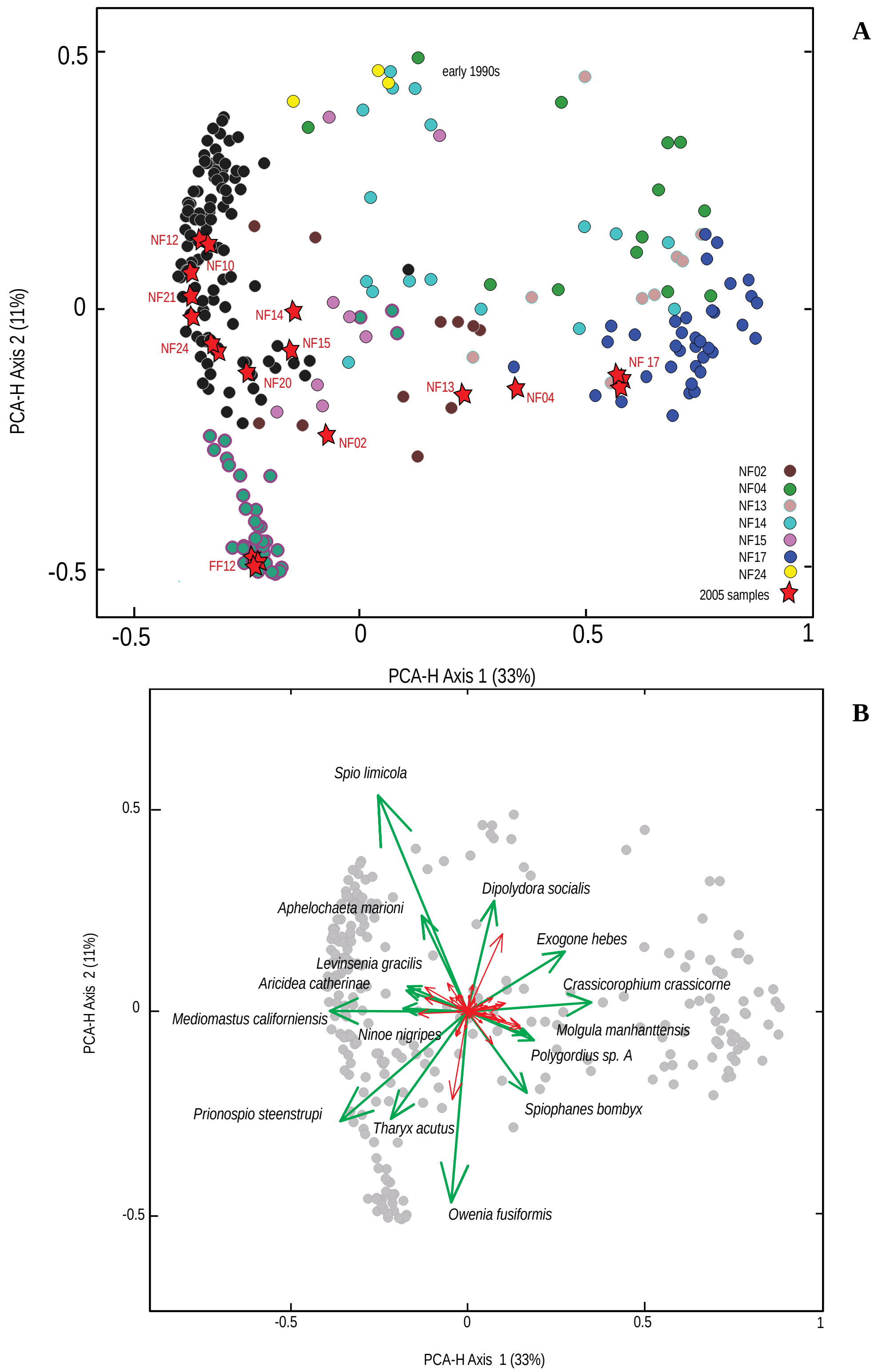


Figure 5-12. Metric scaling on PCA-H axes 1 and 2 of the 258 nearfield benthic infaunal samples collected 1992–2005 (A) and the Euclidean distance biplot showing the species responsible for at least 2% of the CNESS (*m*= 15) variation.

Table 5-4. Contributions to PCA-H axes by species accounting for at least 2% of the CNESS variation among the infaunal samples collected from nearfield stations 1992-2005 (see Figure 5-12 B 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*	12	12	6	29
2	*Prionospio steenstrupi*	12	23	13	7
3	*Mediomastus californiensis*	12	35	15	0
4	*Crassicorophium crassicorne*	9	44	12	0
5	*Exogone hebes*	6	51	8	2
6	*Owenia fusiformis*	6	56	0	22
7	*Tharyx acutus*	5	61	5	7
8	*Spiophanes bombyx*	3	64	3	4
9	*Polygordius* sp. A	3	67	3	0
10	*Aphelochaeta marioni*	3	70	2	6
11	*Ninoe nigripes*	3	72	3	0
12	*Aricidea catherinae*	2	75	3	0
13	*Levinsenia gracilis*	2	77	3	0
14	*Dipolydora socialis*	2	79	1	8
15	*Molgula manhattensis*	2	81	3	0
Important species: Axis 1 vs. 3					
PCA-H Rank	**Species**	**Contr.**	**Total Contr.**	**Axis 1**	**Axis 3**
1	*Mediomastus californiensis*	13	13	15	0
2	*Prionospio steenstrupi*	11	24	13	2
3	*Crassicorophium crassicorne*	11	35	12	4
4	*Exogone hebes*	9	44	8	17
5	*Spio limicola*	6	50	6	3
6	*Tharyx acutus*	4	54	5	2
7	*Pseudunciola obliquua*	4	58	2	11
8	*Polygordius sp. A*	3	61	3	3
9	*Spiophanes bombyx*	3	64	3	4
10	*Exogone verugera*	3	67	1	13
11	*Levinsenia gracilis*	3	70	3	3
12	*Ninoe nigripes*	3	73	3	0
13	*Aricidea catherinae*	3	75	3	0
14	*Molgula manhattensis*	2	77	3	0
15	*Dipolydora socialis*	2	79	1	10
Important species: Axis 2 vs. 3					
PCA-H Rank	**Species**	**Contr.**	**Total Contr.**	**Axis 2**	**Axis 3**
1	*Spio limicola*	19	19	29	3
2	*Owenia fusiformis*	15	34	22	4
3	*Dipolydora socialis*	8	43	8	10
4	*Exogone hebes*	8	50	2	17
5	*Exogone verugera*	7	58	4	13
6	*Prionospio steenstrupi*	5	63	7	2
7	*Tharyx acutus*	5	68	7	2
8	*Aphelochaeta marioni*	4	72	6	2
9	*Pseudunciola obliquua*	4	77	0	11
10	*Spiophanes bombyx*	4	81	4	4
11	*Scoletoma hebes*	3	84	5	0

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, stations were divided into three zones: greater than 10 km from the diffuser, between 10 and 2 km from the diffuser, and less than 2 km from the diffuser.

The mean species abundances and other variables, including species richness and total abundance, were plotted separately by zone on a log scale (Figures 5-13–5-14, Appendix C6). 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.

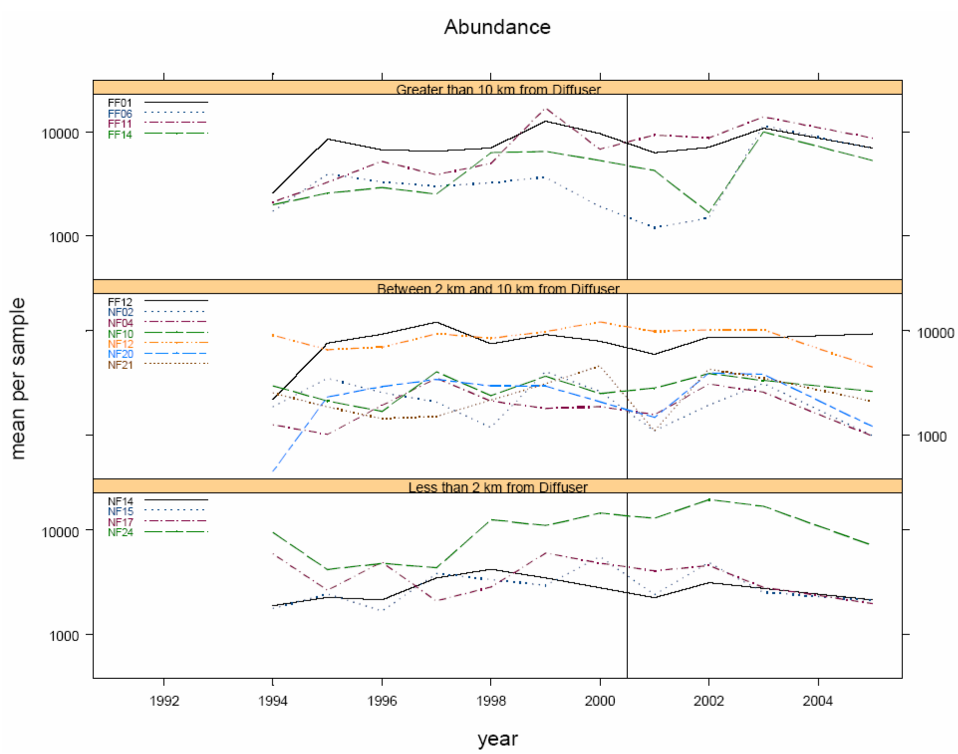
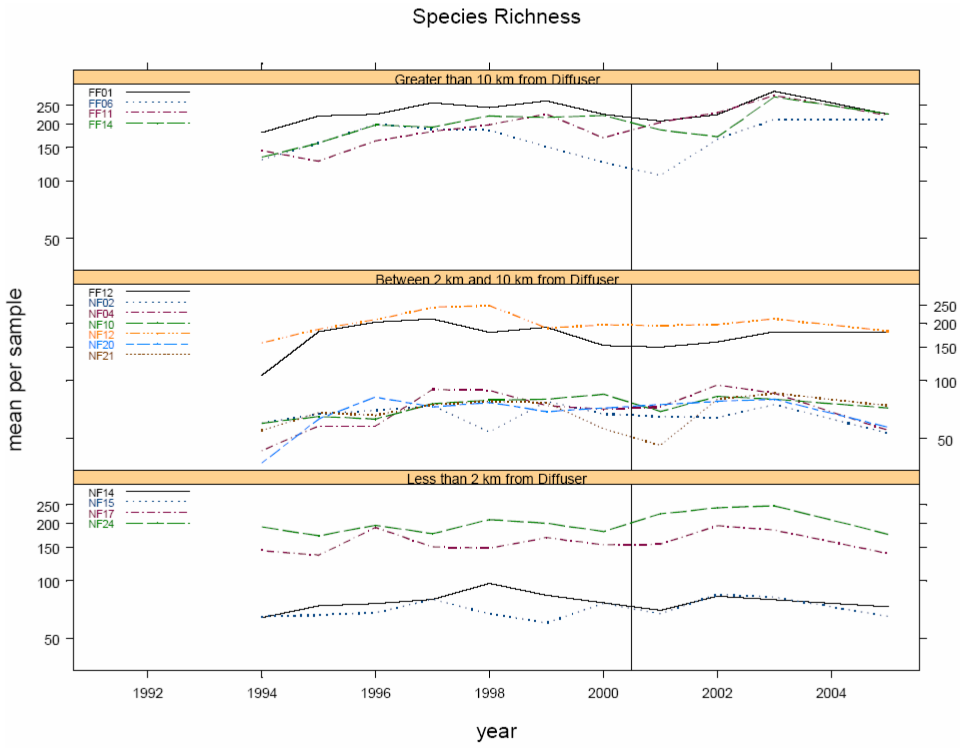


Figure 5-13. Log plot of total abundance at nearfield stations.



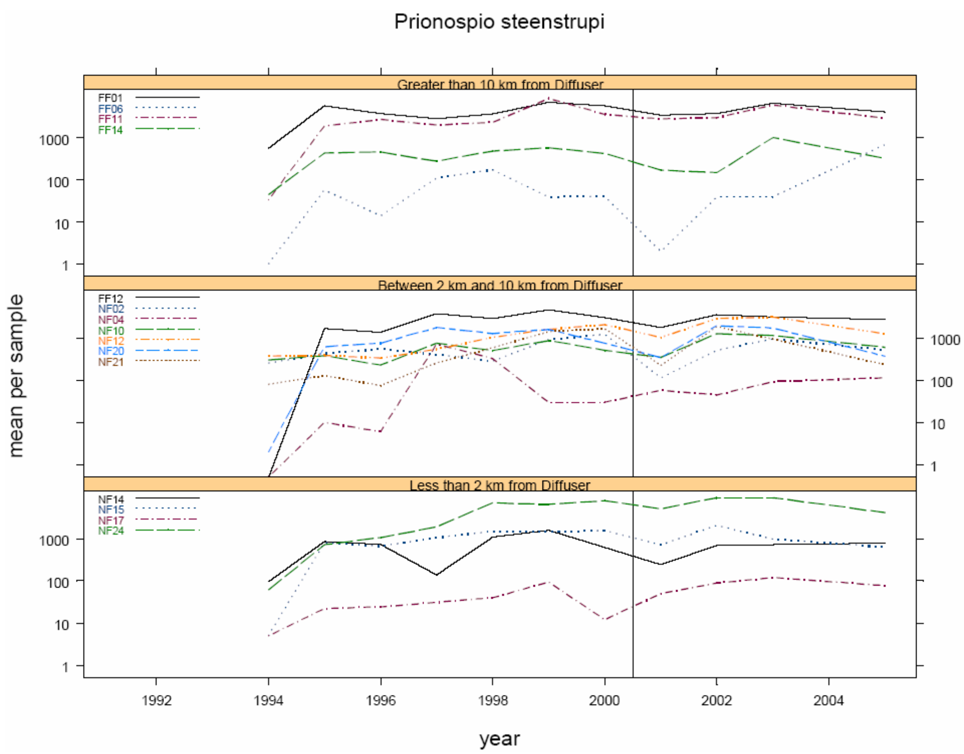


Figure 5-14. Log plots of species richness and a common species, *Prionospio steenstrupi*, at the nearfield stations. Additional plots are presented in Appendix C6.

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 the nearfield after September 2000. Where the nearfield is the area less than 10 km from the outfall, the mean abundances are shown in the lower two panels in the plots. An additional parameter, change in abundance at stations less than 2 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 63 species abundances were analyzed using this method (Appendix C6). Total abundances for these species ranged from 215 (*Gattyana amondseni*) to 157,747 (*Prionospio steenstrupi*). 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 a 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 5-5 and 5-6 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 5-5, the only important association is an estimated 1.54 relative increase in *Clostridium* in the less-than-2-km zone. That is, there was an estimated relative increase in this zone of approximately 54% after the diversion. Approximately 90% of the variance was explained by the complete model, which included year, station, and fine sediment as explanatory variables. However, only 2.9% of the variation was explained by the zone-by-diversion sub-model. Thus, this environmental survey was able to detect a post-outfall 50% 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. Neither of the infaunal parameters (total abundance and species richness) were significant.

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

	Zone-by-Diversion Effect				Log (Silt) Covariate		R-squared	
	Within 10 km		Within 2 km					
	multiplier	**P-value**	**multiplier**	**P-value**	**coefficient**	**P-value**	**Complete Model**	**Diversion by Zone Submodel**
Clostridium	1.100	0.252	1.549	**0.000**	0.700	**0.000**	0.898	0.029
Total Organic Carbon	0.979	0.744	1.069	0.317	0.920	**0.000**	0.948	0.000
Abundance	0.874	0.109	1.031	0.714	-0.104	0.334	0.719	0.006
Species Richness	0.955	0.085	1.025	0.356	-0.012	0.732	0.948	0.001

The analysis of the individual species abundance data is reported in Table 5-6. 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 km or at greater distances from the diffuser. In the zone closest to the diffuser, the polychaetes *Eteone longa*, *Scoletoma hebes*, *Trochochaeta multisetosa*; the phoronid *Phoronis architecta*; and the nemertean *Amphiporus caecus* showed a significant zone-by-diversion effect. In the between 2-and 10-km zone, polychaetes *Aphelochaeta marioni*, *Euchone incolor*, *Euclymene collaris*, *Exogone verugera*, *Ninoe nigripes*, and *Scoletoma hebes*, as well as the nemertean *Micrura* spp., the bivalve *Hiatella arctica*, and the amphipod *Photis pollex* showed significant results.

Table 5-6. Results of the analysis of species abundances at the nearfield infaunal stations.

	Zone by Diversion Effect							Pseudo R-squared	
	Within 10 km		Within 2 km		Log (Silt) Covariate			Proportion Chi-squared	
Species Tested	**multiplier**	**P-value**	**multiplier**	**P-value**	**coefficient**	**P-value**	**Negative Binomial Theta**	**Complete Model**	**Diversion by Zone Submodel**
Aglaophamus circinata	1.042	0.929	0.984	0.961	-1.411	**0.002**	0.902	0.788	0.000
Ampharete acutifrons baltica	1.311	0.667	0.780	0.596	-0.524	0.300	0.690	0.716	0.001
Amphiporus caecus	0.614	0.061	1.736	**0.003**	0.289	0.808	2.314	0.612	0.026
Anobothrus gracilis	0.944	0.999	1.179	0.548	0.452	0.354	1.038	0.796	0.000
Aphelochaeta marioni	0.423	**0.000**	1.150	0.543	-0.403	0.100	1.144	0.677	0.031
Apistobranchus typicus	2.020	0.026	0.706	0.311	-0.613	0.303	0.855	0.596	0.016
Arctica islandica	1.236	0.457	1.038	0.883	-0.261	0.504	0.869	0.578	0.001
Aricidea catherinae	0.761	0.530	1.412	0.081	-0.182	0.307	1.248	0.705	0.006
Aricidea quadrilobata	0.849	0.293	0.998	0.992	0.969	0.066	2.182	0.904	0.001
Asabellides oculata	0.578	0.114	0.605	0.592	-0.792	0.200	0.407	0.689	0.008
Astarte undata	1.093	0.634	0.658	0.025	0.369	0.100	2.018	0.789	0.007
Capitella capitata complex	1.447	0.010	1.765	0.013	-0.376	0.199	1.025	0.511	0.034
Cephalothricidae sp. 1	0.411	0.027	2.110	0.006	0.093	0.644	1.517	0.686	0.031
Cerastoderma pinnulatum	0.761	0.283	0.826	0.457	-0.484	0.205	0.888	0.719	0.003
Cerebratulus lacteus	1.053	0.613	1.446	0.149	0.286	0.676	2.316	0.727	0.005
Ceriantheopsis americanus	0.926	0.842	1.072	0.696	0.196	0.456	2.715	0.658	0.000
Crassicorophium crassicorne	1.219	0.610	1.518	0.334	-0.822	0.169	0.598	0.893	0.001
Crenella decussata	0.623	0.018	0.834	0.469	-0.315	0.252	1.274	0.805	0.008
Dentalium entale	0.814	0.952	2.088	0.042	0.344	0.481	1.804	0.885	0.005
Dipolydora socialis	1.019	0.804	0.755	0.434	-0.841	0.091	0.496	0.452	0.002
Dyopedos monacanthus	NA	0.999	0.700	NA	-0.129	0.956	0.942	0.862	0.001
Echinarachnius parma	0.723	0.288	0.777	0.543	-0.340	0.438	0.868	0.843	0.002
Edotia montosa	0.858	0.644	1.150	0.446	0.208	0.524	1.732	0.790	0.001
Enchytraeidae sp. 1	NA	0.985	1.016	NA	-0.107	0.949	0.286	0.915	-0.002
Eteone longa	0.745	0.389	1.632	**0.003**	-0.278	0.017	2.381	0.653	0.018
Euchone incolor	0.375	**0.000**	1.383	0.167	0.215	0.967	0.986	0.615	0.032
Euclymene collaris	0.312	**0.001**	0.430	0.041	-1.092	0.025	0.490	0.671	0.042
Exogone hebes	0.972	0.899	1.000	0.998	-0.131	0.527	2.197	0.892	0.000
Exogone verugera	0.417	**0.000**	0.875	0.455	-0.132	0.681	1.644	0.829	0.022
Gattyana amondseni	1.291	0.230	0.986	0.954	0.355	0.335	1.948	0.468	0.005
Hiatella arctica	0.420	**0.002**	0.914	0.756	0.057	0.701	0.738	0.667	0.018
Leitoscoloplos acutus	0.763	0.057	1.015	0.925	-0.056	0.692	2.403	0.746	0.005
Levinsenia gracilis	0.888	0.343	1.135	0.257	0.066	0.855	5.162	0.811	0.002
Mediomastus californiensis	1.143	0.046	1.345	0.025	0.070	0.804	2.691	0.736	0.013

	Zone by Diversion Effect							Pseudo R-squared	
	Within 10 km		Within 2 km		Log (Silt) Covariate			Proportion Chi-squared	
Species Tested	**multiplier**	**P-value**	**multiplier**	**P-value**	**coefficient**	**P-value**	**Negative Binomial Theta**	**Complete Model**	**Diversion by Zone Submodel**
Metopella angusta	0.903	0.476	0.934	0.757	-0.134	0.531	1.485	0.546	0.002
Micrura spp	0.725	**0.001**	0.933	0.604	-0.244	0.173	4.056	0.611	0.021
Molgula manhattensis	1.290	0.201	1.650	0.221	0.026	0.876	0.487	0.753	0.006
Monticellina baptisteae	1.030	0.343	1.309	0.282	-0.079	0.702	0.870	0.667	0.004
Monticellina dorsobranchialis	0.871	0.566	1.002	0.991	-0.381	0.149	2.705	0.841	0.000
Nemertea sp. 12	0.930	0.861	1.122	0.538	0.109	0.761	1.742	0.719	0.001
Nephtys cornuta	0.752	0.719	1.519	0.308	-0.016	0.683	0.887	0.707	0.003
Nephtys incisa	0.857	0.154	0.758	0.209	0.553	0.043	1.827	0.698	0.007
Ninoe nigripes	0.621	**0.001**	0.912	0.569	-0.082	0.426	1.839	0.643	0.022
Nucula delphinodonta	1.142	0.248	1.198	0.381	-0.249	0.310	1.415	0.632	0.004
vOwenia fusiformis	1.110	0.939	0.774	0.413	0.802	0.144	0.700	0.765	0.001
Parougia caeca	0.681	0.111	1.424	0.033	-0.038	0.521	1.750	0.539	0.017
Pholoe minuta/tecta/spp.	1.068	0.874	0.790	0.085	0.292	0.037	2.905	0.669	0.006
Phoronis architecta	0.423	0.014	2.081	**0.003**	-0.309	0.098	0.945	0.601	0.032
Photis pollex	0.450	**0.000**	0.813	0.336	0.254	0.932	1.376	0.554	0.051
Phyllodoce maculata	0.326	0.141	1.486	0.855	-2.270	0.005	0.624	0.684	0.007
Phyllodoce mucosa	0.861	0.462	1.049	0.769	-0.737	**0.002**	1.781	0.736	0.001
Polygordius sp. A	1.176	0.754	0.790	0.236	-0.559	0.060	1.783	0.840	0.001
Prionospio steenstrupi	0.890	0.795	1.232	0.176	-0.242	0.180	1.854	0.701	0.003
Scoletoma hebes	5.152	**0.000**	0.000	**0.002**	0.157	0.183	2.907	0.947	0.012
Scoloplos armiger	0.518	0.216	1.346	0.219	-0.226	0.506	1.481	0.731	0.007
Spio limicola	0.582	0.028	1.274	0.302	-0.329	0.233	0.903	0.597	0.013
Spiophanes bombyx	0.815	0.534	1.218	0.209	-0.695	0.006	2.215	0.867	0.002
Tharyx acutus	1.254	0.169	1.186	0.415	-0.291	0.293	1.006	0.622	0.005
Trochochaeta multisetosa	0.470	0.048	2.489	**0.003**	0.716	0.631	1.500	0.766	0.023
Tubificidae sp. 2	1.641	0.262	0.705	0.225	-0.578	0.323	0.801	0.733	0.005
Tubificoides apectinatus	0.909	0.387	0.879	0.528	0.106	0.621	2.378	0.875	0.001
Unciola inermis	0.236	0.077	1.111	0.862	0.558	0.615	0.455	0.895	0.006
Yoldia sapotilla	0.738	0.050	0.756	0.403	-1.604	0.003	2.274	0.812	0.007

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 2003 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, *e.g*., *Prionospio steenstrupi*, which replaced another spionid polychaete, *Spio limicola*, as the dominant at the medium- to fine-grained stations. Species richness also increased, in 2003 reaching the highest mean values in both the nearfield and farfield areas. some of the calculated parameters appeared to fluctuate in a sine-wave-like pattern, with increases followed by declines (Figure 5-6). The apex values for density and species richness seen in 2003 were in fact followed by lower values in 2004, and again by a further decline in 2005. *P. steenstrupi* declined in abundance, and all calculated parameters also decreased, including species richness, Shannon diversity, evenness and log-series *alpha*. Species richness and *alpha* also declined in the farfield, but Shannon diversity and evenness increased at those stations (Figure 5-6). Although the subset of stations sampled in 2005 differed from those sampled in 2004, the decline in mean station parameters appears to be real when compared with the same subset of stations in 2003. However, based on the statistical analyses performed on the 2005 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 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* have suggested a modest impact of the discharge (Chapter 3, this report).

6. 2005 HARD-BOTTOM BENTHIC HABITATS AND FAUNA

by Barbara Hecker and Woollcott K. Smith

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 12 years. These benthic communities have been surveyed utilizing a remotely operated vehicle (ROV) to photograph the sea floor. 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 2005). 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 sea floor on the tops 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 sea floor 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 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 usually appeared to reflect 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. One of the southern reference sites, located southwest of the outfall, represents a relatively extreme habitat characterized by very large boulders with heavy sediment drape. This area 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 four post-discharge surveys were remarkably similar to those observed during the baseline period (Maciolek *et al*., 2004, 2005). Several modest differences have been noted between the pre- and post discharge periods. 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 first two post discharge years. Decreased percent cover of coralline algae was also observed at an additional northern reference site during the third post-discharge year, but not during the fourth one. 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 fifth post-discharge survey of the hard-bottom communities conducted during late June 2005. This chapter presents the results of the 2005 survey and compares these results to pre-discharge baseline conditions and to the previous post-discharge conditions. All of the waypoints were successfully surveyed during 2005, including an actively discharging diffuser head at the eastern end of the outfall.

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 still 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 Table 2-2 and Figure 2-3). Photographic coverage ranged from 20 to 26 minutes of video footage and 27 to 34 still photographs (35-mm slides) at each waypoint. A total of 726 still photographs was taken and used in the following data analysis.

Table 6-1. Photographic coverage at locations surveyed during the 2005 nearfield hard-bottom survey.

Station	Location on drumlin	Depth (m)	Video (min)	Stills (# frames)
T1-1	Flank	28	25	30
T1-2	Top	25	22	34
T1-3	Top	23	22	33
T1-4	Top	24	25	32
T1-5	Flank	28	22	31
T2-1	Flank	27	21	32
T2-2	Flank	26	22	33
T2-3	Flank	27	21	32
T2-4	Flank	31	21	33
T4-2	Flank	28	21	31
T4/6-1	Top	23	21	30
T6-1	Flank	33	21	31
T6-2	Flank	30	23	32
Northern reference				
T7-1	Top	26	22	31
T7-2	Top	27	23	31
T9-1	Top	27	24	31
Southern reference				
T8-1	Top	23	21	33
T8-2	Top	23	21	34
T10-1	Top	26	26	31
T12-1	Top	24	23	31
Far-field reference				
T11-1		36	25	31
Diffusers				
T2-5	Diffuser #2	34	22	27
Diffuser	#44	35	20	32

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 in terms of 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 in terms of 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 2005 slide analysis is included in Appendix E1.

Several changes in taxonomic designations have occurred during the years of this survey. Coralline algae, which were originally referred to as *Lithothamnion* spp., were found to belong to at least five species: *Leptophytum laevae*, *L. foecundum*, *Phymatolithon lamii*, *P. laevigatum*, and *Lithothamnion glaciale*. Differences between these species can not be discerned on the basis of photographs, so all pink encrusting coralline algae were lumped into one taxon. Additionally, an abundant red filamentous alga that had previously been designated as *Asparagopsis hamifera* was subsequently identified as *Ptilota serrata*. Based on a specimen that was retrieved from the ROV during the 2003 diffuser inspection survey, hydroids on or near the diffuser heads that had previously been referred to as *Campanularia* sp. have been found to be *Tubularia* sp. The generic name for dulse has been changed from *Rhodymenia* to *Palmaria*. The sponge that had previously been referred to as *Halichondria panecia* (crumb of bread sponge), is a species of papillate sponge that most likely belongs to the genus *Polymastia*. This species is now being called *Polymastia* sp. A to distinguish it from the previously identified siphon sponge *Polymastia*? sp., which is now called *Polymastia* sp. B. *Polymastia* sp. A is a circular yellow sponge on hard substrate, while *Polymastia* sp. B is an irregular whitish sponge whose basal cushion is partially buried in sediment.

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 2005 video analyses is included in Appendix E2.

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.

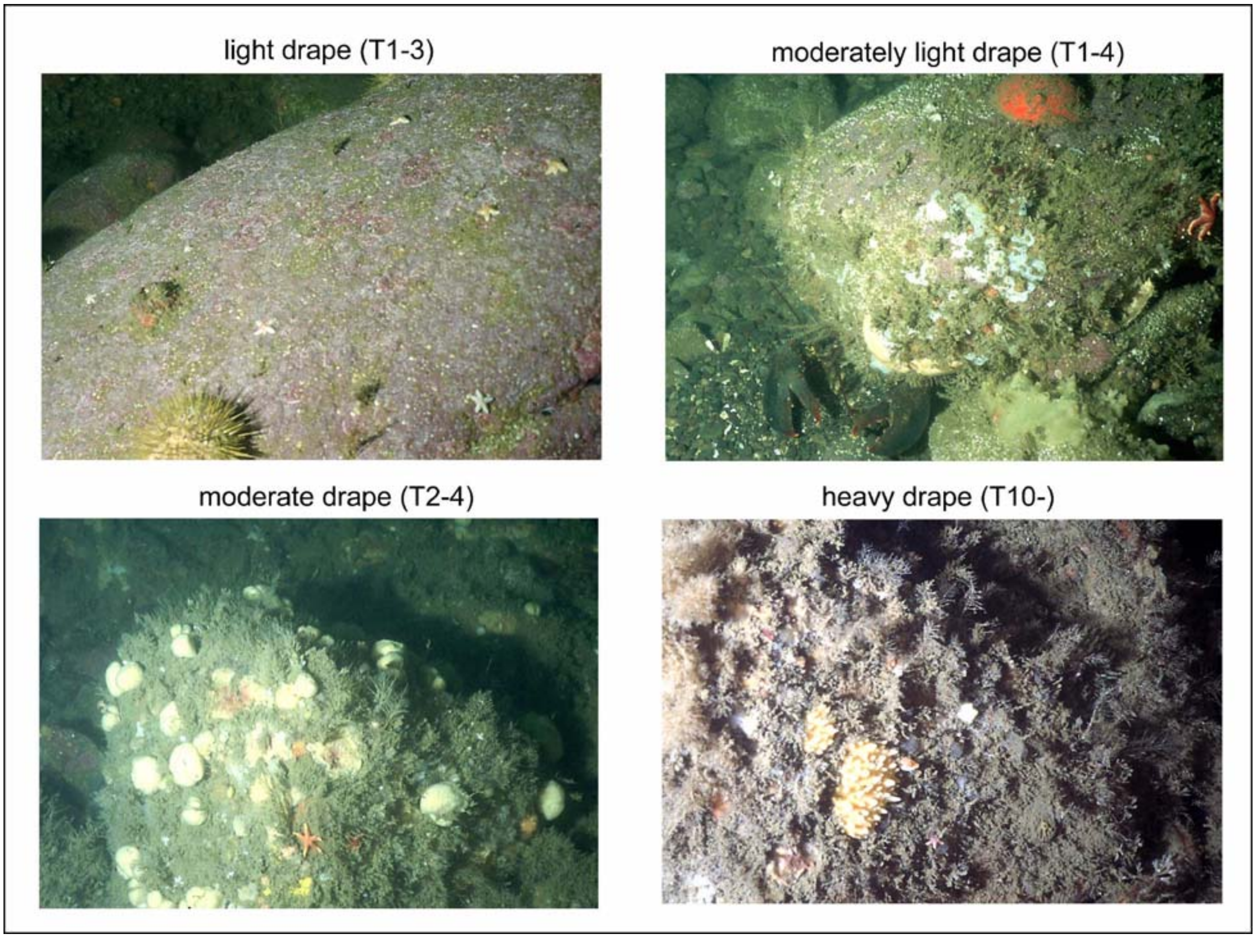


Figure 6-1. Photographs representative of sediment drape categories. Light drape is the presence of a dusting or small patches of sediment leaving the rock surfaces clearly visible. Moderately light drape is the presence of larger patches of sediment, yet still leaving most of the rock surfaces visible.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

6.2.2 Data analysis

Data were pooled for all slides taken at each waypoint. 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 2005 data, only taxa with an abundance of ten or more individuals in the data set were retained. This resulted in 45 of the original 77 taxa being retained for community analysis. Community analysis of the entire data set (years 1996 to 2005) 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 66 of the original 111 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 seeks to "map" samples based on the rank order of their species dissimilarities, and plots species with similar species composition close together and dissimilar species composition further apart.

One general question for this monitoring program is: *Does a pattern exist in the ten years of hard-bottom monitoring data that is correlated with diversion of the outfall in the fall of 2000?* A standard statistical model, described below, was developed to address this question. Since, like all monitoring studies, this is an observational study, rather than a designed experiment, care should be taken in assigning a causal relationship to any observed correlation.

Two versions of the model were run, one with continuous variables and one with species counts. Five continuous variables were used: percent cover of coralline algae and sediment drape were used because they had previously been identified as possible indicators of change, and the three axes from the NMDS were used to reflect possible changes in community structure. The species count models were run only on species that were present in >1000 individuals in the entire dataset, were present in more than a few stations, and had been identified consistently over the years.

The continuous variable models start with the following basic linear model for mean value of a variable, μ_{ij}, at station *i* in year *j*.

$$\mu_{ij} = \mu + \alpha_{si} + \alpha_{yj} ,$$

where α_{si} denotes the fixed effect associated with station *i* and α_{yj} denotes the fixed effect associated with year *j*.

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 $I_{NS}(station)$ denotes the location of the field station,

$$I_{NS}(\text{station}) = \begin{cases} 1 & \text{if station is north of the outfall.} \\ 0 & \text{otherwise.} \end{cases}$$

A linear model that includes the distance-by-diversion covariate can be written as

$$\mu_{ij} = \mu + \alpha_{si} + \alpha_{yj} + \alpha_{NS} I_{NS}(station_i) I_D(y_j) + \beta_1 x_i I_D(y_j) \qquad (0.3)$$

where β_1 denotes the parameter describing the distance-by-diversion interaction and x_i denotes the distance station *i* is from the diffuser. The goal is to estimate "the gradient, β_1, of the differences after the diversion."

The species count 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*.

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

where α_{si} denotes the fixed effect associated with station *i* and α_{yj} denotes the fixed effect associated with station year *j.*

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

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

A linear model that includes the distance-by-diversion covariate can be written as

$$\log\left(\mu_{ij}\right) = \mu + \alpha_{si} + \alpha_{yj} + \beta_1 x_i I_D(y_j) \, (0.4)$$

where β_1 denotes the parameter that describes the distance-by-diversion interaction and x_i denotes the distance in kilometers from station *i* to the diffuser. The goal is to estimate the gradient, β_1, of the relative changes after the diversion. These analyses estimate this gradient and the degree of statistical uncertainty associated with the estimation.

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 sea floor on the tops of the drumlins consisted of a mix of glacial erratics in the boulder and cobble size categories. The sea floor on the drumlin immediately north of the outfall ranged from areas of moderate to moderately high relief characterized by numerous boulders interspersed with cobbles, to areas of moderately low relief characterized by a mix of cobbles, occasional boulders, and gravel in the slightly deeper areas. The sea floor on the top of the drumlin located south of the outfall (T4/6-1) also had a moderate relief mix of boulders and cobbles. The sea floor at the three northern reference sites ranged from moderate to moderately high and consisted primarily of boulders interspersed with cobbles. The sea floor at the southern reference sites ranged from moderately low to high relief. The two southern reference sites that consisted mainly of cobbles with occasional boulders (T8-1 and T8-2) had moderately low relief. Another southern reference site T12-1 that consisted mainly of boulders with occasional cobbles had moderate relief, while the remaining southern reference site T10-1 consisted mainly of large boulders and had high relief. The sea floor of the drumlin flank sites usually consisted of a moderately low to moderate relief mix of cobbles, occasional boulders, and gravel. The sea floor 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 drape at T8-1 to a moderately heavy drape at T10-1. Most drumlin top areas had moderately light sediment drape, while a few had moderate drape. One of the four southern reference sites had light drape (T8-1), two had moderately light drape (T8-2 and T12-1), while the remaining one had moderately heavy drape (T10-1). In contrast, all three northern reference sites had moderate drape (T7-1, T7-2, and T9-1). Sediment drape was moderate 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 2005 survey, one that was actively discharging effluent (T2-5, Diffuser #2) and one that has not been activated (Diffuser #44). The sea floor 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).

6.3.2 Distribution and Abundance of Epibenthic Biota

Seventy-nine taxa were seen during the visual analyses of the 2005 nearfield hard-bottom survey still photographs and videotapes (Table 6-2). Seventy-seven of these taxa were seen on the still photographs and 51 were seen on the video footage. Taxonomic counts or estimates of abundances from the still photographs included 4,657 algae, 32,962 invertebrates, and 1,261 fish (Table 6-3). Coralline algae was the most abundant algal taxon observed during the survey, with an estimated abundance of 3,168 individuals. Two other algae commonly seen were dulse (*Palmaria palmata*) and a red filamentous alga (*Ptilota serrata*) with abundances of 1,036 and 413 individuals, respectively. The least abundant alga encountered was the shotgun kelp, *Agarum cribosum* (40 individuals).

The four most abundant invertebrates observed on the slides were the northern sea star *Asterias vulgaris* (6,692 juveniles and 729 adults), the frilled anemone *Metridium senile* (3,944 individuals), the horse mussel *Modiolus modiolus* (2,955 individuals), and the northern white-crust tunicate *Didemnum albidum* (2,690 individuals). Other abundant invertebrates observed on the still photographs were unidentified encrusting bryozoans (2,040 individuals), the brachiopod *Terebratulina septentrionalis* (2,010 individuals), and sea peach tunicates *Halocynthia pyriformis* (1,922 individuals). Other commonly seen invertebrate inhabitants of the drumlins included the blood sea star *Henricia sanguinolenta* (1,196 individuals), an unidentified orange/tan sponge (1,160 individuals), an unidentified whitish translucent sponge (1,065 individuals) and numerous sponges and encrusting organisms. The most abundant fish observed in the still photographs were the cunner *Tautogolabrus adspersus* (1,213 individuals), cod *Gadus morhua* (18 individuals), rock gunnel *Pholis gunnellus* (7 individuals), winter flounder *Pseudopleuronectes americanus* (6 individuals), sculpin *Myoxocephalus* spp. (5 individuals), ocean pout *Macrozoarces americanus* (3 individuals), and the sea raven *Hemitripterus americanus* (2 individuals).

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 0.2% cover at T6-1 to 48.3% cover at T4/6-1. Figure 6-2 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 light to 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, *P. serrata* and *P. palmata* had much more restricted distributions, with *P. serrata* being common at only the two northernmost reference sites and *P. palmata* being common at only seven of the sites (the three northern reference sites, three sites on a drumlin immediately north of the outfall, and the new southern reference site). 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, while 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. Juvenile *Asterias* were usually much more abundant than adults and were most abundant on the top of drumlins, while adults appeared to have less of a habitat preference. The blood sea star *H. sanguinolenta* was also observed at all sites.

Table 6-2. Taxa observed during the 2005 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 encrusting)
	Haliclona oculata	finger sponge
	Haliclona spp.	encrusting sponge
	Melonanchora elliptica	warty sponge
	Polymastia sp. A	yellow papillate sponge
**	*Polymastia* sp. B	whitish papillate sponge
	Suberites spp.	fig sponge (globular)
	white divided	sponge on brachiopod
*	orange/tan encrusting	sponge
*	orange encrusting	sponge
*	gold encrusting	sponge
*	pink fuzzy encrusting	sponge
*	white translucent	sponge
*	cream encrusting	sponge
*	filamentous white	encrusting sponge
*	frilly white sponge	sponge?
*	encrusting organism	general
*	grey translucent material	*Diplosoma listerianum?*
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
Mollusks		
*	*Tonicella marmorea*	mottled red chiton
*	*Notoacmaea testudinalis*	tortoiseshell limpet
	Buccinum undatum	waved whelk
*	*Neptunea decemcostata*	ten-ridged whelk
*	general nudibranch	
*	*Arctica islandica*	ocean quahog
	Modiolus modiolus	horse mussel
	Placopecten magellanicus	sea scallop
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
*	*Ophiopholis aculeata*	daisy brittle star
	Cucumaria frondosa	orange-footed holothurian
	Psolus fabricii	scarlet holothurian
	burrowing holothurian	
Tunicates		
	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
	Halocynthia pyriformis	sea peach tunicate
*	clear globular tunicate	
Bryozoans		
*	general bryozoan	
	Membranipora sp.	sea lace bryozoan
*	red crust bryozoan	bryozoan
Miscellaneous		
	Myxicola infundibulum	slime worm
	spirorbids	
*	sabellid	
	Terebratulina septentrionalis	northern lamp shell
Fish		
	general fish	
	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
** Seen only on video

Table 6-3. Taxa seen in still photographs taken during the 2005 nearfield hard-bottom survey, arranged in order of abundance.

Taxon	Count	Taxon	Count
Algae		burrowing holothurian	23
Coralline algae	3168*	*Alcyonium digitatum*	21
Palmaria palmata	1036	*Haliclona* spp. (encrusting)	18
Ptilota serrata	413*	*Urticina felina*	16
Agarum cribosum	40	*Haliclona oculata*	15
Total algae	**4657**	*Membranipora* sp.	14
		Tonicella marmorea	13
Invertebrates		*Homarus americanus*	12
small white starfish	6692	filamentous white encrust sponge	9
Metridium senile	3944	*Tubularia* sp.	9
Modiolus modiolus	2955	*Pteraster militaria*	9
Didemnum albidum	2690	general nudibranch	5
bryozoan	2040	clear globular tunicate	5
Terebratulina septentrionalis	2010	*Cerianthus borealis*	4
Halocynthia pyriformis	1922	*Buccinum undatum*	4
Henricia sanguinolenta	1196	*Placopecten magellanicus*	4
orange/tan encrusting sponge	1160	*Boltenia ovifera*	4
white translucent sponge?	1065	*Crossaster papposus*	3
Dendrodoa carnea	792	sabellid	3
Asterias vulgaris	729	*Melonanchora elliptica*	2
white divided sponge	728	dark grey translucent material	2
orange encrusting sponge	679	*Notoacmaea testudinalis*	2
Aplidium spp.	647	general starfish	2
general encrusting organism	528	frilly white sponge	1
pink fuzzy encrusting sponge	471	*Neptunea decemcostata*	1
Psolus fabricii	423	*Solaster endeca*	1
Polymastia sp. A	374	*Cucumaria frondosa*	1
Myxicola infundibulum	303	red crust bryozoan	1
general sponge	228	hydroids	**
Gersemia rubiformis	198	spirorbids	**
Botrylloides violaceus	147	**Total invertebrates**	**32962**
Aplysilla sulphurea	134		
Ophiopholis aculeata	129		
cream encrusting sponge	120	**Fish**	
Strongylocentrotus droebachiensis	87	*Tautogolabrus adspersus*	1213
Suberites spp.	85	*Gadus morhua*	18
Balanus spp.	59	General fish	7
Boltenia echinata	59	*Pholis gunnellus*	7
gold encrusting sponge	45	*Pseudopleuronectes americanus*	6
Arctica islandica	41	*Myoxocephalus* spp.	5
Obelia geniculata	32	*Macrozoarces americanus*	3
general anemone	23	*Hemitripterus americanus*	2
Cancer spp.	23	**Total fish**	**1261**

* Estimated

** Not counted

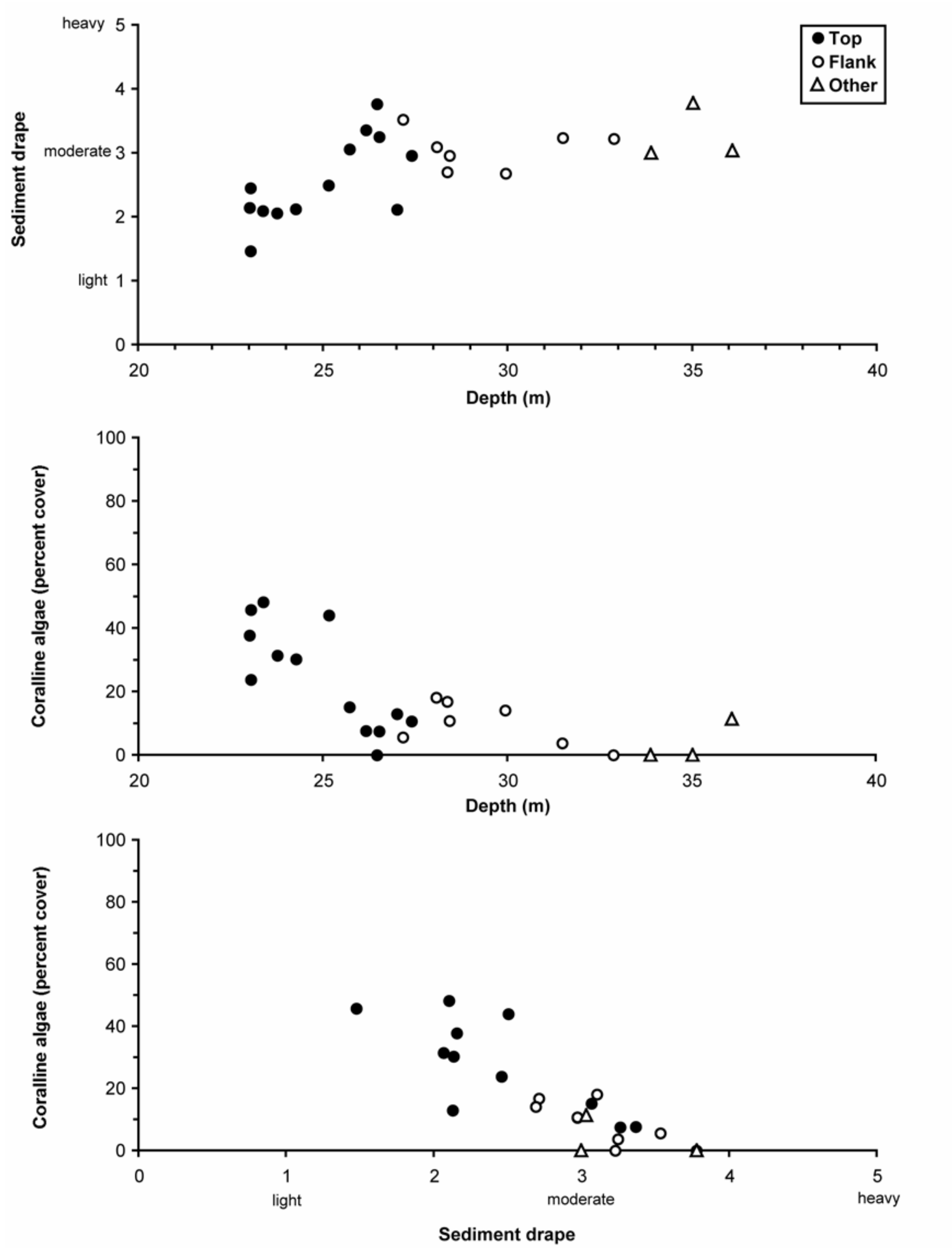


Figure 6-2. Depth, sediment drape, and percent cover of coralline algae of the sites from the 2005 nearfield hard-bottom survey.

This species was most abundant on larger boulders. The horse mussel *M. 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. Twenty-five individuals of this mussel were observed near one of the ports of the head of Diffuser #2. The sea peach tunicate *H. pyriformis* was found at 22 sites but was only found in high abundances at two sites, the head of the inactive diffuser (Diffuser #44) and a southern reference site (T12-1). 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 *T. septentrionalis* was found at 16 of the sites, but was only seen in high abundances at seven of them (T2-4, T4-2, T7-2, 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 *M. senile* was another species that was markedly more abundant on large boulders. This anemone was found at 12 sites, but was common to abundant at only four of them. *Metridium senile* was exceptionally abundant on the head of the active diffuser (Diffuser #2) and somewhat less abundant on the head of the inactive diffuser (Diffuser #44). It was also commonly observed on the larger boulders found at sites T1-2 and T12-1. This anemone was usually seen on the tops and upper sides of large boulders. One species with a very restricted distribution was the soft red coral *Gersemia rubiformis*, which was seen only at T10-1, where they inhabited the tops of large boulders.

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 14 sites. This urchin was common only in regions that had a moderately high percent cover of coralline algae (T1-2, T1-3, T1-4, T4/6-1, and T8-2), on which it grazes (Sebens 1986). The red holothurian *Psolus fabricii* also was widely distributed. This holothurian was found at 19 sites, but was abundant at only five of them (T1-3, T1-4, T4-2, T8-2, and T12-1). Reasons for its high abundance in some areas, and not in others, were not readily apparent.

Two invertebrate taxa were newly recognized this year. One taxon that was newly designated this year was the invasive tunicate *Botrylloides violaceus* (Figure 6-3a). This tunicate was found at 14 sites, and was common at five of them (T2-3, T2-4, T6-2, T10-1, and T12-1). The species designation of *B. violaceus* was only assigned to colonies where the surface structure was clearly visible, and the species assignment could be made with a fair amount of certainty. A total of 146 colonies was identified as *B. violaceus*, however some orange encrusting organisms seen at these and other sites may also belong to this species. It is unlikely that this species is new to the area, and it has probably been identified in the past as a combination of red/orange encrusting organism, red encrusting organism, and dark red/brown encrusting sponge. The other taxa newly encountered this year was a large unidentified holothurian that was found only at T11-1, the farfield station near Scituate (Figure 6-3b). Twenty-three individuals of this holothurian were counted on the still photographs. Only the respiratory tree of this holothurian was

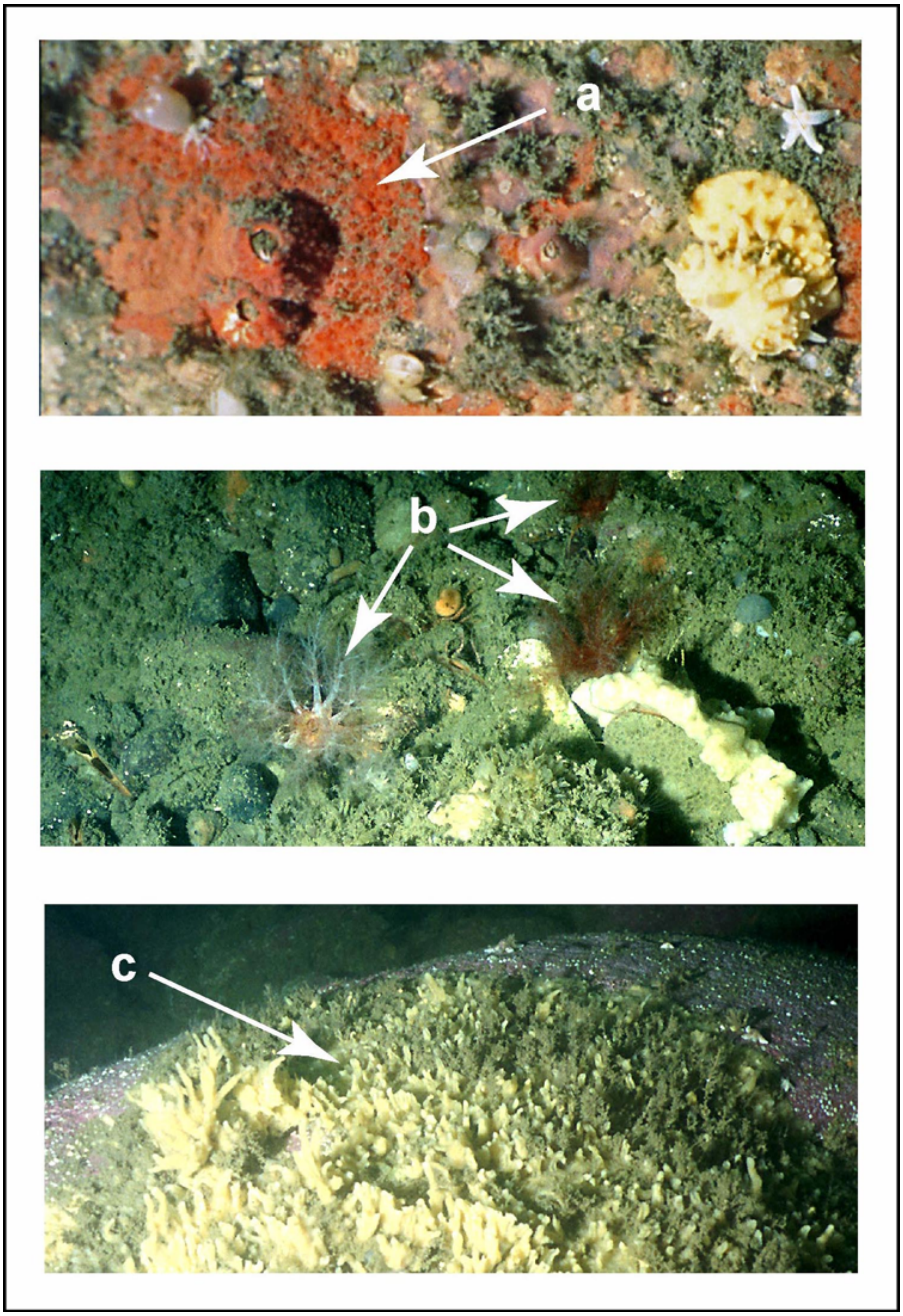


Figure 6-3. Photographs of three species "newly" observed in 2005: (a) *Botrylloides violaceus*, an invasive encrusting tunicate, (b) an unidentified holothurian observed at T11-1, and (c) a large yellowish encrusting sponge observed at T4/6-1.

visible, while the body remained hidden in the spaces between cobbles. As a result of seeing only part of the animal, a species designation for this holothurian was not attempted at this time. This holothurian occurred in two color morphs, a pale pink form and a deep maroon form. One other organism newly encountered in 2005 was a pale yellowish encrusting sponge (Figure 6-3c). Several large colonies of this sponge were seen on large boulders at T4/6-1. 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.

Only several colonies of two species first observed in 2004, a frilly white encrusting sponge and a dark-grey translucent material (tentatively identified as *Diplosoma listerianum*), were seen in 2005. Both species were again seen only on boulders that had die-offs of the 2003 barnacle settlement.

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 (T2-3, T7-1, and T10-1). In areas of heterogeneous or low relief, *T. adspersus* was usually seen only in the immediate vicinity of boulders. Six other fish species, cod (*G. morhua*), rock gunnel (*P. gunnellus*), winter flounder (*P. americanus*), sculpin (*Myoxocephalus* spp.), ocean pout (*M. americanus*), and sea raven (*H. americanus*) 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 seen only around boulders.

6.3.3 Community Structure

Classification analysis of the 23 waypoints and 45 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 three more cohesive clusters of stations and one solitary station. The clustering structure appeared to reflect a combination of topography, habitat characteristics, and geographic proximity. Neighboring waypoints with similar habitat characteristics tended to cluster together (T7-1 and T7-2; T8-1 and T8-2). Non-metric multidimensional scaling (NMDS) of the same data set is presented in 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, one slight adjustment in the hierarchical ordering of stations was noted and is discussed below. 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.

The first cluster (cluster 1) consisted of the three northern reference sites (T7-1, T7-2, and T9-1) grouped together at a faunal similarity of 75.5 percent (subgroup 1a), joined by a southern reference station (T10-1) at a similarity of 67.1 percent. All four sites in this cluster were drumlin top sites that had boulders as their primary substrate and had moderate to moderately high relief. Sediment drape was moderate at the three northern sites and moderately heavy at the southern site. The three northern reference stations supported numerous upright algae and a moderately low cover of coralline algae (7.7 to 15.3 percent). In contrast, the southern reference station in cluster 1, T10-1, supported a few dulse and very little coralline algae (0.2 percent cover). However, all four of the stations in this cluster supported relatively high numbers of sea stars and cunner (*T. adspersus*). The large boulders at station T10-1 also supported numerous *G. rubiformis* and *T. septentrionalis*.

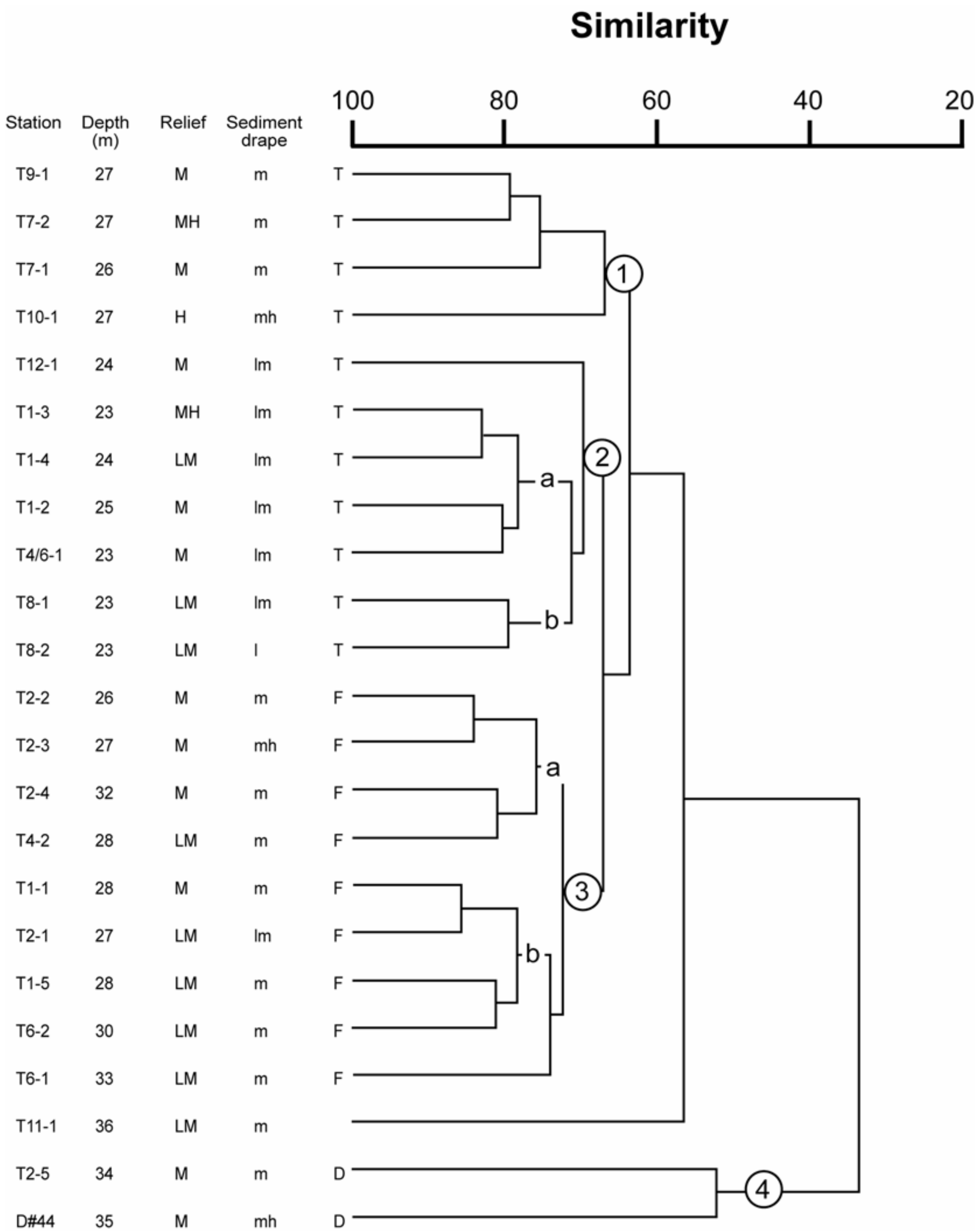


Figure 6-4. Cluster analysis of data collected from still photographs taken during the 2005 nearfield hard-bottom survey.

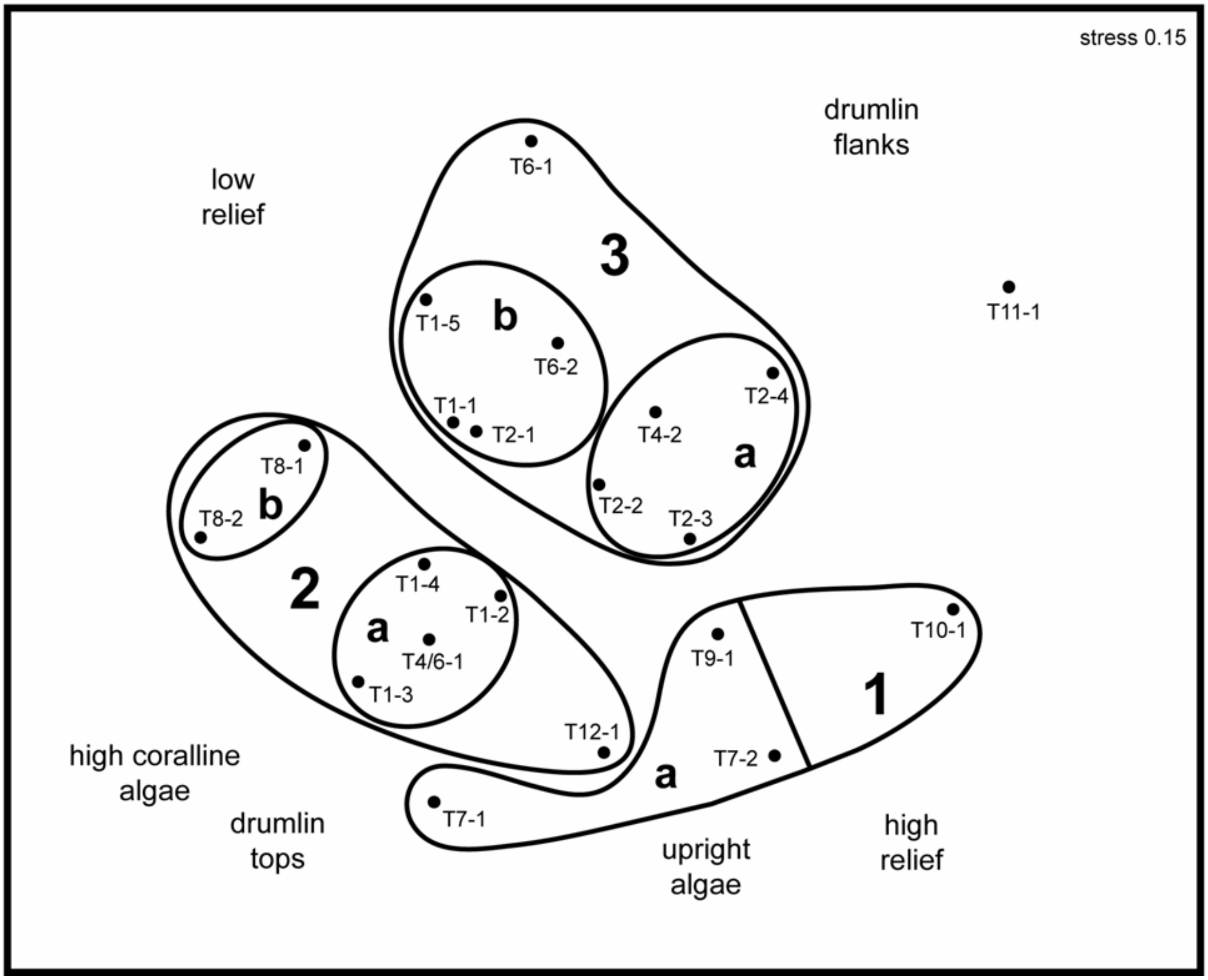


Figure 6-5. Non-metric multidimensional scaling plot of the 2005 nearfield hard-bottom still photograph data, with cluster designations from hierarchical classification superimposed.

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**			**3**				**4**	
	1a	**T10-1**	**T12-1**	**2a**	**2b**	**3a**	**3b**	**T6-1**	**T11-1**	**T2-5**	**D#44**
Depth (m)	26-27	27.0	24.3	23-25	23	26-32	27-30	33	36	34	35
Relief[1]	M-MH	H	M	LM-MH	LM	LM-M	LM-M	LM	LM	M	M
Drape[2]	m	mh	lm	lm	l-lm	m-mh	lm-m	m	m	m	mh
Coralline algae (% cover)	7.7-15.3	0.2	**30.4**	**31.6-48.3**	**23.9-45.9**	3.8-10.9	13.2-18.2	0.2	11.4	-	-
Ptilota serrata	**1.00-8.42**	-	<0.1	0.00-0.24	<0.1	<0.1	<0.1	-	-	-	-
Palmaria palmata	**2.03-8.77**	0.48	2.39	0.03-1.36	0.15-1.09	0.00-2.91	0.00-2.93	-	-	-	-
Coralline algae	2.03-4.03	<0.1	**7.48**	**7.69-11.50**	**5.76-11.09**	1.12-2.87	3.63-4.40	0.16	2.87	-	-
Small white sea star	**10.32-13.39**	**6.81**	**5.74**	**7.31-16.41**	**3.91-6.24**	**7.94-12.65**	**3.58-12.72**	**7.97**	1.87	3.15	3.84
Asterias vulgaris	**1.48-3.03**	**2.87**	0.45	0.62-1.80	0.06-0.45	0.16-0.79	0.52-1.19	**2.16**	0.29	0.41	0.88
Henricia sanguinolenta	**2.03-2.68**	**3.68**	1.23	**1.78-2.73**	0.70-1.21	1.61-2.36	1.03-1.93	1.10	<0.1	0.37	0.44
Aplidium spp.	<0.1	-	**3.03**	0.06-1.62	**1.70-2.68**	0.58-1.61	0.81-1.87	0.68	-	-	<0.1
Modiolus modiolus	2.61-7.13	3.94	2.61	1.93-11.79	**6.48-9.29**	1.42-6.36	1.28-6.20	0.81	3.48	0.93	-
Dendrodoa carnea	1.00-1.42	0.65	1.71	0.36-1.21	**4.00-4.24**	0.30-1.45	0.33-1.66	0.13	0.39	-	-
Didemnum albidum	1.23-2.00	3.06	2.77	1.17-2.97	0.59-3.27	**4.27-8.90**	**5.44-6.91**	**5.74**	0.84	2.33	0.69
Gersemia rubiformis	-	**6.39**	-	-	-	-	-	-	-	-	-
Terebratulina septentrionalis	0.00-9.45	**8.13**	**11.61**	0.00-1.56	<0.1	0.58-11.09	0.03-0.16	0.10	**8.65**	-	-
Psolus fabricii	0.07-0.16	-	**3.10**	0.43-1.55	0.48-1.88	0.03-1.77	0.17-0.31	-	<0.1	-	-
Ophiopholis aculeata	-	-	-	<0.1	<0.1	-	-	-	**4.10**	-	-
Metridium senile	<0.1	0.13	1.58	0.06-1.50	-	0.00-0.10	-	-	-	**127.67**	11.03
Halocynthia pyriformis	0.32-0.68	0.68	**7.65**	0.22-2.50	0.00-0.09	0.21-2.06	0.06-0.19	<0.1	0.16	1.04	**41.50**
Tautogolabrus adspersus	**1.58-3.90**	**3.39**	**2.55**	**1.97-2.27**	0.36-0.38	0.97-4.84	0.23-1.34	0.35	0.16	**2.15**	0.44
Number of species	37-40	37	41	35-42	31-37	37-41	30-39	31	38	25	20
Total algae	**5.81-17.32**	0.55	**9.90**	**8.88-11.53**	**6.88-11.24**	1.12-4.82	3.94-7.37	0.16	2.87	-	-
Total invertebrates	36.74-45.06	**58.39**	**52.29**	26.16-46.62	30.36-34.62	42.41-64.30	27.39-40.10	29.90	37.71	**139.04**	**61.59**
Total fish	1.61-4.03	**3.48**	2.58	2.00-2.41	0.39-0.41	1.00-4.84	0.30-1.38	0.39	0.19	2.41	0.47

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

The second cluster (cluster 2) also consisted of drumlin top stations, three on top of the drumlin north of the outfall (T1-2, T1-3, and T1-4), one on the drumlin south of the outfall (T4/6-1), and the remaining three southern reference sites (T8-1, T8-2, and T12-1). The four stations on either side of the outfall clustered together at a similarity of 78.3 percent (subgroup 2a), while two of the southern reference stations (T8-1 and T8-2) clustered together at a similarity of 79.6 percent (subgroup 2b). The remaining southern reference station (T12-1) joined these two subgroups at a similarity of 69.6 percent. Habitat relief of stations in cluster 2 ranged from moderately low to moderately high, while sediment drape ranged from light to moderately light. All of the stations in cluster 2 supported moderate percent cover of coralline algae (23.9 to 48.3 percent), and few upright algae. Drumlin-top stations on either side of the outfall (subgroup 2a) supported high numbers of juvenile northern sea stars (*A. vulgaris*), blood sea stars (*H. sanguinolenta*), and cunner (*T. adspersus*). In contrast, the two southern reference stations (subgroup 2b) supported fewer sea stars and fewer cunner. Station T12-1 differed from the other stations in cluster 2 by supporting some dulse, many brachiopods (*T. septentrionalis*) and scarlet sea cucumbers (*P. fabricii*), and relatively many sea peach tunicates (*H. pyriformis*). The NMDS analysis reflects some of these faunal differences by placing station T12-1 nearer the stations in cluster 1a than the other stations in cluster 2. The placement of T12-1 in cluster 2 appeared to be related to its relatively high percent cover of coralline algae (30.4 percent), while the presence of dulse pulled it into the NMDS space of the stations in cluster 1.

The third cluster (cluster 3) consisted of nine stations located on the flanks of drumlins on either side of the outfall. This cluster divided into two subgroups of stations, with four stations close to the outfall (T2-2, T2-3, T2-4, and T4-2) clustered together at a similarity of 75.7 percent (subgroup 3a), and four stations farther removed from the outfall (T1-1, T1-5, T2-1, and T6-2) clustered together at a similarity of 78.3 percent (subgroup 3b). The remaining station (T6-1) joined subgroup 3b at a similarity of 74.1 percent. Habitat relief at the stations in cluster 3 was moderately low to moderate, while sediment drape was usually moderate. All but one of these stations (T6-1) supported moderately low cover of coralline algae (3.8 to 18.2 percent) and few if any upright algae. All nine stations in this cluster supported numerous northern white crust tunicates (*Didemnum albidum*), and moderate to high numbers of juvenile *Asterias*. The four stations in subgroup 3a supported fewer algae, more invertebrates, and fewer fish than the four stations in subgroup 3b. The flank station closest to the outfall T6-1 consisted of a moderately low relief cobble pavement that supported few algae a moderate number of invertebrates and few fish.

The stations in the first three clusters joined together at a similarity of 63.7 percent and were joined by the far-field southern station T11-1 at a similarity of 56.5 percent. Station T11-1 supported moderately low cover of coralline algae (11.4 percent) and no upright algae. However, it did support numerous brachiopods (*T. septentrionalis*), daisy brittle stars (*Ophiopholis aculeata*), and unidentified sponges.

The remaining cluster (cluster 4) consisted of the two diffuser stations that loosely clustered together at a similarity of 52.2 percent, and joined the main group of clusters at a similarity of 33.5 percent. These sites consisted of the diffuser heads and the riprap immediately surrounding them. The head of the active diffuser (#2 at T2-5) was colonized by numerous frilled anemones (*M. 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. 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*. The diffuser heads and their immediate surroundings also supported a fairly high number of invertebrates. Also more fish were observed in the vicinity of the active diffuser. Both diffuser stations supported fewer numbers of species (20 and 25 species), than the drumlin stations (30 to 42 species)

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 12 years. Seven of the surveys occurred under pre-discharge "baseline" conditions, while the last five 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 have evolved to maximize the probability of detecting potential impacts of outfall operations. The present design includes 13 sites near the outfall, 7 near-field reference sites (3 north and 4 south of the outfall), one far-field reference site off Scituate, and an inactive and an active diffuser head. Additionally, the emphasis on data products also has evolved. Still photographs and video footage are both utilized to provide a detailed characterization of the sea floor 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 6-6 shows the mean habitat relief observed during the 1996 to 2005 surveys. Location on the drumlins appeared to be a primary factor in determining habitat relief. The sea floor 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 sea floor 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, T4/6-1, T6-2, and T7-1).

Figure 6-7 shows the amount of sediment drape seen on the rock surfaces during the 1996 to 2005 surveys. Sediment drape was lightest on the shallowest part of the 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 heavier 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.

Encrusting coralline algae has historically been the most abundant and widely distributed taxon encountered during the hard-bottom surveys. Figure 6-8 shows the percent cover of coralline algae estimated from the slides taken during the 1996 to 2005 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

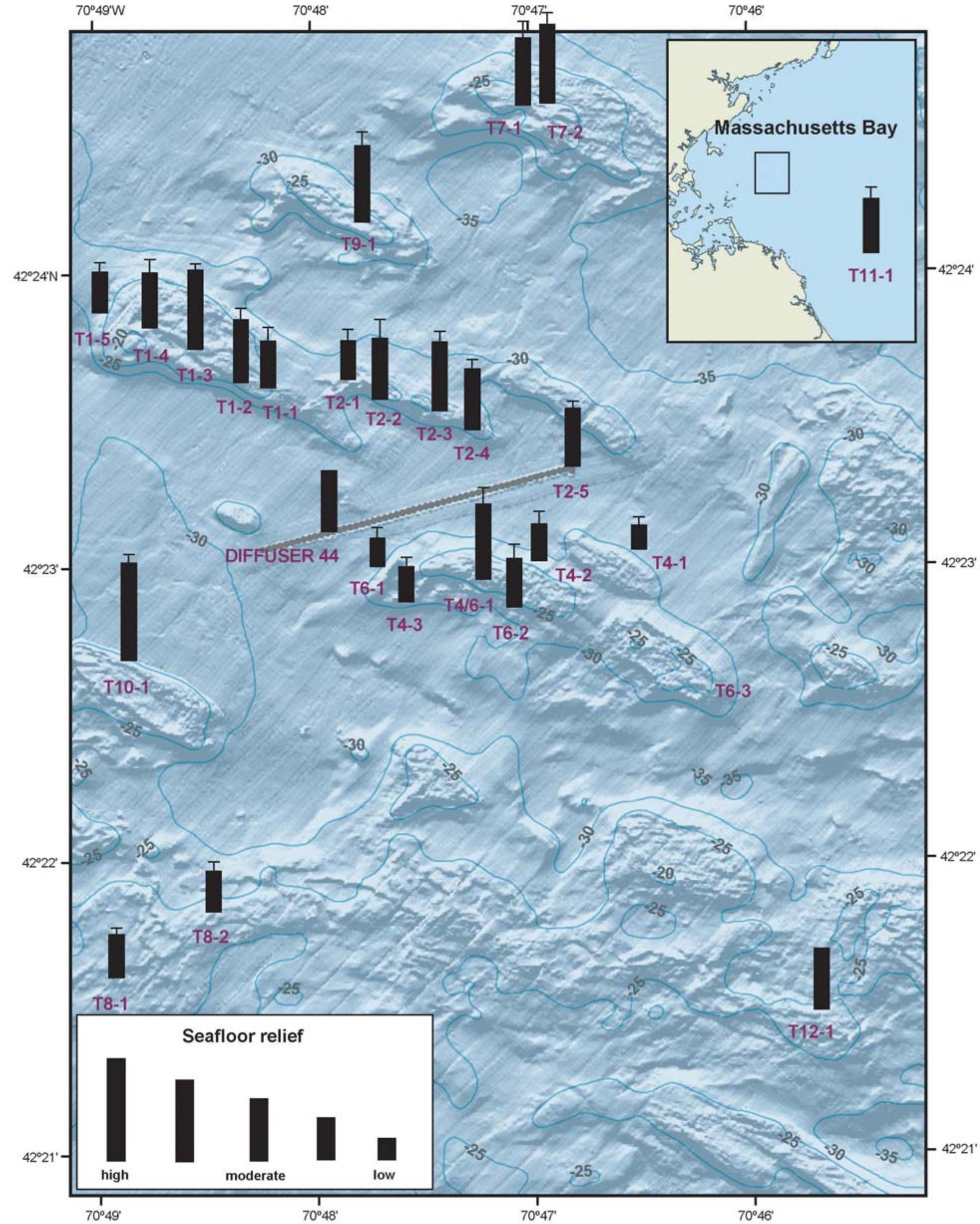


Figure 6-6. Habitat relief (mean values) determined from the 1996 to 2005 nearfield hard-bottom surveys. Error bars are one standard deviation To generate the relief bars habitat relief was coded as: low=1, moderately low=2, moderate=3, moderately high=4,and high=5.

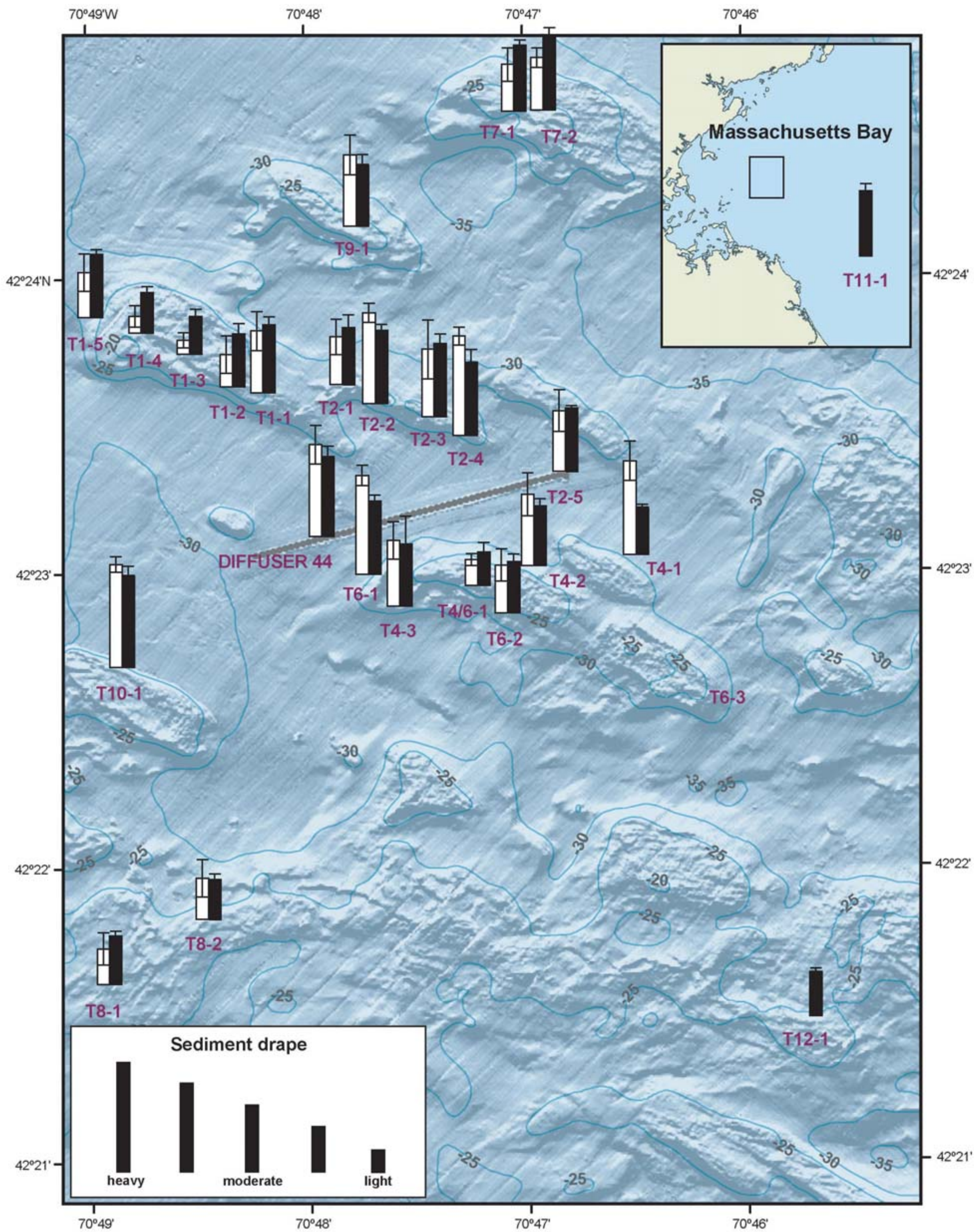


Figure 6-7. Sediment drape determined from 35-mm slides collected during the 1996 to 2005 nearfield hard-bottom surveys. White bars are mean pre-diversion values and black bars are mean post-diversion values. Error bars are one standard deviation.

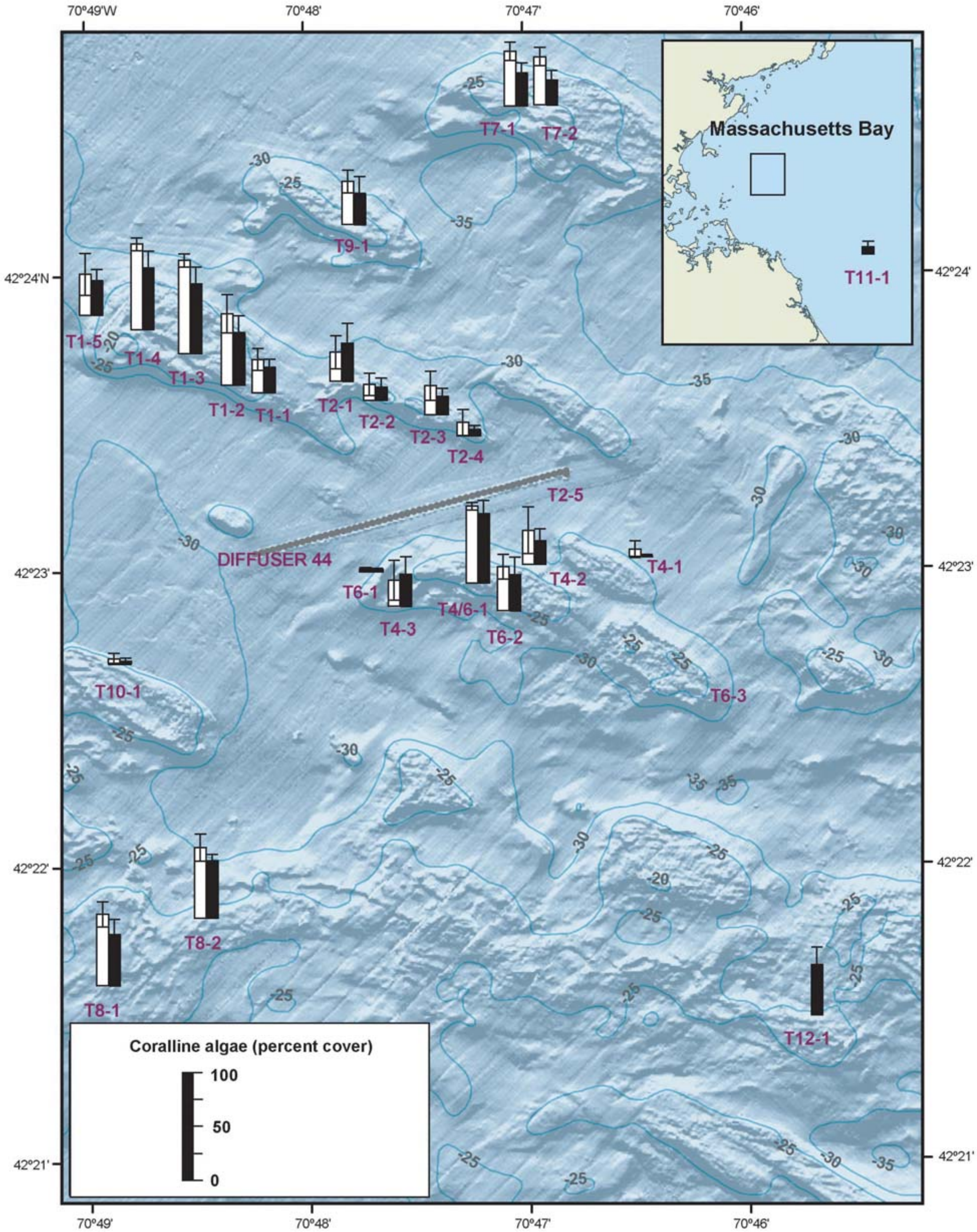


Figure 6-8. Percent cover of coralline algae determined from 35-mm slides collected during the 1996 to 2005 nearfield hard-bottom surveys. White bars are mean pre-diversion values and black bars are mean post-diversion values. Error bars are one standard deviation.

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 2005 time period. The decrease in percent cover of coralline algae was particularly pronounced in 2005 at the northern stations mentioned above. Additionally, in 2005 decreases in percent cover of coralline algae were observed at a number of other stations located both north and south of the outfall. This was the first year that a marked decrease in percent cover of coralline algae was noted at many (13) stations. 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). In contrast, one station located north of the outfall (T2-1) had higher percent cover of coralline algae in 2003 and 2004, but this also decreased in 2005.

It is unlikely that light attenuation with depth is a limiting factor for coralline algae, within the range of depths covered during this survey (Vadas and Steneck 1988, Sears and Cooper 1978). 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 6-9. The widespread decrease in percent cover of coralline algae in 2005 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, where very slight increases in sediment drape were noted at only three of the stations (T1-3, T1-4, and T4/6-1). Reasons for the dramatic decrease in coralline algae noted 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 also not readily apparent, but may be related to the discharge.

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 (Figure 6-10). Additionally, their abundances varied quite widely during both the pre- and post-diversion periods (Figure 6-11). 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 the fact 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. Both *P. serrata* and *P. palmata* 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). *Ptilota serrata* was most abundant in 1996 and 1998, and least abundant in 1997. Additionally, the density of this filamentous red alga has declined since 1998 at many of the stations. In contrast, the density of *P. palmata* followed a different trend. Dulse 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 two years. *Agarum cribosum* had the most restrictive 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, and has since been increasing again. The peak density of shotgun kelp in 2000 coincided with the appearance of numerous lacy bryozoans *Membranipora* sp.

Table 6-5. Estimated percent cover of coralline algae from 1996 to 2005. Large differences between pre- and post-diversion are highlighted by shading. Asterisks mark differences that appear to be related to shifts in position of the areas surveyed.

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

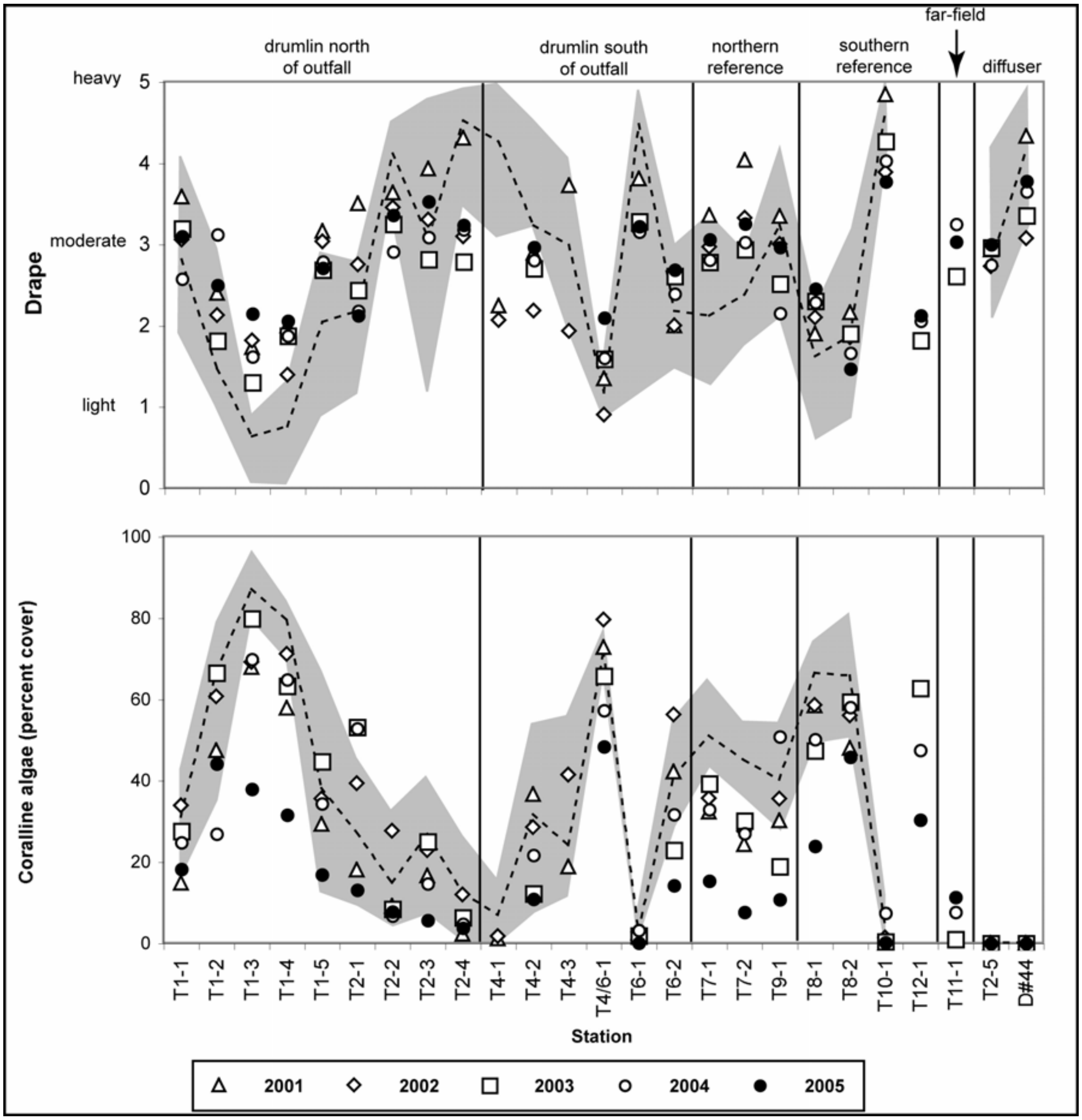


Figure 6-9. Sediment drape and percent cover of coralline algae at the nearfield hard-bottom sites determined from 35-mm slides taken during the 1996 to 2005 surveys. The dashed line shows the mean baseline value and the shaded area shows the range of baseline values.

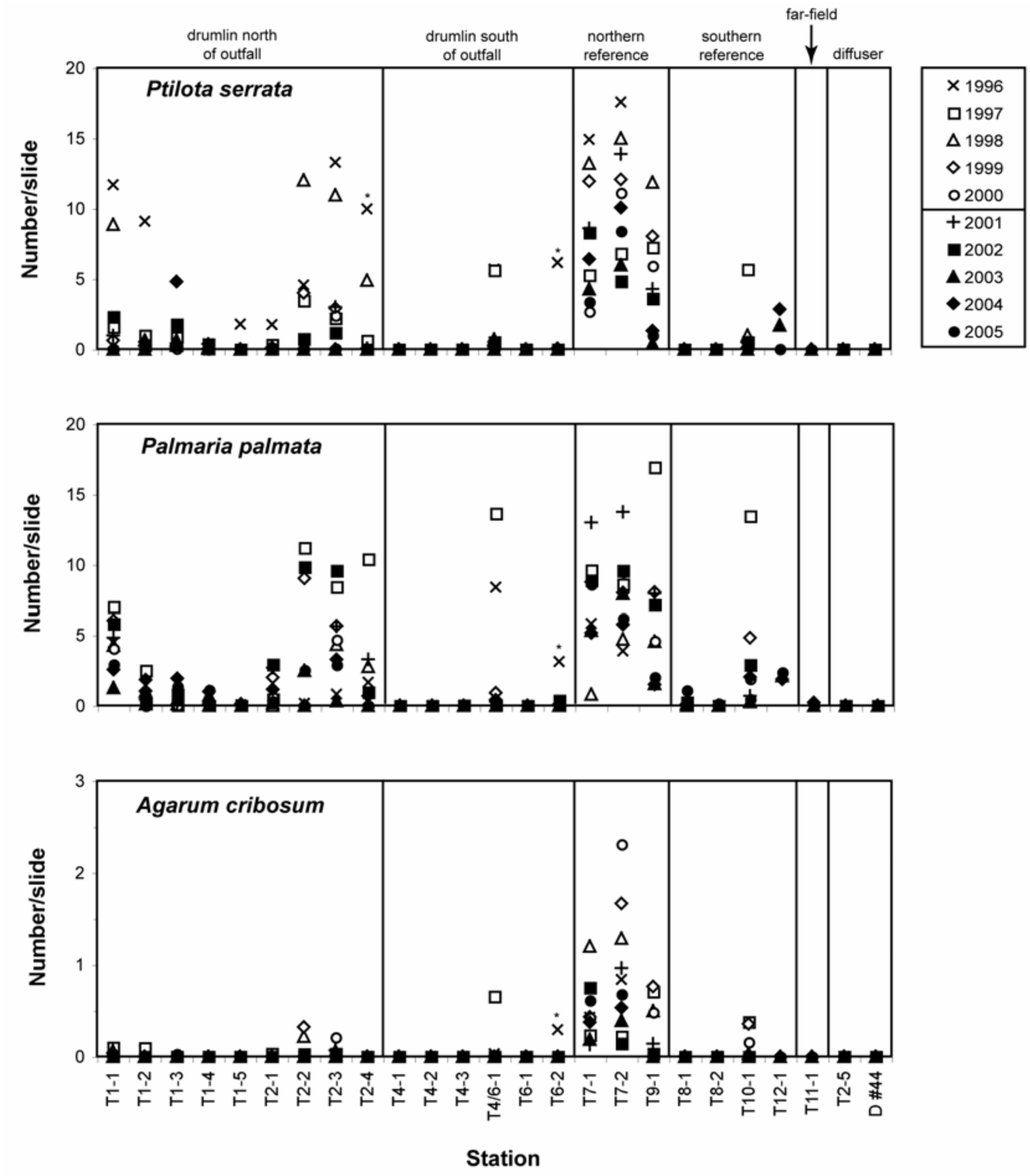


Figure 6-10. Abundance of three species of upright algae, (a) *Ptilota serrata*, (b) *Palmaria palmat*a, and (c) *Agarum cribosum* at the nearfield hard-bottom sites, as determined from 35-mm slides taken during the 1996 to 2005 surveys. Asterisks denote changes related to shifts in position.

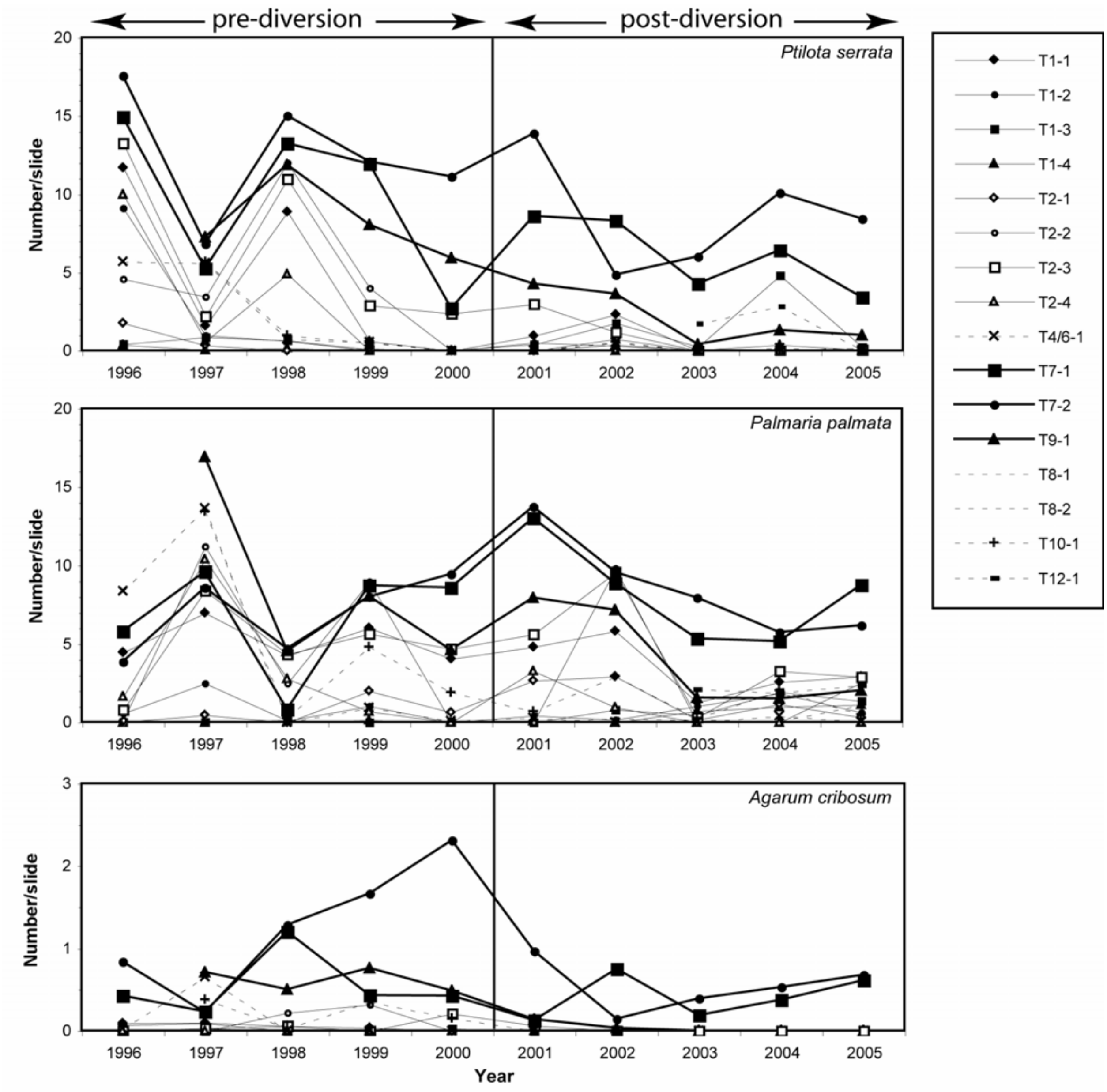


Figure 6-11. Abundance over time (1996 to 2005) of three species of upright algae, (a) *Ptilota serrata*, (b) *Palmaria palmata*, and (c) *Agarum cribosum* at the nearfield hard-bottom sites.

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.

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*. 2004, Appendix D3). By 2004 most of these barnacles had died off due to 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, a frilly white encrusting sponge? and a grey translucent encrusting organism, were seen only on boulders that had previously been colonized by the barnacles. Both of these species were very sparse in 2005.

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 6-12). 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 6-13 shows the results of hierarchical classification of data collected from still photographs taken during the 1996 to 2005 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. The stations grouped into ten clusters of stations joined by several individual stations. 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 first half of cluster 2 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); the largest group in cluster 3, which consisted mainly of southern reference stations (T8-1 and T8-2); cluster 4, which consisted of neighboring stations on the drumlin north of the outfall (T1-3, T1-4, and T1-5); 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 two groups 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 two major groups in cluster 2 (the drumlin top and the drumlin flank groups) each further divided into pre- and post-diversion years. Additionally, several of the groups in cluster 5 consisted of only post-diversion years, while cluster 4 and a group in clusters 3 and cluster 6 consisted of only pre-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 three groups 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.

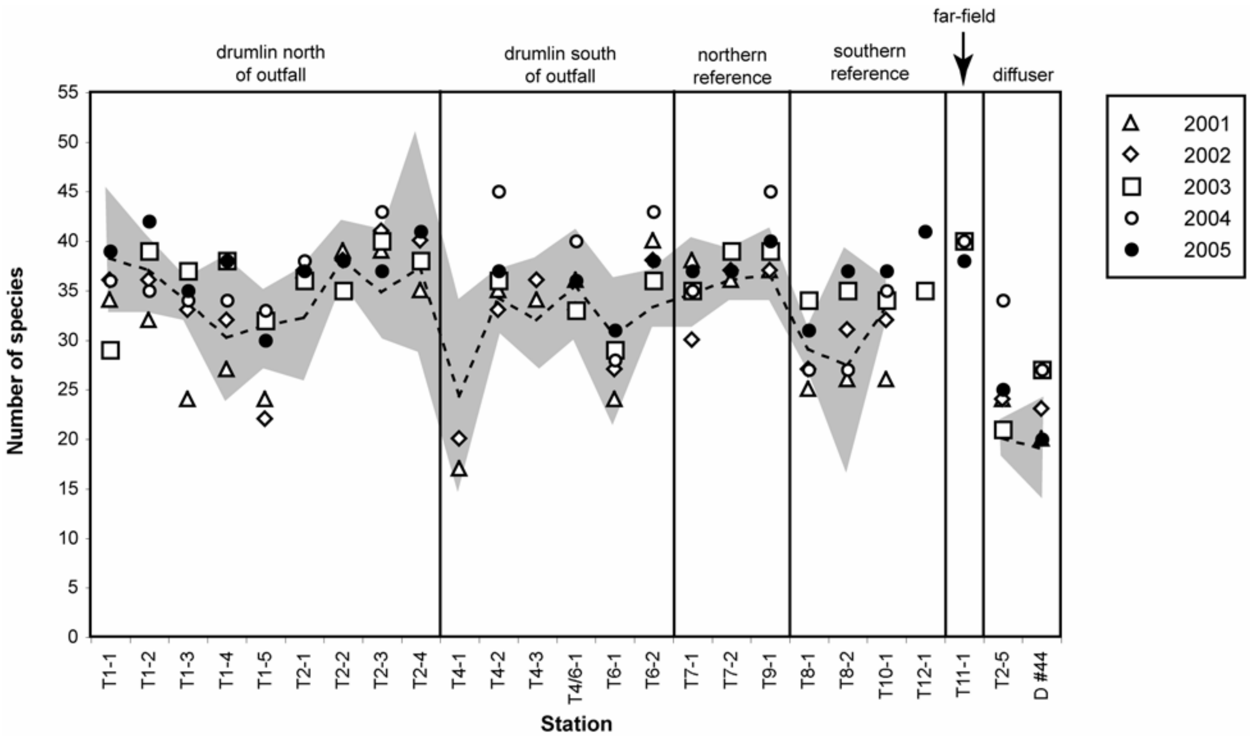


Figure 6-12. Total number of species seen on still photographs collected at the nearfield hard-bottom sites during the 1996 to 2005 surveys. The dashed line shows the mean baseline value and the shaded area shows the range of baseline values.

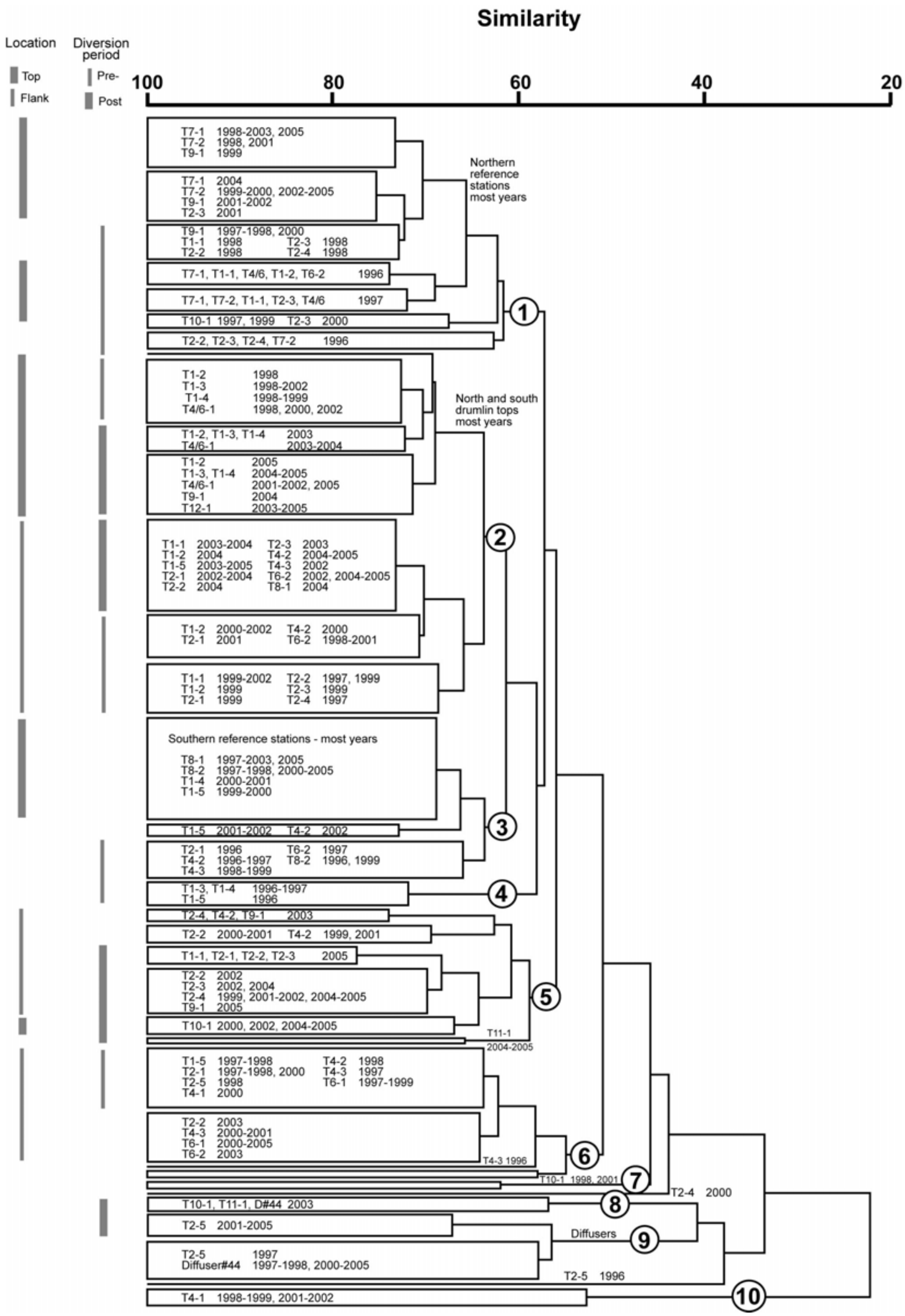


Figure 6-13. Summarized cluster analysis of data collected from still photographs taken during the 1996 to 2005 nearfield hard-bottom surveys. Location, topography, and diversion period are noted for cohesive clusters.

Table 6-6 shows the dominant species that control much of the clustering structure. 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 *P. serrata* and *P. palmata*). The stations in clusters 2, 3, and 4 all supported relatively high numbers of coralline algae and few if any upright algae. The drumlin top stations in cluster 4 (T1-3 and T1-4) supported the most coralline algae and many horse mussels (*Modiolus modiolus*) in 1996 and 1997. In contrast, the stations in clusters 2 and 3 supported slightly fewer coralline algae. The drumlin top stations in cluster 2 supported more coralline algae than the drumlin flank stations. Additionally, the drumlin top stations supported more mussels and small white sea stars, while the flank stations frequently supported more encrusting taxa. The stations in cluster 2 also supported northern white crust tunicates (*Didemnum albidum*), while the stations in cluster 3 did not. The stations in cluster 5 were mainly drumlin flank stations and one of the southern reference stations (T10-1) that supported few coralline algae and numerous brachiopods (*T. septentrionalis*), small white sea stars, and *D. albidum*. The stations in cluster 6 consisted mainly of drumlin flank stations that had few coralline algae and no other distinctive taxa. Cluster 7 consisted of two years (1998 and 2001) at station T10-1, when high numbers of the red soft coral *G. rubiformis* were encountered. 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 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 *M. 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 years 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 6-14 shows the NMDS analysis of the 1996–2005 data. The stations in clusters 8 (the 2003 barnacle settlement), 9 (diffuser stations), and 10 (depauperate flank station, T4-1) separated quite clearly from the remaining stations. Clusters 4 and 7 also separated from the other clusters. In contrast, the remaining clusters had a fair amount of spatial overlap in the NMDS space. Cluster 2 showed the greatest amount of overlap with the other clusters, while clusters 1, 3, 5 and 6 rarely overlapped with each other. This is not surprising since cluster 2 consisted of both drumlin top and drumlin flank stations from both the pre- and post-diversion periods. 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 indicates the degree to which the data do not 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 were 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.

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 3 and 6, where four years at station T1-5 were in close proximity even though they were in different clusters. 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 were located toward the bottom of the ordination space.

Table 6-6. Abundance (mean number per slide) of selected taxa in clusters defined by classification analysis of hard-bottom stations from 1996 to 2005. Numbers indicating major differences among clusters are highlight by shading.

Cluster	1	2 top	2 flank	3	4	5	6	7	8	9	10
Coralline algae	8.42	15.60	7.85	12.59	20.59	2.67	2.57				0.46
Ptilota serrata	7.82										
Palmaria palmata	6.65		2.01			1.83		0.51			
Aplidium spp.		1.45	2.57	2.88		0.84	1.09	0.28			
Didemnum albidum	1.31	1.84	2.99			3.21	0.73	0.55			
Modiolus modiolus	3.7	5.07	1.44	2.24	10.65	2.45	0.36	1.14			
Orange/tan encrusting sponge	1.19	1.16	2.14	1		2.47	1.54		2.22		
Small white sea star	3.96	7.84	4.47	2.3	1.43	5.34	2.6	2.92		2.17	0.61
Terebratulina septentrionalis	2.46					5.7					
Gersemia rubiformis								7.72			
Henricia sanguinolenta	1.33	1.78	1.04	0.52	0.81	1.56	0.42	2.59			
Balanus spp.		3.64			1.23		0.63		59.7		
Metridium senile		1.60							5.48	34.55	
Halocynthia pyriformis										8.54	
Cerianthus borealis											0.12
Placopecten magellanicus											0.45
Strongylocentrotus droebachiensis					1.51						
Tautogolabrus adspersus	1.94	2.68	1.38			1.76		3.24			

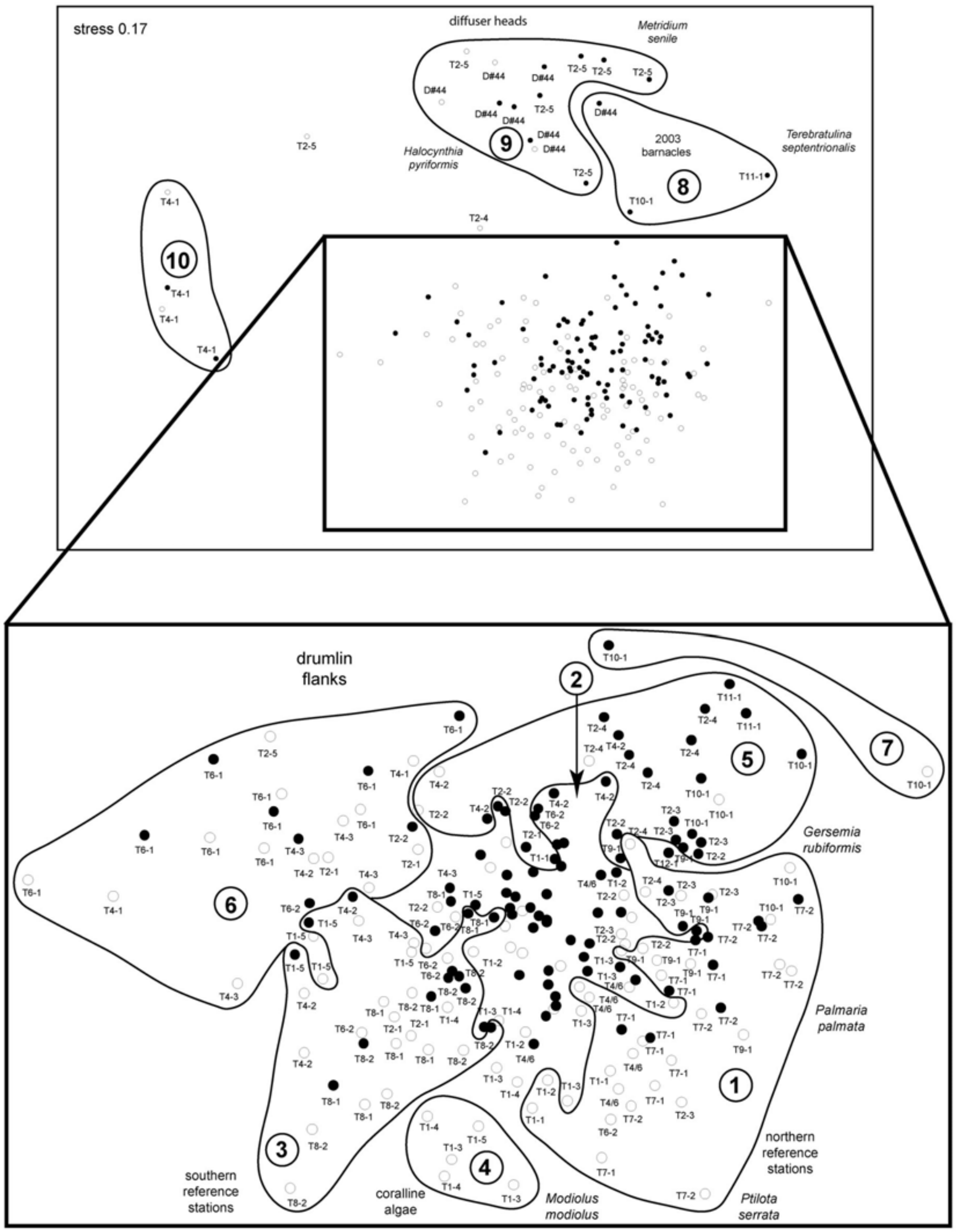


Figure 6-14. Non-metric multidimensional scaling plot of data collected from still photographs taken during the 1996 to 2005 nearfield hard-bottom surveys, with cluster designations from hierarchical classification superimposed. Open circles are stations in the pre-diversion period and closed circles are stations in the post-diversion period.

The benthic communities inhabiting the hard-bottom areas have been relatively stable over the years, with many of the sites remaining unchanged from year to year. Figure 6-15 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 three years has been noted at T9-1 and this is reflected by shifts in the 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. The benthic communities at these stations have consistently been dominated by coralline algae. 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 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 (*M. senile*) and sea peach tunicates (*H. pyriformis*). The different cluster designation of T2-5 in 1998 reflected the fact that 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, when 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 highlights several trends that appear to reflect widespread temporal changes in the population structure of individual taxa 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 *S. droebachiensis* appear to follow a cyclical pattern, declining from 0.88 individuals per photograph in 1996 to 0.28 individuals per photograph in 2000, then increasing slightly in 2001 and 2002 (0.33 and 0.39 individuals per photograph, respectively), and again decreasing between 2003 and 2005 (<0.17 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. In the still photographs, *Cancer* crabs increased from one to six individuals seen annually between 1996 and 1999, to 53 individuals seen in 2002, and decreased from 2003 to 2005. This pattern was also reflected in the video data, with 3–14 *Cancer* crabs observed annually between 1996 and 1999, increasing to 143 individuals in 2002, and decreasing again from 2003 to 2005. The video data for lobsters showed a similar trend, with the highest numbers of lobsters being seen in 2002 and 2003. With the exception of 2003, the number of cod observed during these surveys has also increased over time, with the highest numbers of cod observed in 2005. 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 survey of the diffuser heads in June 2003, where the presence of codfish was frequently used as an indicator of proximity to an actively discharging diffuser head.

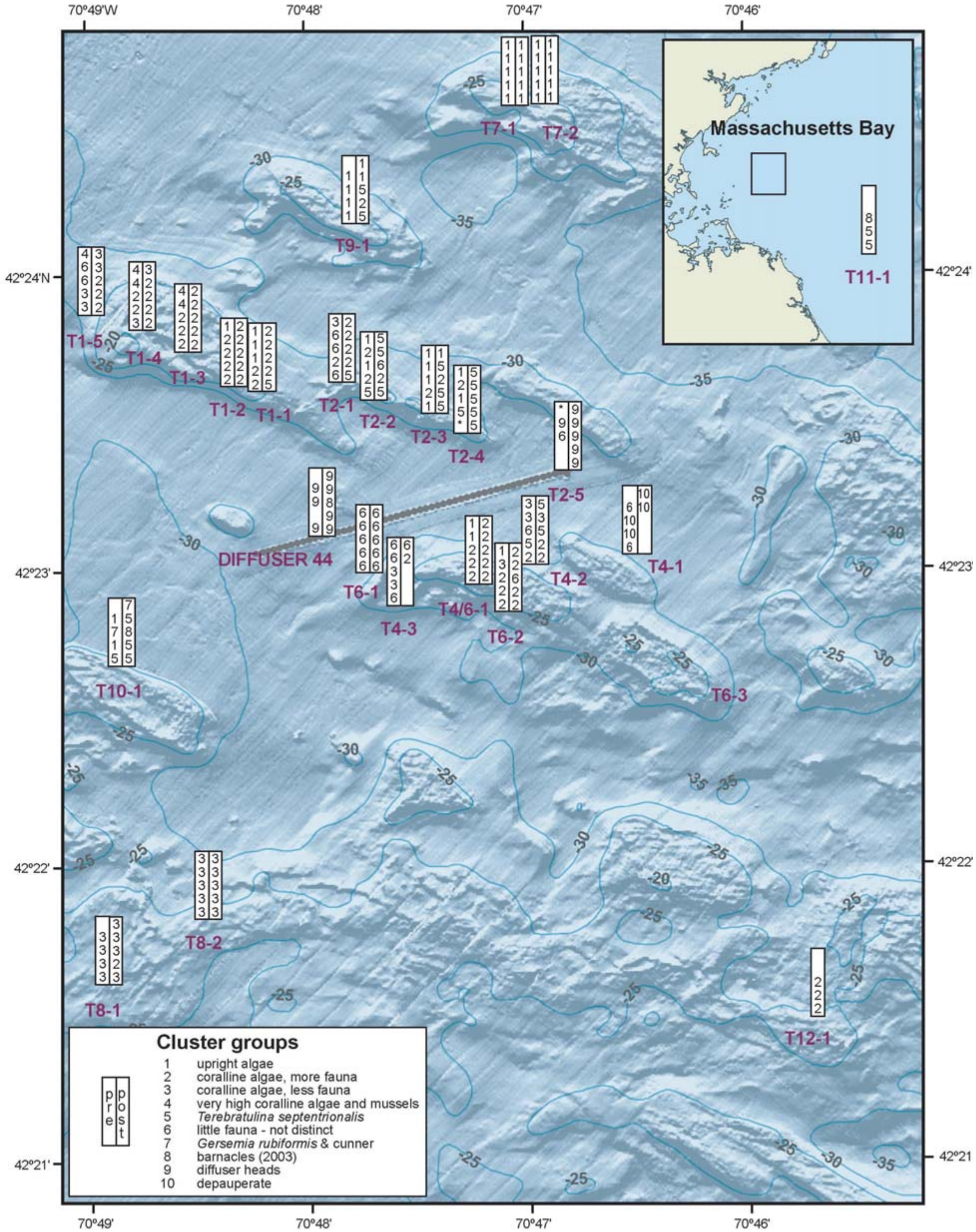


Figure 6-15. Benthic communities defined from classification of the 35-mm images taken during the 1996 to 2005 nearfield hard-bottom surveys. Bars show the successive years in the pre- and post-diversion periods. Asterisks indicate no cluster designation.

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 ten years.

	Pre-diversion					Post-diversion				
	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005
Video										
Minutes of video	401	448	317	374	380	354	373	386	364	396
Cancer spp. (rock crab)	6	3	3	14	70	112	143	135	111	56
Gadus morhua (cod)	-	6	12	17	11	22	22	6	30	57
Homarus americanus (lobster)	6	2	9	3	17	14	23	29	12	8
Still Photographs										
Number of photographs	501	504	514	491	542	483	528	538	551	570
Strongylocentrotus droebachiensis	441	329	279	285	150	159	204	85	70	74
Cancer spp. (rock crab)	3	1	2	6	12	43	53	44	14	21
Gadus morhua (cod)	-	-	2	3	-	7	4	-	-	16
Homarus americanus (lobster)	1	-	3	3	5	4	12	4	5	6

6.3.5 Statistical Model

The basic goal of this analysis was to assess the difference in hard-bottom stations after the outfall diversion event in the fall of 2000. Clearly there are differences between stations and years that are not related to the diversion event. A model that accounts for these sources of variation first can then more efficiently estimate changes associated with the diversion.

For this analysis stations were divided into two areas, north and south of the diffuser, and by distance from the diffuser. The variables were plotted separately for each of these four sets of stations. Appendix E3 presents graphs of the continuous variables and Appendix E4 presents graphs of the species count variables. The vertical line indicates when the effluent was diverted to the outfall. The log-scale is used for species abundance data. On the log-scale zero abundance at a station cannot be plotted. Zero values on these plots are not shown and can be thought of as lying just below the plotted area

It is clear from the plots for nearly all variables that stations have different means across years and that years have different means across stations. And indeed, a large proportion of the variation in the data can be explained with this simple linear year and station effect model.

The question answered by the analyses is: *How much of the variation in the data is associated with diversion to the outfall in fall 2000?* To model this effect we included a parameter for the relative increase (decrease) in the response variable with distance after the diversion in the fall of 2000. This is modeled as a covariate that is zero if the sampling year is less than 2001 and is the distance from the diffuser when the sampling year is 2001 or greater. This single parameter describes the interaction between station distance from the outfall and the post-diversion years.

Table 6-8 presents the results of a linear model for the five selected continuous variables. This table reports only on the parts of the model estimation that are related to estimation of the distance-by-diversion sub-model. Sediment drape was significantly more abundant away from the outfall (P=0.000). In contrast, percent cover of coralline algae was significantly less abundant with distance from the outfall (P=0.011). A station's score on axes 1 and 2 of the NMDS analysis did not appear to be related to outfall diversion, while its score on axis 3 did appear to reflect some marginal signal from the diversion of the outfall. Basically, a P value of 0.011 is marginal for an analysis of scores on ordination axes and this needs to be explored further. Stations near the outfall scored higher on NMDS axis 3 post-diversion than pre-diversion, while stations further away from the outfall scored lower.

Table 6-8. Results of the linear model of five selected continuous variables for the hard-bottom stations.

	Distance by Diversion Effect		**R-squared**	
	Slope Coefficient	P-value	Complete Model	Diversion by Distance Submodel
Coralline algae (percent cover)	-10.232	**0.011**	0.862	0.007
Sediment Drape	1.189	**0.000**	0.806	0.052
Score on NMDS Axis 1	-0.028	0.802	0.833	0.000
Score on NMDS Axis 2	-0.037	0.665	0.781	0.000
Score on NMDS Axis 3	-0.181	**0.011**	0.833	0.008

Approximately 90% of the variance of all five variables was explained by t he complete model (R-squared value), which included year and station effects as well as the distance-by-diversion sub-model. However, only 5% of the variation was explained by the distance-by-diversion sub-model. Thus, this analysis was able to detect post-outfall changes in the hard-bottom stations in the vicinity of the outfall, even though these changes accounted for only a small percent of the total natural variation in the data. At this point we can think of no plausible "outfall effect" mechanism that would explain a greater effect (*i.e.*, more sediment drape and less coralline algae) further from the discharge than close in. Additionally, it should be remembered that even though the observed changes are correlated with and to a large extent coincident with the outfall startup, they may not specifically be caused by the outfall. Further refinement of the model should include examining differential impact based on topography.

Table 6-9 presents the results of the log linear model for selected species counts. To account for the over-dispersion, a negative binomial model was used. The "pseudo R^2" denotes the proportion of the variation in the count data explained by the model. For count data the natural measure of variation is the chi-squared statistic rather than the total sum of squares. Two measures of the proportion of the variation explained by the sub-model are used. The partial R^2 is the variation explained by the sub-model divided by the residual variation for the model with the sub-model removed. The final column is the variation explained by the sub-model divided by the total variation in the data. This table reports only on the parts of the model estimation that are related to the estimation of the distance-by-diversion sub-model.

Approximately 70% of the variation, as measured by the chi-squared statistic, was explained by the complete model, which included year, station effects as well as the distance-by-diversion sub-model.

However, partial correlation was at most 0.078 for the distance-by-diversion sub-model. Thus, this analysis detected a change in relative abundances that was correlated with distance from the outfall after the year 2000, even though the sub-model accounted for only a small proportion of the residual variation. Since multiple tests of hypotheses are performed in this table, a multiple comparison procedure was used. The bold p-values indicates those that are significant at the 0.05 level when controlling for the false discovery rate (Benjamini and Hocberg 1995).

Only one species, *Ptilota serrata,* showed a significant distance by diversion effect (P=0.002). Basically, it appears as though this filamentous red algae decreased at the stations near the outfall, relative to the stations further away from the outfall.

Table 6-9. Results of the linear model of species counts for the hard-bottom stations.

	Distance by Diversion Effect			Pseudo R^2		
Taxon	**coefficient**	**p-value**	**Neg. Binomial Theta**	**Complete Model**	***Submodel**	****Expl. by Submodel**
Coralline algae	-0.168	0.291	6.712	0.792	0.006	0.001
Ptilota serrata	**2.516**	**0.002**	0.679	0.824	0.078	0.015
Palmaria palmata	1.532	0.015	0.706	0.697	0.036	0.011
Aplysilla sulphurea	0.589	0.258	1.156	0.506	0.007	0.003
Polymastia sp. A.	-0.947	0.011	3.056	0.689	0.036	0.012
Suberites spp.	-0.032	0.953	1.413	0.637	0.000	0.000
White divided sponge on brachiopod	0.084	0.936	0.420	0.771	0.000	0.000
Orange/tan encrusting	0.305	0.125	5.125	0.595	0.013	0.005
Orange encrusting	-0.232	0.334	3.422	0.411	0.005	0.003
Pink fuzzy encrusting	0.623	0.103	1.533	0.559	0.014	0.006
Metridium senile	0.267	0.747	0.493	0.568	0.001	0.000
Modiolus modiolus	-0.364	0.150	2.897	0.661	0.012	0.004
Balanus spp.	0.029	0.958	0.735	0.704	0.000	0.000
Strongylocentrotus droebachiensis	0.390	0.278	2.363	0.710	0.007	0.002
Small white starfish	0.356	0.031	7.033	0.670	0.027	0.009
Asterias vulgaris	-0.389	0.217	2.417	0.489	0.009	0.005
Henricia sanguinolenta	0.022	0.895	8.203	0.689	0.000	0.000
Psolus fabricii	-0.127	0.757	1.885	0.696	0.001	0.000
Aplidium spp.	0.490	0.174	1.569	0.554	0.010	0.004
Dendrodoa carnea	-0.059	0.852	2.194	0.579	0.000	0.000
Didemnum albidum	-0.682	0.031	2.002	0.622	0.024	0.009
Halocynthia pyriformis	-0.572	0.301	0.927	0.507	0.006	0.003
Myxicola infundibulum	0.508	0.100	2.754	0.527	0.015	0.007

*Partial R^2 Distance-by-Diversion Submodel
**Proportion of Total Variation Explained by Submodel

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 slight 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. 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. This variability has continued into the post-diversion period and appears to reflect inherent cyclical changes.

Another post-discharge change that has been observed in the hard-bottom communities is 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 6-16). The decrease in coralline algae has been noticeable in all five 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 observed in 2005 were not accompanied by concurrent increases in sediment drape. 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.

The outfall might be expected to alter the amount of particulate material reaching the sea floor. 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 five years of discharge monitoring have shown only modest changes suggestive of outfall impact at a subset of five stations, and some additional subtler changes at a number of other stations. Lush epifaunal growth continues to thrive on the diffuser heads surveyed for this study (Figure 6-17), 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.

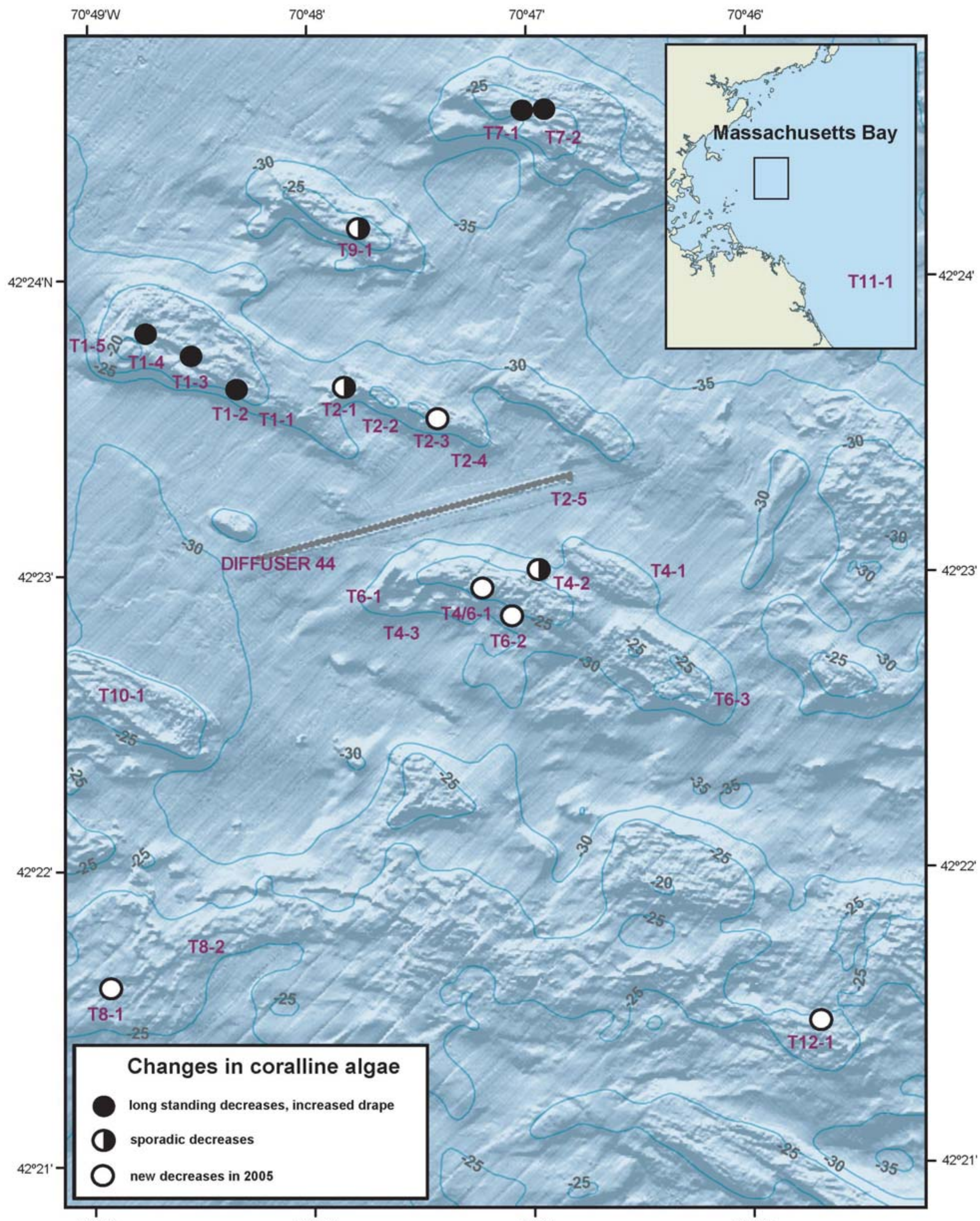


Figure 6-16. Map of changes observed in percent cover of coralline algae.

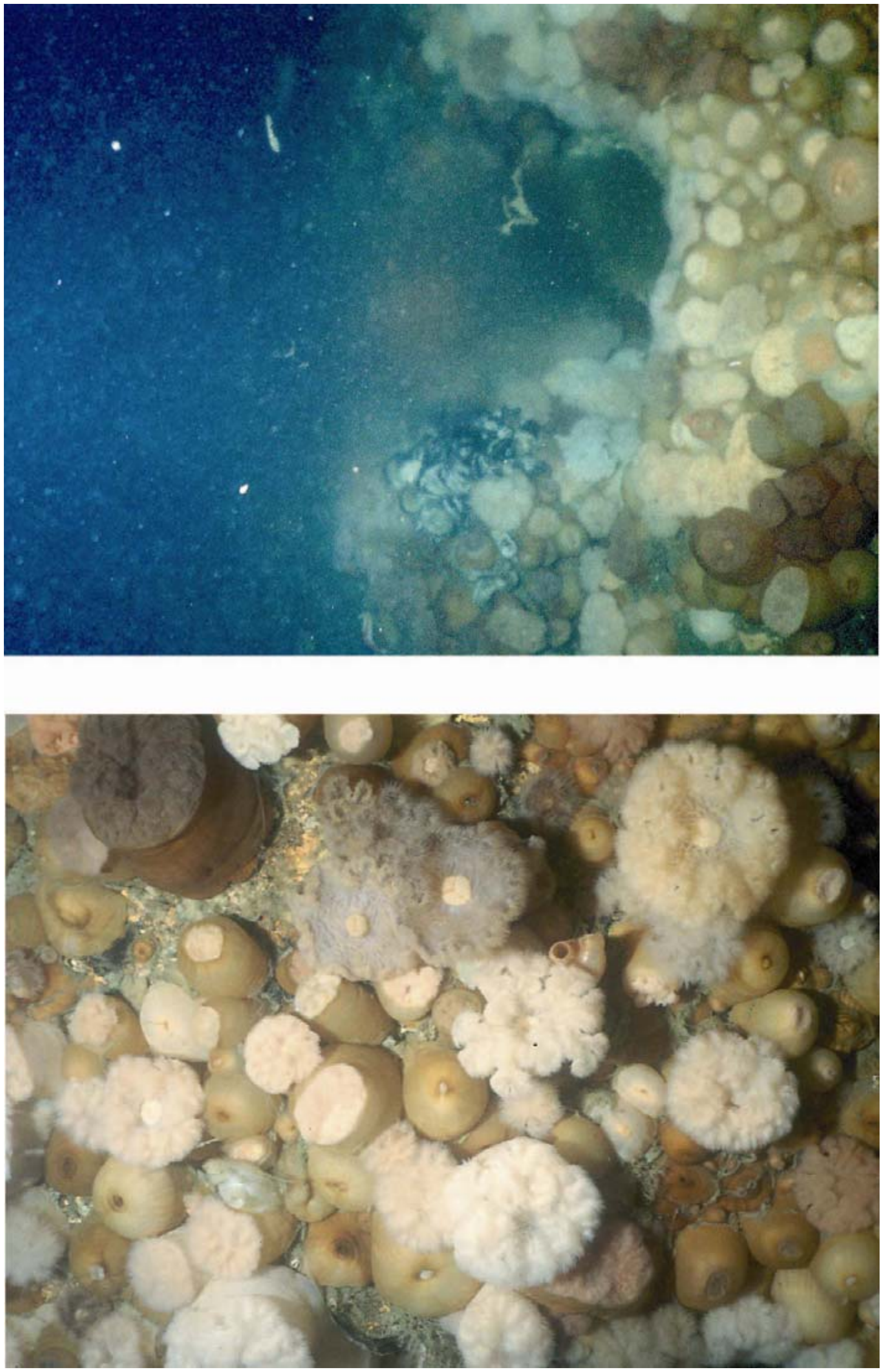


Figure 6-17. Photograph of the head of the active diffuser at T2-5 (Diffuser #2). Note the numerous frilly anemones *Metridium senile* surrounding the discharge port. A large blood star *Henricia sanguinolenta* is also visible.

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Appendices

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