2006 Boston Harbor benthic monitoring report

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2006 Boston Harbor Benthic Monitoring Report

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Massachusetts Water Resources Authority
Environmental Quality Department
100 First Avenue
Charleston Navy Yard
Boston, MA 02129
(617) 242-6000

prepared by

Nancy J. Maciolek[1]
Robert J. Diaz[2]
Deirdre Dahlen3
Isabelle P. Williams[1]

[1]ENSR Marine & Coastal Center
89 Water Street
Woods Hole, MA 02543

[2]Diaz and Daughters
6198 Driftwood Lane
Ware Neck, VA 23178

[3]Battelle
397 Washington Street
Duxbury, MA 02332

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EXECUTIVE SUMMARY

The direct discharge of waste products into Boston Harbor has had a profound impact on the composition of biological communities in the harbor. Most pollutants are particle reactive; therefore the sediments become the final sinks for these pollutants and represent the part of the ecosystem where disruption by toxic or enrichment effects is expected. Surficial sediments are critical to many ecosystem functions with energy flows (organic carbon, living biomass, secondary production) and nutrients (nitrogen, phosphorus) regulated by processes at the sediment-water interface. Thus, characterization of the benthic environment from physical and biological points of view has been a key part of the MWRA's long-term sediment monitoring within Boston Harbor.

As the MWRA improved the quality of the discharge and then diverted it to the new offshore outfall in September 2000, biological monitoring was conducted twice a year, in April and August, to track changes in the sediments and infaunal communities at eight stations throughout the harbor. In 2003, sampling was reduced to once a year (August), and, in 2004, an additional station was added in the inner harbor near a Combined Sewer Overflow (CSO). All stations were reoccupied in early August 2006 and sampled in triplicate using a traditional sediment grab sampler.

The sediment profile imaging (SPI) camera is a means of obtaining *in situ* data on the dynamics of seafloor processes and biogenic activity. In this monitoring program, SPI is used to characterize the benthic environment from both physical and biological perspectives and related trends to major changes in wastewater disposal within Boston Harbor to long-term changes in habitat condition and quality that could be related to reductions in sewage discharge to the harbor. SPI sampling at 60 stations was conducted in late August 2006.

Values of all infaunal benthic community parameters, including density, species richness, Shannon diversity, evenness, and log-series *alpha*, were essentially identical in 2006 compared with 2005, in spite of the fact that the benthic infauna at several stations was overwhelmingly dominated by a small polychaete, *Nephtys cornuta*, which has been found in increasing numbers for the past three years. The population irruption of this species coincided with the decline of the large amphipod populations in 2004, and it is likely that it is fueled by the detrital remnants of the crustaceans and/or other organisms exposed by the storms in subsequent seasons. It is probable that the *N. cornuta* population will soon crash throughout the harbor, as resource items are consumed to the point that the numbers cannot be sustained.

The occurrence, spread and retreat of *Ampelisca* tube mats at stations in the harbor has been followed closely over the course of the monitoring program. Reish and Barnard (1979) found that slight increases in organic matter resulted in increased amphipod abundance, but beyond or below a certain level, amphipod numbers decreased. Following a major peak in numbers in 2003, *Ampelisca* populations were virtually eliminated from the harbor in 2005. Images recorded with the SPI camera indicated a small rebound of the amphipod population, particularly at R30 in Hingham Bay and R21 in Nantasket Roads, where tube mat densities were observed. A small increase was also seen in the 2006 grab samples, with the majority of individuals found at T03.

While increases in ampeliscid populations in the harbor through the 1990s have been partly explained as a response to cleaner sediments, the recent decline in numbers is most likely the result of severe storms in December 2003, December 2004, and May 2005, which affected the bottom substrate, altering the sediment texture and bottom habitats. Additionally, the reduction of available particulate organic carbon in recent years, including a shift from wastewater-derived to phytoplankton-derived carbon, not all of which can be used by these crustaceans, may account for the slow recovery of amphipod populations.

TOC content in the sediments at the nine stations sampled by grab increased in 2006 compared with 2005 values at all stations except T05A. This increase is not surprising, considering that TOC content measured in 2005 were among the lowest, or the lowest, measured values during the monitoring program (1991–2006). The unusually low values in 2005 were attributed to sediment bed disturbance from the May 2005 nor'easters which contributed to a coarsening of grain size at some harbor stations (Maciolek *et al.* 2006c). While TOC content increased in 2006 at most harbor stations, the decreasing trend observed since 1992 at T01 and T03 continued to be apparent, suggesting a reduction in carbon loading to the northern harbor consistent with the improvements to wastewater treatment practices.

Temporal changes in sediment grain-size composition at the harbor stations are difficult to discern because of the high variability among the data over time; however, silt content increased in 2006 compared with 2005 values, especially at stations T01, T02, and T07.Decreasing trends in the sewage tracer, *Clostridium perfringens* (normalized to percent fines), also continued at most harbor stations (except CO19 and T08) in 2006. The continued decrease in *Clostridium* illustrates that actions taken by the MWRA to minimize wastewater impacts to Boston Harbor have improved the quality of sediment in Boston Harbor.

Long-term Patterns: Has the Harbor Changed?

Taylor (2005, 2006) summarized the major patterns in freshwater flows and loadings of total nitrogen (TN), total phosphorus (TP), total suspended solids (TSS), and particulate organic carbon (POC) to Boston Harbor for a 15-year period between 1991 and 2005. He elucidated four periods, which were related to the timing of improvements to the wastewater treatment in the harbor: Period I, prior to December 1991, Period II from the end of sludge dumping in December 1991 through mid-1998, Period III, from mid-1998 to September 2000, and Period IV, which began in September 2000 with the transfer of the discharge to the new offshore outfall.

Benthic community parameters for the harbor overall were summarized for Taylor (2006) time periods, offset by one year to allow for any lag time in the response of benthic populations to decreased pollutant loads (Table 1). Periods II and III appear the most similar for all parameters. Fisher's *alpha* shows a steady increase through all time periods, whereas the mean values of other parameters appear identical or decline between subsequent periods (*e.g.*, number of species, periods II and III; Shannon diversity, periods III and IV), reflecting the increase and decline of amphipod populations, and, in the last two or three years, the irruption of *Nephtys cornuta*.

Detailed analyses of the infaunal communities at the traditional stations, as well as other lines of evidence, such as the continuing decrease in levels of the sewage marker *Clostridium perfringens* (Appendix B, this report) support the conclusion that the benthic environment in the harbor is indeed recovering from years of pollutant input, but has not yet become stable in terms of benthic species composition.

Table 1. Benthic community characteristics for Boston Harbor grab stations summarized by time periods defined by Taylor (2006).

Parameter	Period			
	I **before Dec. 1991**	**II** **Dec 1991–mid-1998**	**III** **mid-1998–Sep. 2000**	**IV** **after Sep. 2000** ***(after outfall diversion)***
Groupings offset by one year	***n*= 48** **(1991–1992)**	***n* = 144** **(1993–1998)**	***n*= 71** **(1999–2001)**	***n* = 120** **(2002–2006)**
Number of Species	25.1 ± 14.25	34.7 ± 13.6	33.7 ±14.2	41.9 ± 17.5
H′	2.12 ± 0.81	2.41 ± 0.90	2.80 ±0.78	2.79 ± 0.89
log-series *alpha*	4.17 ± 2.14	5.50 ± 2.00	6.16 ± 2.25	7.61 ± 3.01
Rarefaction curves	1991 lowest	low	intermediate	highest
Fauna	highest abundances of opportunistic species such as *Streblospio benedicti* and *Polydora cornuta*	declining abundances of opportunistic species, some amphipod species numerous	fewer opportunists, more oligochaetes, some amphipod species numerous	some species from Massachusetts Bay, rise and decline of amphipods, increase in *Nephtys*.

1. INTRODUCTION

1.1 Background

1.1.1 History of Discharges to Boston Harbor

Boston Harbor has had a long history of anthropogenic impacts dating back at least to colonial times (Loud 1923). In addition to the damming of rivers and the filling of salt marshes and shallow embayments to create the present footprint of the city, the direct discharge of waste products has had a profound impact on the composition of the biological communities in the harbor. Prior to the 1950s, raw sewage was discharged into Boston Harbor primarily from three locations: Moon Island, Nut Island, and Deer Island. In 1952, the Nut Island treatment plant became operational and began treating sewage from the southern part of Boston's metropolitan area. The Deer Island treatment plant was completed in 1968, thus providing treatment for sewage from the northern part of the area. (The third location, Moon Island, was relegated to emergency status at that time and not used routinely thereafter.) The effluent was discharged continuously from both plants; an annual average of 120 million gallons per day (MGD) from Nut Island and 240 MGD from Deer Island. Storm events caused up to 3.8 billion gallons per year (BGY) of additional material to be occasionally discharged to the harbor through the system of combined sewer overflows (CSOs) (Rex *et al.* 2002).

Sludge, which was separated from the effluent, was digested anaerobically prior to discharge. Digested sludge from Nut Island was pumped across Quincy Bay and discharged through an outfall near Long Island on the southeastern side of President Roads. Sludge from Deer Island was discharged through that plant’s effluent outfalls on the northern side of President Roads. Sludge discharges were timed to coincide with the outgoing tide, under the assumption that the tide would carry the discharges out of the harbor and away offshore. Unfortunately, studies have shown that the material from Nut Island often was trapped near the tip of Long Island and carried back into the harbor on incoming tides (McDowell *et al.* 1991).

In 1972, the Federal Clean Water Act (CWA) mandated secondary treatment for all sewage discharges to coastal waters, but an amendment allowed communities to apply for waivers from this requirement. The metropolitan Boston area’s application for such a waiver was denied by the US Environmental Protection Agency (EPA), partly on the basis of the observed degradation of the benthic communities in Boston Harbor. In 1985, in response to both the EPA mandate to institute secondary treatment and a Federal Court order to improve the condition of Boston Harbor, the Massachusetts Water Resources Authority (MWRA) was created. The MWRA instituted a multifaceted approach to upgrading the sewage treatment system, including an upgrade in the treatment facility itself and construction of a new outfall pipe to carry the treated effluent to a diffuser system in Massachusetts Bay located 9.5 mi offshore in deep water.

In 1989, discharge of more than 10,000 gallons per day of floatable pollutants comprising grease, oil, and plastics from the Deer Island and Nut Island treatment plants was ended. Sludge discharge ceased in December 1991, marking the end of one of the most significant inputs of pollutants to Boston Harbor. In 1995, a new primary treatment plant at Deer Island was completed, increasing the system's overall capacity and the effectiveness of the treatment. In August 1997, the first phase of secondary treatment was completed, increasing the level of solids removal to 80%. For the first time, the MWRA's discharge met the requirements of the CWA (Rex *et al.* 2002).

In July 1998, a new screening facility at Nut Island became operational, with sand, gravel, and large objects being removed from the wastewater flow prior to transport via tunnel to Deer Island for further processing. In October 1998, the old Nut Island plant was officially decommissioned, ending more than

100 years of wastewater discharges to the shallow waters of Quincy Bay. By 2000, the average effluent solids loading to the harbor had decreased to less than 35 tons per day (TPD), reduced from the 138 TPD discharged through the 1980s. On September 6, 2000, all wastewater discharges were diverted to the new outfall in Massachusetts Bay, and in early 2001, the final battery of secondary treatment became operational.

Ongoing MWRA pollution abatement projects for Boston Harbor involve reducing the number and discharge volumes from Combined Sewer Overflows (CSOs). In 1988, 88 CSOs discharged a total of about 3.3 billion gallons per year (BGY). By 1998, 23 CSOs had been closed, and pumping improvements reduced discharges to about 1 BGY, of which about 58% is screened and disinfected. By 2008, ongoing projects will reduce the number of CSO outfalls to fewer than 50, with an estimated discharge of 0.4 BGY, of which 95% will be treated by screening and disinfection (Rex *et al.* 2002).

Taylor (2005, 2006) summarized the major patterns in freshwater flows and loadings of total nitrogen (TN), total phosphorus (TP), total suspended solids (TSS), and particulate organic carbon (POC) to Boston Harbor between 1995 and 2005. He found four major periods of pollutant loadings (Figure 1-1):

- Period I was prior to December 1991. Freshwater inflows, which came primarily from area rivers, and loadings of all four fractions were elevated, principally because of discharges from the sewage treatment facilities.

- Period II was from December 1991 (end of sludge dumping) through mid-1998. During this time, discharges into the harbor were released from both the Nut Island and Deer Island facilities. Freshwater inflows and loadings of TN and TP, averaged for the entire 6.5-year period, were not significantly different from Period I. Average TSS and POC loadings, however, were significantly lower than during Period I, due to the end of sludge dumping and because of increased removal of TSS and POC from the effluent stream following improved primary treatment and upgrade to secondary treatment at Deer Island.

- Period III began in mid-1998, after the April transfer of Nut Island wastes to Deer Island for treatment and discharge, and lasted until September 2000. Freshwater flows were not significantly lower than during Periods I and II, but loadings of TSS and POC, and to a lesser extent TN and TP, did decrease significantly. For all four variables, the decreases were primarily the result of the transfer of the Nut Island discharges to the mouth of the harbor, and increased secondary treatment of the now-combined Deer Island and Nut Island flows at Deer Island.

- Period IV began in September 2000 with the transfer of the discharge offshore. For this 5-year period, average freshwater inflows and loadings of TN, TP, TSS, and POC were all significantly lower than during all three of the previous periods.

The changes in wastewater discharge from 1991 to 2005 resulted in an 80–95% decrease in loadings to Boston Harbor. Annual average loadings of TSS and POC showed a progressive decrease, starting in 1991/1992 and proceeding through 2001, after which the average loadings remained low and similar between years. For TN and TP, loadings showed some decrease with the end of sludge discharge, but remained elevated through 1998, when Nut Island flows were discharged closer to the mouth of the harbor, resulting in decreased inputs to the harbor. TN and TP showed additional, larger decreases with the transfer of the effluent discharge offshore in 2000.

1.1.2 Benthic Studies in Boston Harbor

The first extensive studies of the infaunal benthos of Boston Harbor were conducted in the summers of 1978, 1979, and 1982 in support of the secondary treatment waiver application (Maciolek 1978, 1980; McGrath *et al.* 1982). These studies documented spatial and temporal variability in infaunal communities in Boston Harbor prior to any pollution abatement projects, and informed the design of the current monitoring program.

As MWRA's long-term sediment monitoring was being developed, reconnaissance surveys were carried out using sediment profile imaging in 1989 and 1990 (SAIC 1990). This technique provides information on the depth of the apparent redox potential discontinuity (RPD), an estimation of sediment grain-size composition, the successional stage of the infauna, and the presence of any biogenic features such as burrows and tubes (Rhoads and Germano 1986). The sediment profile stations provided the means to assess benthic conditions over most of the outer Boston Harbor and Dorchester, Quincy, Hingham, and Hull Bays.

Quantitative infaunal sampling was initiated in 1991and was intended to characterize the infauna of Boston Harbor so that changes following the various phases of the Boston Harbor Project (*e.g*., sludge abatement) could be documented. Eight stations (one was later relocated) were positioned near the major effluent and sludge discharges and in key reference locations. Benthic infaunal communities and correlated sediment parameters were first sampled in September 1991, approximately three months prior to the cessation of sludge discharge. Post-abatement surveys were conducted in April/May and August 1992 to 2002; beginning in 2003 samples were collected only in August.

In 2004, a new station in the inner harbor, C019, was added to the benthic monitoring program. Sediment contaminants have been monitored at this site periodically since 1994 as part of an MWRA study of the effect of CSOs on sediment contamination in Dorchester Bay (Durell 1995, Lefkovitz *et al.* 1999). MWRA's system upgrades will greatly reduce the amount of CSO discharge to the Fort Point Channel and the bulk of the remaining flow will be treated; therefore, C019 was added to help identify environmental improvements that may result from these upgrades.

Reconnaissance surveys at 25–50 additional stations using sediment profile imaging have been carried out annually. Reports to the MWRA on the results of these surveys are available through their website (http://www.mwra.state.ma.us/harbor/enquad/trlist.html).

1.2 Report Overview

The Boston Harbor benthic monitoring program currently includes two major components: sediment imaging (SPI) and analysis of benthic infaunal communities, complemented by the determination of sedimentary parameters. Results from the 2006 survey are presented in this report and compared with results from previous years. Recent reports (Maciolek *et al.* 2004, 2005, 2006a) have suggested that the infaunal community is responding to some degree to changes in the discharges to the harbor. The occurrence and spread or retreat of *Ampelisca abdita* tube mats, and the increase in species numbers and diversity at some of the stations are considered especially important.

The sampling design and field methods are presented in Chapter 2, with detailed station data in Appendix A. Sediment images are discussed in Chapter 3 and the infaunal benthic communities in Chapter 4. The sediment studies, which include grain-size analysis, total organic carbon (TOC) content determination, and quantification of the sewage tracer, *Clostridium perfringens*, are summarized in Appendix B. The raw data generated for all of these components are available from the MWRA; summaries are included in the appendices to this report.

2. 2006 HARBOR FIELD OPERATIONS

by Isabelle P. Williams

2.1 Sampling Design

The station array provides spatial coverage of the major bays that make up Boston Harbor (Figure 2-1). The nine stations designated as “traditional” (T) are those that are sampled for benthic infauna, followed by a full taxonomic analysis of the organisms in each sample. These stations were selected after consideration of previous sampling programs in the harbor (*e.g.,* those conducted for the 301(h) waiver application) and water circulation patterns and other inputs to the harbor (*e.g*., combined sewer overflow). The 52 stations designated as “reconnaissance” (R) are those at which only sediment profile images (SPI) are taken.

2.1.1 Sediment Profile Images

The Boston Harbor SPI survey was conducted in August 2006 at the nine traditional and 52 reconnaissance stations (Figure 2-1). The SPI data supplement the infaunal data to provide a large-scale picture of benthic conditions in the harbor. Sediment profile imagery permits a faster evaluation of the benthos than can be made by traditional infaunal analyses. This qualitative evaluation can then be integrated with the quantitative results from the infaunal and sediment chemistry analyses. The target locations for Boston Harbor SPI stations are listed in Table 2-1. Field data and specific locations of all sediment profile images collected in 2006 are listed in Appendix A1 (Tables A1-1 and A1-2).

2.1.2 Sediment Samples

Samples for analysis of benthic infauna and sedimentary parameters were collected in August 2006 from nine traditional stations (Figure 2-1). Target locations for these stations are given in Table 2-1. Field data and actual station coordinates for each biology and chemistry grab sample, along with a brief description of each sample, are given in Appendix A2 (Tables A2-1 and A2-2).

The Combined Sewer Overflow (CSO) Survey, designed to provide information on improvements in sediment quality in Boston Harbor after CSO upgrades (see CSO Sediment Synthesis Report, Durell, in prep.), was conducted in conjunction with the 2006 Harbor Traditional Survey so that samples for sediment chemistry and infauna would be collected on the same day.

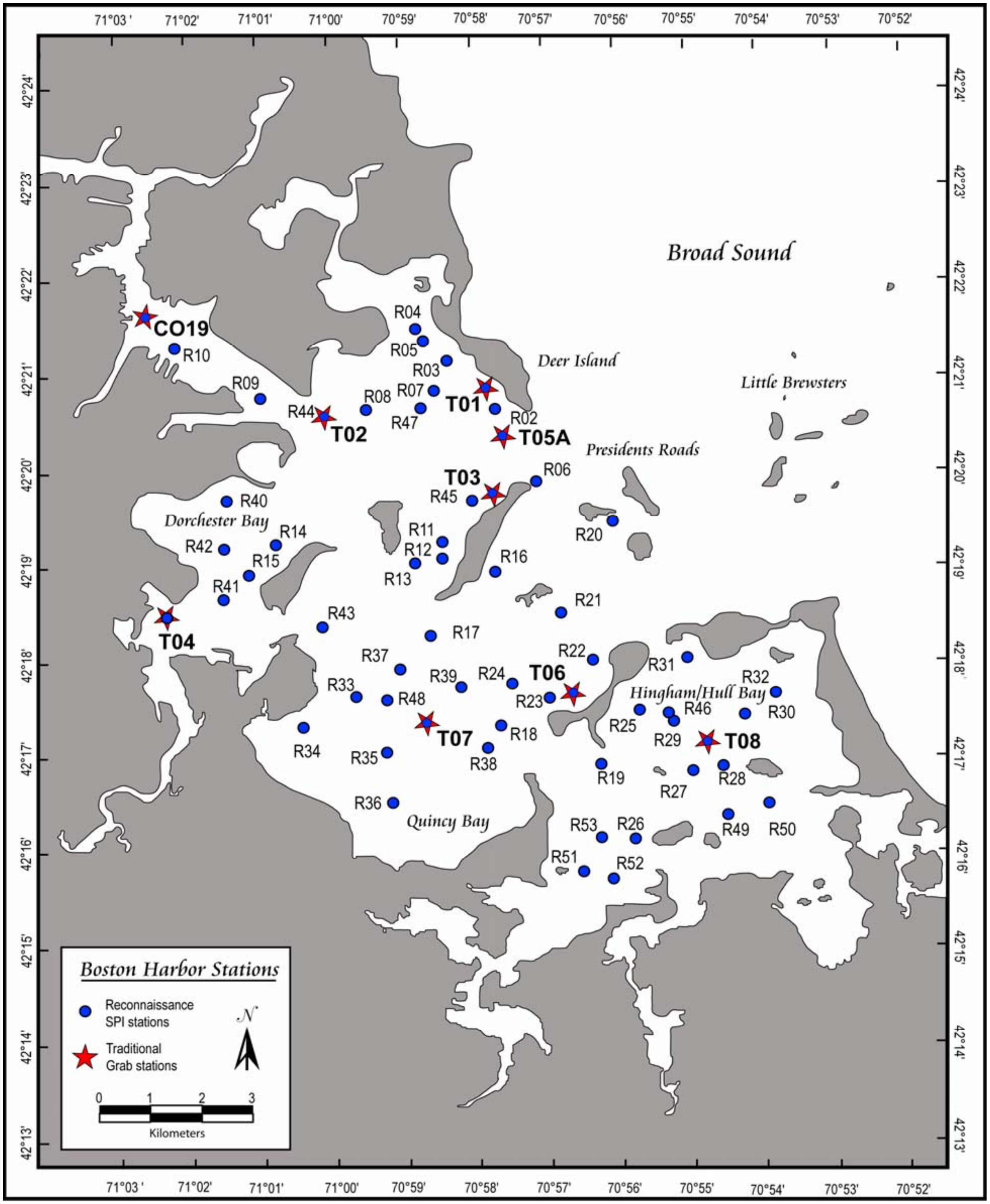


Figure 2-1. Locations of Boston Harbor grab and SPI stations sampled in 2006. Circles indicate Reconnaissance SPI stations sampled in August. Stars show Traditional stations sampled by grab and SPI in August.

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

Station	Latitude	Longitude	Depth (m)
Traditional Stations			
C019	42°21.55'N	71°02.71'W	7.9
T01	42°20.95'N	70°57.81'W	4.9
T02	42°20.57'N	71°00.12'W	6.8
T03	42°19.81'N	70°57.72'W	8.7
T04	42°18.60'N	71°02.49'W	3.2
T05A	42°20.38'N	70°57.64'W	17.5
T06	42°17.61'N	70°56.66'W	6.6
T07	42°17.36'N	70°58.71'W	5.9
T08	42°17.12'N	70°54.75'W	11.3
Reconnaissance Stations			
R02	42°20.66'N	70°57.69'W	13.8
R03	42°21.18'N	70°58.37'W	4.5
R04	42°21.52'N	70°58.78'W	7.2
R05	42°21.38'N	70°58.68'W	5.7
R06	42°19.91'N	70°57.12'W	10.9
R07	42°20.85'N	70°58.53'W	5.6
R08	42°20.66'N	70°59.50'W	2.6
R09	42°20.80'N	71°00.98'W	11.6
R10	42°21.32'N	71°02.20'W	12.8
R11	42°19.28'N	70°58.48'W	7.3
R12	42°19.10'N	70°58.47'W	6.1
R13	42°19.03'N	70°58.84'W	6.7
R14	42°19.25'N	71°00.77'W	7.0
R15	42°18.92'N	71°01.15'W	3.2
R16	42°18.95'N	70°57.68'W	8.0
R17	42°18.29'N	70°58.63'W	8.1
R18	42°17.33'N	70°57.67'W	8.0
R19	42°16.92'N	70°56.27'W	9.2
R20	42°19.49'N	70°56.10'W	11.2
R21	42°18.53'N	70°56.78'W	8.7
R22	42°18.02'N	70°56.37'W	9.4
R23	42°17.63'N	70°57.00'W	10.8

Table 2.1 (continued)

Station	Latitude	Longitude	Depth (m)
R24	42°17.78'N	70°57.51'W	7.4
R25	42°17.48'N	70°55.72'W	7.3
R26	42°16.13'N	70°55.80'W	7
R27	42°16.83'N	70°54.98'W	6
R28	42°16.90'N	70°54.52'W	7
R29	42°17.38'N	70°55.25'W	11
R30	42°17.43'N	70°54.25'W	5
R31	42°18.05'N	70°55.03'W	10
R32	42°17.68'N	70°53.82'W	5
R33	42°17.65'N	70°59.67'W	5
R34	42°17.33'N	71°00.42'W	4
R35	42°17.05'N	70°59.28'W	6
R36	42°16.53'N	70°59.20'W	5
R37	42°17.93'N	70°59.08'W	6
R38	42°17.08'N	70°57.83'W	7
R39	42°17.73'N	70°58.22'W	8
R40	42°19.73'N	71°01.45'W	2
R41	42°18.67'N	71°01.50'W	4
R42	42°19.18'N	71°01.50'W	2
R43	42°18.40'N	71°00.13'W	3
R44	42°20.62'N	71°00.13'W	9.3
R45	42°19.70'N	70°58.05'W	6.8
R46	42°17.46'N	70°55.33'W	10.5
R47	42°20.67'N	70°58.72'W	6.5
R48	42°17.61'N	70°59.27'W	5.9
R49	42°16.39'N	70°54.49'W	6.1
R50	42°16.50'N	70°53.92'W	6.1
R51	42°15.80'N	70°56.53'W	5.3
R52	42°15.71'N	70°56.09'W	5.2
R53	42°16.15'N	70°56.27'W	6

2.2 Field Program Results

2.2.1 Survey Dates and Samples Collected

A summary of the samples collected during the 2006 Boston Harbor surveys is given in Table 2-2.

Table 2-2. Survey dates and numbers of samples collected in Boston Harbor in 2006.

Survey Type	Survey ID	2006 Date(s)	Samples Collected				
			Inf	TOC	GS	Cp	SPI
SPI	HR061	28–29 Aug					190
Benthic	HT061	1–2 August	27	27	27	27	

Key: Inf: Infauna, TOC: total organic carbon, GS: grain size, Cp: *Clostridium perfringens*, SPI: individual sediment profile images.

2.2.2 Vessel and Navigation

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

At each sampling station, the vessel was positioned as close to target coordinates as possible. The NAVSAM© navigation and sampling software collected and stored navigation data, time, and station depth every 2 seconds throughout the sampling event, and assigned a unique designation to each sample when the sampling instrument hit the bottom. The display on the BOSS computer screen was 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 in Boston Harbor.

2.2.3 Sediment Profile Imagery (SPI)

Dr. Robert Diaz was the Senior Scientist for the 2006 Boston Harbor SPI survey (HR061). Three replicate SPI images were successfully collected at 52 reconnaissance and nine traditional stations. The digital camera captured a 5.2-megapixel image that produced a 14.1-megabyte RBG image that was recorded to a 2-gigabyte microdrive. The camera was also equipped with a video-feed that sent 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 viewing a video monitor 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. Images were usually taken at about 1 and 15 sec after bottom contact.

This sampling protocol helped ensure that at least one usable photograph was produced during each lowering of the camera. The video signal from the video camera showing the surface of the seafloor was recorded on 8-mm videotape for later review. Because the images were viewed by video in real time, it was only occasionally necessary to lower the camera to the seafloor more than three times at each station. The date, time, station, water depth, photo number, and estimated camera penetration were recorded in the field log, with each touchdown of the camera also marked as an event on the NAVSAM©.

The microdrive is capable of recording more images than can be collected during a day of sampling. Consequently, the camera housing does not have to be taken apart as long as the batteries supplying the camera or the strobe do not fail. Camera system upgrades made subsequent to the 2004 SPI survey use the video cable to send some recharging capability to the batteries and permit longer deployments. Consequently, during this survey, the microdrive was replaced and new batteries installed only at the end of each survey day. Images were downloaded from the microdrive to the laptop computer at that time. Digital capability allowed a review of the collected images within 20 min of downloading the microdrive so that it was possible to determine quickly whether or not three analyzable images had been collected at each station. Test shots on deck were not necessary, as loss of battery power to the strobe or camera would have been noticed immediately when the video cable failed to relay any images. While still in the field, images were transferred from the microdrive to a computer and then to a compact disc (CD) for long-term storage.

2.2.4 Grab Sampling

At each station, a 0.04-m^2 Young-modified Van Veen grab sampler was used to collect three replicate sediment samples for infaunal analysis. Three replicate samples for analysis of sedimentary parameters (*Clostridium perfringens*, sediment grain-size, and TOC) were obtained using the 0.10-m^2 Kynar-coated grab. Samples for organics and metals analysis were collected from these same sediment samples as part of the CSO survey (see CSO Sediment Synthesis Report, Durell, in prep.). In addition, following the apportionment of the required sediment samples, a subsample of the remaining homogenized sediment was reserved for a University of Massachusetts study of diatoms in Massachusetts Bay.

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 with a Kynar-coated scoop and homogenized in a clean glass bowl before being distributed to appropriate storage containers. The TOC samples were frozen, whereas the *C. perfringens*, grain size, and diatom samples were stored on ice in coolers.

3. 2006 SEDIMENT PROFILE IMAGING

by Robert J. Diaz

3.1 Introduction

Understanding the response of the Boston Harbor ecosystem following major reductions in pollutant input is key to restoration of ecosystem function within the harbor. Improvements started in the late 1980s with the formation of the Massachusetts Water Resources Authority (MWRA), which improved treatment facilities and moved sewage discharge to an offshore location over a period of about 15 years. In the 1980s, nutrient loadings to Boston Harbor were among the highest in the world (Kelly 1997). Bothner *et al.* (1998) and Gallagher and Keay (1998) present a history of environmental degradation within Boston Harbor and showed that sediment quality did improve after reductions in pollutant inputs in the 1990s, but that contaminated sediments remain a "lingering legacy of the long history of contaminant discharge." Recently, there are indications of reductions in heavy metal concentrations in surficial sediments (Zago *et al.* 2001). The main issues that still need to be addressed, however, relate to the response of the benthos and restoration of ecosystem function following cessation of wastewater discharge within the harbor in September 2000, which reduced carbon and nutrient loading to the harbor by over 90% (Taylor 2006).

Given that most pollutants are particle reactive, the sediments are the final sinks where pollutant accumulation occurs (Olsen *et al.* 1982) and where ecosystem function is most likely to be disrupted by toxic and/or enrichment effects (Kimball and Levin 1985). Surficial sediments are critical to many ecosystem functions with flows of energy (organic carbon, living biomass, and secondary production) and nutrients (nitrates and phosphates) all regulated by processes at or near the sediment-water interface (Rhoads 1974, Pearson and Rosenberg 1978, Diaz and Schaffner 1990). In shallow coastal systems, factors structuring surface sediments, down to 20–30 cm from the sediment-water-interface (SWI), are a combination of physical, chemical, and biological processes. While physical processes deliver sediment to the seafloor, it is the activities of benthic organisms, or bioturbation, that alter primary physical sedimentary structures, such as laminations, and produce secondary biogenic structures, such as defecation mounds, feeding pits, and mixed fabrics strongly influencing the rate and depth of solute exchange (Aller and Aller 1998). The ability of the benthos to process organic carbon is related to community maturity (successional stage) and the organic loading rate. At relatively low rates of organic carbon loading, deep bioturbation controls pore-water chemistry and stimulates mineralization of carbon through microbial gardening (Yingst and Rhoads 1979). At higher rates of organic loading, microbial gardening is compromised by the inability of deep bioturbators to control pore-water (Pearson 1982) and the benthic system switches to an alternate state characterized by anaerobic processes and accumulation of carbon away from the state where organic matter does not accumulate and is alternatively exposed to oxidative and reductive redox conditions (Aller 1994). The tipping point between states is reached when the benthos can no longer aerobically metabolize and recycle the organic matter reaching the bottom.

Surface and near-surface sedimentary structures are a time-integrated record of these biological and physical-chemical processes. Sedimentary fabric and structures therefore can be used to evaluate trends in ecosystem status and recovery. To investigate processes structuring the sediment-water interface, Rhoads and Cande (1971) developed the sediment profile camera as a means of obtaining *in situ* data on the dynamics of seafloor processes and biogenic activity. The technology of remote ecological monitoring of the sea floor (REMOTS) or sediment profile imaging (SPI) has allowed the development of a better understanding of the complexity of sediment dynamics, from both biological and physical points of view (Nilsson and Rosenberg 2000, Rosenberg *et al*. 2001, Solan *et al*. 2005). In this monitoring program, SPI is used to characterize the benthic environment from both physical and biological perspectives and related trends to major changes in wastewater disposal within Boston Harbor to long-term changes in habitat condition and quality that could be related to reductions in sewage discharge to the harbor.

3.2 Methods

As about half of Boston Harbor consists of reworked and nondepositional bottom (Knebel and Circé 1995), a series of reconnaissance surveys were carried out from 1989 to 1990 to locate soft-sediment areas throughout the harbor that would likely be depositional or at least low-energy bottoms with a higher likelihood of responding to effects related to wastewater discharge effects (SAIC 1990). In May and August 1992, stations from the 1989–1990 surveys were occupied, along with eight traditional (T) stations at which long-term infaunal monitoring started in September 1991. Since 1993, fully consistent annual SPI surveys have been conducted with summer (August) sampling at a series of 42 reconnaissance (R) stations and eight T stations. In 1995, an additional eight reconnaissance stations were added and in 2004 another traditional station (C019) was added (Figure 2-1). At the traditional stations, grab samples for infauna and sediment analysis were also collected (Maciolek *et al.* 2006a).

At each station, a Hulcher sediment profile camera was deployed a minimum of three times. From 1993 to 2000, a 35-mm film camera was used with Fujichrom 100P film. From 2001 to 2006, a digital Minolta Dimage-7i camera (2560 X 1920 pixels) that captured a 5.2-megapixel image was used. Approximately 75 to 150 pounds of lead were added to the camera frame to improve penetration at all stations. After development, the film images were digitized at a resolution similar to the digital images. Analysis of the SPI followed the methods of Rhoads and Germano (1986), Diaz and Schaffner (1988), and Williams *et al.* (2005). Parameters evaluated from SPI included prism penetration, modal sediment grain-size, processes structuring the sediment surface, depth of the apparent RPD layer as reflected in sediment color, presence of biogenic structures, and estimation of infaunal community maturity, a surrogate for successional stage. For quantitative variables, data from the three replicates were averaged. For categorical variables, the median or modal value was assigned to a station.

Given the nonrandom selection of station locations, fixed-effect longitudinal designs were used to analyze patterns in the data. Generalized estimating equations (GEE) were applied with two basic model structures (Zeger *et al.* 1988). For binary dependent variables, the binomial distribution was used as the random component and the logit as the link function. For continuous variables, the normal distribution and identity link were applied. In both models the cross-station correlations were assumed to be equal. Analysis of variance (ANOVA) and analysis of covariance were also used to test for differences between and within areas for quantitative parameters. Normality was checked with the Shapiro-Wilk test and homogeneity of variance with Bartlett's test. If variance was not homogeneous, Welch analysis of variance, which allows standard deviations to be unequal, was used in testing for mean differences (Zar 1999). Tukey's LSD test was used for multiple mean comparisons. Fisher Exact Test was used for comparison involving odds and odds ratios (Agresti 1990). All statistical tests were conducted using SAS® (SAS Institute, Inc., Allison 1999).

3.3 Results

3.3.1 Regional Harbor Trends

From 1993 to 2006 the predominant sediment type at the stations sampled appeared to be mixed fine-sand-silt-clay (modal Phi 4.5 to 5.5) and was found at 44% of 820 station-year combinations. Sediments appeared to be finer silt-clay (modal Phi >6) 41% of the time, and sandy, mostly fine- to medium-sands with a few coarser stations (modal Phi <3), for 15% of the station-year combinations. From the T stations, grain-size analysis and estimated grain-size from SPI were highly correlated (r = 0.83, N = 118, p = <0.0001) indicating that the visual estimates are reasonable proxies for sediment grain-size.

As the stations sampled were not randomly selected, our observed distribution of grain size was not representative of Boston Harbor, which has a significant amount of hard bottom from pebble-sized grains and larger. Knebel and Circé (1995) characterized the harbor seabed as a patchwork with over 51% being long-term depositional, 29% being reworked sediments containing patches of fine-grained sediments, and 20% erosional/nondepositional. The majority of our stations were in the long-term depositional areas of the harbor.

There was interannual variation in sediment grain-size within and between stations. Sediments in 1993 appeared to be sandier than subsequent years with the odds of encountering a sandy station versus a muddy station (>4.5 Phi) at 1.9. In 1994 the odds of encountering a sandy station declined to 0.3 and from 1995 and later, the odds declined further to <0.2. This harbor-wide trend towards finer grain size, declining odds of encountering sandy sediment, was significant (repeated measure GEE, Chi Sq = 866, p = 0.005). A similar fining trend was observed in grain-size at the T stations (Maciolek *et al.* 2006a). The odds for the occurrence of finer-grained sediments tended to indicate 1999 was the muddiest year with 62% of the stations being silt-clay (>6 Phi). In 1999, percent fines (silt+clay) at five of eight T stations also increased (Maciolek *et al.* 2006a).

From 1993 to 2006, the grain-size observed at 21 stations was consistently muddy (fine-sand-silt-clay to silt-clay). At 38 stations sediments were mostly muddy but appeared to be sandy at least in one year. Four stations were primarily sandy almost all years: R23 in Nantasket Roads was sandy all years, T08 in Hingham Bay was muddy only in 1999, R06 off Long Island and R19 were sandy in all years, except 2005 and 2006 for R06 and 1996 and 1999 for R19 (Table 3-1). Maximum grain-size as seen in SPI, which was recorded from 2002 to 2006, tended to increase through time. Pebble-size grains occurred at about 10% of the stations from 2002 to 2004, about 15% in 2005, and about 25% of stations in 2006. This trend may have been related to the reduction in TSS that could have covered pebble-sized grains and obscured them in the SPI. Spatially, there were the same proportion of sandy and muddy stations located in the inner and outer half of the Harbor. Regionally, stations in Nantasket Roads, Hingham Bay, Deer Island Flats, and off Long Island all had the same odds of having sandy stations. These areas were sandier than stations in Dorchester Bay (odds ratio 3.8, Fisher's Exact test, p = 0.013), Quincy Bay (3.6, p = 0.007), or Charles River (11.1, p = 0.026).

Table 3-1. Modal grain-size estimated from SPI from 1993 to 2006. Sandy sediments were categorized as fine-sand (FS) and coarser (SA),and muddy sediments as mixed fine-sand-silt-clay (FSSICL) or finer silt-clay (SICL).

Sta.	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006
C019												SICL	SICL	SICL
R02	SICL	SICL	FSSICL	FSSICL	FSSICL	SICL	SICL	SICL	SICL	SICL	SICL	FSSICL	FSSICL	SICL
R03	FS	FSSICL	SA	FSSICL	FSSICL	SICL	FSSICL	FSSICL	FSSICL	FSSICL	FSSICL	FSSICL	FSSICL	FSSICL
R04	FS	FSSICL	SICL	SICL	SICL	SICL	SICL	SICL	SICL	SICL	SICL	SICL	SICL	SICL
R05	FS	FSSICL	SICL	SICL	FSSICL	SICL	SICL	SICL	SICL	SICL	SICL	SICL	SICL	SICL
R06	FS	SA	SA	SA	SA	SA	SA	SA	SA	SA	SA	SA	FSSICL	FSSICL
R07	FS	FSSICL	SICL	FSSICL	FSSICL	SICL	SICL	SICL	SICL	SICL	SICL	SICL	SICL	SICL
R08	SA	FS	SA	FSSICL	SA	FS	FSSICL	FSSICL	FSSICL	FS	FS	FS	FS	FS
R09	FS	SICL	SICL	FSSICL	FSSICL	SICL	FSSICL	FSSICL	FSSICL	FSSICL	FSSICL	FSSICL	FSSICL	FSSICL
R10	SICL	SICL	SICL	SICL	SICL	SICL	SICL	SICL	SICL	SICL	SICL	SICL	SICL	SICL
R11	FSSICL	SICL	FSSICL	SICL	SICL	SICL	SICL	SICL	SICL	FSSICL	FSSICL	SICL	SICL	SICL
R12	FSSICL	SICL	FSSICL	SICL	FSSICL	SICL	SICL	SICL	SICL	FSSICL	SICL	SICL	SICL	SICL
R13	FSSICL	FSSICL	FSSICL	FSSICL	FSSICL	SA	SICL	SICL	SICL	FSSICL	FSSICL	FSSICL	SA	SICL
R14	FS	FSSICL	FSSICL	FSSICL	FSSICL	FSSICL	FSSICL	FSSICL	FSSICL	FSSICL	FSSICL	FSSICL	FSSICL	FSSICL
R15	FSSICL	SICL	FSSICL	FSSICL	FSSICL	SICL	FSSICL	SICL	FSSICL	FSSICL	FSSICL	FSSICL	FSSICL	FSSICL
R16	FSSICL	SICL	FSSICL	FSSICL	FS	SICL	SICL	FSSICL	FSSICL	FSSICL	FSSICL	FSSICL	FSSICL	FSSICL
R17	FSSICL	SICL	FSSICL	FSSICL	SICL	SICL	SICL	SICL	FSSICL	SICL	SICL	SICL	SICL	SICL
R18	FSSICL	FSSICL	FSSICL	FSSICL	SICL	SICL	SICL	SICL	SICL	FSSICL	FSSICL	SICL	SICL	SICL
R19	SA	SA	SA	FSSICL	SA	SA	FSSICL	SA	SA	SA	SA	SA	SA	SA
R20	FSSICL	FSSICL	FSSICL	FSSICL	FSSICL	SA	SICL	SICL	SICL	FSSICL	FSSICL	SICL	FSSICL	FSSICL
R21	FS	FSSICL	FSSICL	FSSICL	FSSICL	FSSICL	FSSICL	FSSICL	FSSICL	FSSICL	FSSICL	SICL	SICL	FSSICL
R22	FS	FS	SA	SA	FSSICL	FSSICL	FSSICL	FSSICL	FSSICL	FSSICL	SA	SA	FSSICL	FSSICL
R23	FS	FS	SA	SA	SA	FS	SA	SA	SA	SA	SA	SA	SA	SA
R24	FS	FS	FSSICL	FSSICL	FSSICL	SICL	SICL	SICL	SICL	FSSICL	FSSICL	SICL	SICL	SICL
R25	FSSICL	FSSICL	SICL	SICL	FSSICL	SICL	SICL	SICL	SICL	SICL	SICL	SICL	SICL	SICL
R26	FS	FSSICL	SICL	FSSICL	SA	SICL	SICL	SICL	SICL	SICL	SICL	SICL	SICL	SICL
R27	FS	FSSICL	FSSICL	SICL	FSSICL	SICL	SICL	SICL	SICL	FSSICL	FSSICL	SICL	SICL	SICL
R28	FS	FSSICL	FSSICL	SICL	FSSICL	FSSICL	FSSICL	SICL	SICL	FSSICL	FSSICL	SICL	FSSICL	FSSICL
R29	FS	FSSICL	FSSICL	SICL	FSSICL	FSSICL	SICL	SICL	SICL	FSSICL	FSSICL	SICL	SICL	SICL
R30	FS	FSSICL	FSSICL	SICL	FSSICL	FSSICL	FSSICL	FSSICL	FSSICL	FSSICL	FSSICL	SICL	SICL	SICL
R31	FS	FSSICL	FSSICL	SICL	FSSICL	SICL	SICL	SICL	SICL	FSSICL	FSSICL	SICL	SICL	SICL
R32	FS	FSSICL	SICL	SICL	FSSICL	SICL	SICL	SICL	SICL	FSSICL	SICL	SICL	SICL	SICL
R33	FS	FSSICL	FSSICL	SICL	FSSICL	SICL	SICL	SICL	SICL	FSSICL	SICL	SICL	SICL	SICL
R34	FS	FSSICL	FSSICL	SICL	FSSICL	SICL	SICL	SICL		FSSICL	SICL	SICL	SICL	SICL

Sta.	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006
R35	FS	FSSICL	SICL	SICL	FSSICL	SICL	SICL	SICL		FSSICL	SICL	SICL	SICL	SICL
R36	SA	SA	SA	SA	SA	FSSICL	FSSICL	FSSICL	SA	FSSICL	FSSICL	FS	FS	FS
R37	FS	FSSICL	FSSICL	FSSICL	FSSICL	FSSICL	SICL	FSSICL	FSSICL	FSSICL	FSSICL	SICL	SICL	SICL
R38	FSSICL	FSSICL	SICL	SICL	SICL	SICL	SICL	SICL	SICL	FSSICL	SICL	SICL	SICL	SICL
R39	FSSICL	FSSICL	SA	FSSICL	FSSICL	SICL	SICL	SICL	SICL	FSSICL	SICL	SICL	SICL	SICL
R40	FS	FS	SICL	FSSICL	FSSICL	FSSICL	FSSICL	FSSICL	FSSICL	FSSICL	FSSICL	FSSICL	SICL	FSSICL
R41	FS	FSSICL	FSSICL	FSSICL	FSSICL	FSSICL	SICL	FSSICL	FSSICL	FSSICL	FSSICL	FSSICL	SICL	FSSICL
R42	FS	FS	FSSICL	SA	FSSICL	FS	FSSICL	FSSICL	FSSICL	FSSICL	FSSICL	FSSICL	FSSICL	FSSICL
R43	FS	SICL	FSSICL	FSSICL	FSSICL	SICL	SICL	SICL	SICL	SICL	SICL	SICL	SICL	SICL
R44			FSSICL	SICL	FSSICL	SICL	SICL	SICL	SICL	SICL	SICL	SICL	SICL	SICL
R45			FSSICL	FSSICL	FSSICL	SICL	SICL	SICL	SICL	SICL	SICL	SICL	SICL	SICL
R46			FSSICL	FSSICL	FSSICL	SICL	SICL	SICL	SICL	SICL	SICL	SICL	SICL	SICL
R47			SICL	FSSICL	FSSICL	SICL	SICL	SICL	SICL	SICL	SICL	SICL	SICL	SICL
R48			FSSICL	FSSICL	FSSICL	FSSICL	SICL	FSSICL	FSSICL	FSSICL	FSSICL	FSSICL	FSSICL	FSSICL
R49			FSSICL	SICL	FSSICL	FSSICL	SICL	FSSICL	FSSICL	FSSICL	FSSICL	FSSICL	SICL	SICL
R50			FSSICL	FSSICL	FSSICL	FSSICL	FSSICL	FSSICL	FSSICL	FSSICL	FSSICL	FSSICL	FSSICL	FSSICL
R51			FSSICL	SICL	FSSICL	FSSICL	FSSICL	FSSICL	FSSICL	FSSICL	FSSICL	FSSICL	FSSICL	FSSICL
R52			FSSICL	SICL	FSSICL	FSSICL	FSSICL	FSSICL	FSSICL	FSSICL	FSSICL	FSSICL	FSSICL	FSSICL
R53			FSSICL	FSSICL	SA	FSSICL	FSSICL	FSSICL	FSSICL	FS	FS	FSSICL	FSSICL	FSSICL
T01	FS	SA	FSSICL	SA	FSSICL	FSSICL	FSSICL	FSSICL	FSSICL	FSSICL	FSSICL	FSSICL	FSSICL	FSSICL
T02	FSSICL	FSSICL	SICL	SA	FSSICL	SICL	SICL	FSSICL	FSSICL	SICL	SICL	SICL	SICL	SICL
T03	FSSICL	SICL	SICL	FSSICL	FSSICL	SICL	SICL	SICL	SICL	SICL	SICL	SICL	SICL	SICL
T05		SICL	SICL	SICL	FSSICL	SICL	SICL	SICL	SICL	SICL	SICL	SICL	SICL	SICL
T04	SICL	FS	FSSICL	SA	SA	FS	FSSICL	SA	SA	SA	FSSICL	FSSICL	FSSICL	FSSICL
T06	FS	FSSICL	SICL	SICL	FSSICL	FSSICL	FSSICL	SICL	SICL	FSSICL	FSSICL	FSSICL	FSSICL	FSSICL
T07	FSSICL	FSSICL	SICL	FSSICL	FSSICL	SICL	SICL	FSSICL	FSSICL	FSSICL	FSSICL	FSSICL	FSSICL	SICL
T08	SA	SA	SA	SA	SA	FS	FSSICL	SA	SA	SA	SA	SA	SA	SA

The range of sedimentary habitats within the harbor was also reflected in the average station prism penetration depth, which is a proxy for sediment compaction, with deeper prism penetration in higher water-content, less-consolidated sediments. Prism penetration depth across all years was significantly lower, representing more compact sediments, at coarser sand-gravel stations (3.8±0.2 cm, mean±SE, N = 75) than at fine-sand stations (7.2±0.6, N = 49) than at fine-sand-silt-clay stations (11.1±0.2 cm, N = 362) than at silt-clay stations (16.2±0.2 cm, N = 334), (Welch ANOVA, df = 3, p = <0.0001), which likely had the highest water content. At physically dominated stations with coarse sandy sediments, surface relief was due to sediment grain size (gravel, pebble, or cobble) and bedforms. At biologically dominated stations, surface relief typically consisted of biogenic structures produced by benthic organisms. *Ampelisca* spp. tube mats were the primary relief-creating biogenic features, followed by what appeared to be feeding pits or mounds (Figure 3-1).

The thickness of what appeared to be geochemically oxidized sediments (aRPD) was related to time, region within the harbor, and presence of *Ampelisca* spp. tube mats, (Repeated Measures GEE model, year p = 0.004, Table 3-2). When controlling for region and tube mats, the significant relationship with time was likely related to the reductions in carbon loading to the harbor and to reductions in sedimentary carbon. The loadings reductions were related to the sewage treatment and outfall changes and the sediment reductions related to infaunal sediment processing and bioturbation. It is likely that *Ampelisca* spp. tube irrigation played a major role in remineralizing the harbor's inventory of labile organic matter through the process of redox oscillations (*sensu* Aller 1994). When stations were grouped by harbor region and averaged through time, the area off Long Island (3.5±0.12 cm, mean±SE) and Nantasket Roads (3.1±0.18 cm) had significantly thicker aRPD layers relative to the rest of the harbor (ANCOVA, year p = 0.424, regions df = 6, F = 18.0, p = <0.001). This was likely due more to the location of these areas near the mouth of the harbor to the north than a higher proportion of sandy sediments or TOC content, as both Deer Island Flats and Hingham Bay stations had similar proportions of sand and less TOC, but were to the south of the harbor mouth and further away from input areas (rivers and discharges). Deer Island Flats (2.5±0.14 cm) and Hingham Bay (2.2±0.10 cm) stations did have thicker aRPD layers than Quincy Bay (1.9±0.13 cm), Charles River (1.7±0.12 cm), and Dorchester Bay (1.5±0.12 cm). The latter three regions were all well inside the harbor, had muddier sediments, and higher TOC. Dorchester Bay had the thinnest aRPD layers of all the harbor areas and was the region most affected by land runoff. Each of the harbor regions had one T station with TOC measurements, except Deer Island Flats that had three. Based on T station TOC, Dorchester Bay had the highest organic content sediments of all regions, long-term average of 4.1% (cv = 27%, Maciolek *et al.*2006a).

Biogenic activity associated with the presence of *Ampelisca* spp. had the most influence in deepening the aRPD. When controlling for presence of *Ampelisca* spp. tube mats (tube mats are defined as more than 50 tubes per image), the thickness of the aRPD was not related to sediment type. The tubes observed in Boston Harbor were similar in size and shape to those described by Mills (1967), being about 3.5 x 0.2-0.3 cm with about 1 cm above sediment (Figure 3-1). Where *Ampelisca* spp. tubes were at mat densities, mean aRPD depth, controlling for sediment type and year, was significantly deeper (3.3±0.11 cm, mean±SE) than at stations without *Ampelisca* spp. (1.2±0.07 cm) or at stations with *Ampelisca* spp. present, but at less than tube-mat densities (1.3±0.10 cm) (ANCOVA, sediment type p = 0.976, year p = <0.001, *Ampelisca* p = <0.001). In 1992, prior to the start of annual SPI monitoring, about 40% of stations sampled for establishing the long-term stations had mat densities of *Ampelisca* spp. tubes (Figure 3-2).

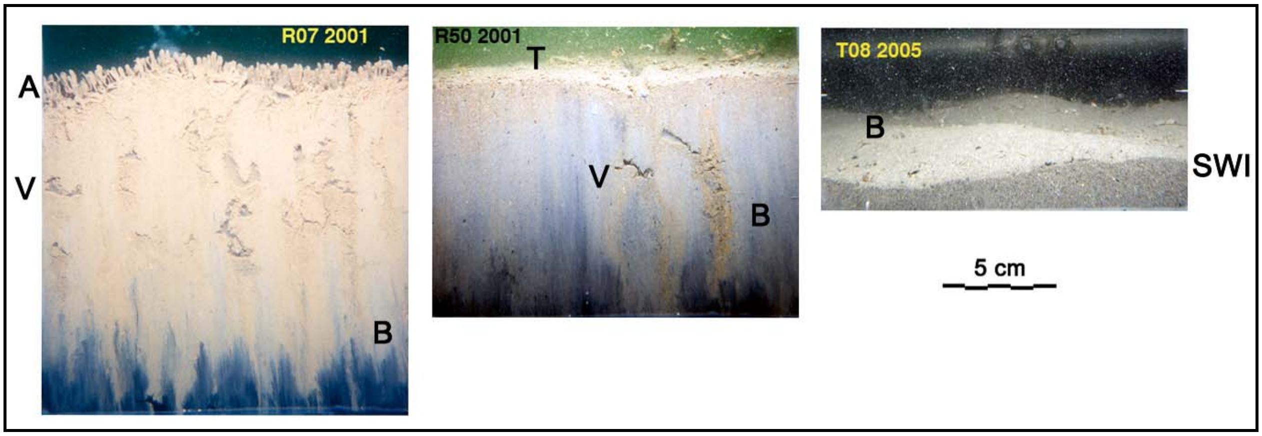


Figure 3-1. SPI showing: R07 for 2001, sediments are silt-clay, surface has a dense *Ampelisca* spp. tube mat (A) with a thick apparent color RPD layer (light brown colored sediment), and other biogenic structures (V: oxic voids and B: burrows); R50 for 2001, sediments are fine-sand-silt-clay, surface has several small tubes, aRPD was about 2.5 cm thick but extended to the bottom of the image by biogenic activities; T08 for 2005, sediments are fine-medium sand with small bedforms (B). SWI is the sediment-water-interface.

Table 3-2. Thickness of the apparent color RPD layer (cm) averaged by Boston Harbor region and presence/absence of *Ampelisca* spp. tube mats through time. N is the number of SPI in each mean.

		Charles River			Dorchester Bay			Deer Island Flats			off Long Island			Nantasket Roads			Quincy Bay			Hingham Bay		
Year	**Ampelisca**	**N**	**Mean**	**SD**	**N**	**Mean**	**SD**	**N**	**Mean**	**SD**	**N**	**Mean**	**SD**	**N**	**Mean**	**SD**	**N**	**Mean**	**SD**	**N**	**Mean**	**SD**
1993	No Mat	2	0.8	0.49	7	1.4	0.61	7	1.0	0.31	3	2.8	1.12	0			3	2.4	1.28	7	2.5	1.07
	Mat	0			0			1	0.6		1			8	3.9	1.49	6	0.7	0.12	3	1.6	1.17
1994	No Mat	1	1.8		5	1.1	0.50	3	0.5		4	4.4	2.18	1	1.0		3	1.7	0.75	7	2.3	0.98
	Mat	1	1.3		2	1.5	0.42	6	1.7	0.38	2	1.9	0.64	7	1.9	0.78	5	2.7	2.80	7	1.2	0.44
1995	No Mat	2	1.4	0.12	4	2.0	1.88	3	1.7	1.05	4	7.2	0.94	0			5	2.2	0.58	9	2.4	1.12
	Mat	0			3	5.4	3.11	8	2.1	0.87	2	2.0		8	4.2	2.53	6	2.0	0.56	1	3.1	
1996	No Mat	1	1.8		5	1.4	0.56	6	2.0	1.25	4	5.4	2.08	2	1.5	0.35	4	1.8	0.54	15	3.4	2.12
	Mat	1	2.8		2	1.7	0.02	5	2.2	0.73	2			6	3.2	1.50	8	1.6	1.88	7	0.8	0.12
1997	No Mat	1	1.6		5	0.9	0.04	5	1.5	0.42	4	4.6	0.69	1			2	5.2	0.12	9	2.6	0.98
	Mat	1	1.5		2	2.9	1.87	6	3.2	1.75	2	1.0		7	3.6	1.09	7	0.6	0.23	8	0.9	0.17
1998	No Mat	1	1.5		6	0.9	0.58	6	1.5	0.48	4	4.3	2.64	2	0.8		3	3.7	1.68	8	3.7	0.91
	Mat	1	1.0		1	1.9		5	2.1	1.33	2	0.6	0.17	6	2.3	1.18	8	0.8	0.45	9	0.8	0.20
1999	No Mat	0			7	0.5	0.21	8	0.9	0.36	4	5.4	2.10	1			2	6.2	0.78	7	2.9	1.13
	Mat	2	2.8	0.85	0			3	5.3	2.80	2	1.0	0.49	7	3.9	2.62	10	1.3	0.54	9	1.0	0.62
2000	No Mat	2	1.4	0.58	7	1.0	0.57	9	1.6	1.27	4	5.2	0.96	1	2.2		5	2.6	2.10	7	2.3	0.56
	Mat	0			0			2	3.8	1.17	1	1.9		7	2.4	0.57	2	5.9	2.30	8	2.4	1.97
2001	No Mat	1	1.8		6	1.1	0.40	5	2.1	0.76	5	4.7	0.95	2	3.7	0.31	1			8	4.6	2.23
	Mat	1	2.4		1	3.4		6	4.7	2.94	2	2.0	0.34	6	4.3	1.61	9	1.7	1.07	14	1.8	0.54
2002	No Mat	2	1.3	0.24	6	1.3	0.42	8	2.0	0.49	4	2.4	0.71	6	1.8	0.76	1	3.0		2	2.1	0.71
	Mat	0			1	1.9		3	2.7	1.27	4	3.9	2.27	2	1.5	0.15	8	2.4	0.86	9	2.1	1.22
2003	No Mat	2	2.1	0.55	7	1.9	0.63	7	3.8	1.45	2	4.8	0.38	5	3.7	1.85	2	5.9	1.35	7	3.0	1.55
	Mat	0			0			4	3.7	1.80	5	2.2	0.72	3	2.5	0.69	10	1.9	0.51	13	1.6	0.57
2004	No Mat	3	1.4	0.20	7	1.3	0.22	10	2.4	1.48	1	2.6	.	5	2.8	1.39	0			3	4.5	0.22
	Mat	0			0			1	2.7		6	1.6	0.39	3	3.1	2.29	10	1.7	0.69	16	1.8	1.01
2005	No Mat	3	2.0	1.07	7	1.8	0.73	11	3.1	1.92	0			8	3.3	2.23	0			0		
	Mat	0			0			0			6	1.8	0.28	0			10	1.5	0.39	15	1.5	0.53
2006	No Mat	3	1.9	0.25	7	1.3	0.33	11	3.3	2.40	0			7	2.8	2.42	0			1	1.4	
	Mat	0			0			0			2	3.9	2.83	1	2.2		6	1.0	0.16	3	1.3	0.07

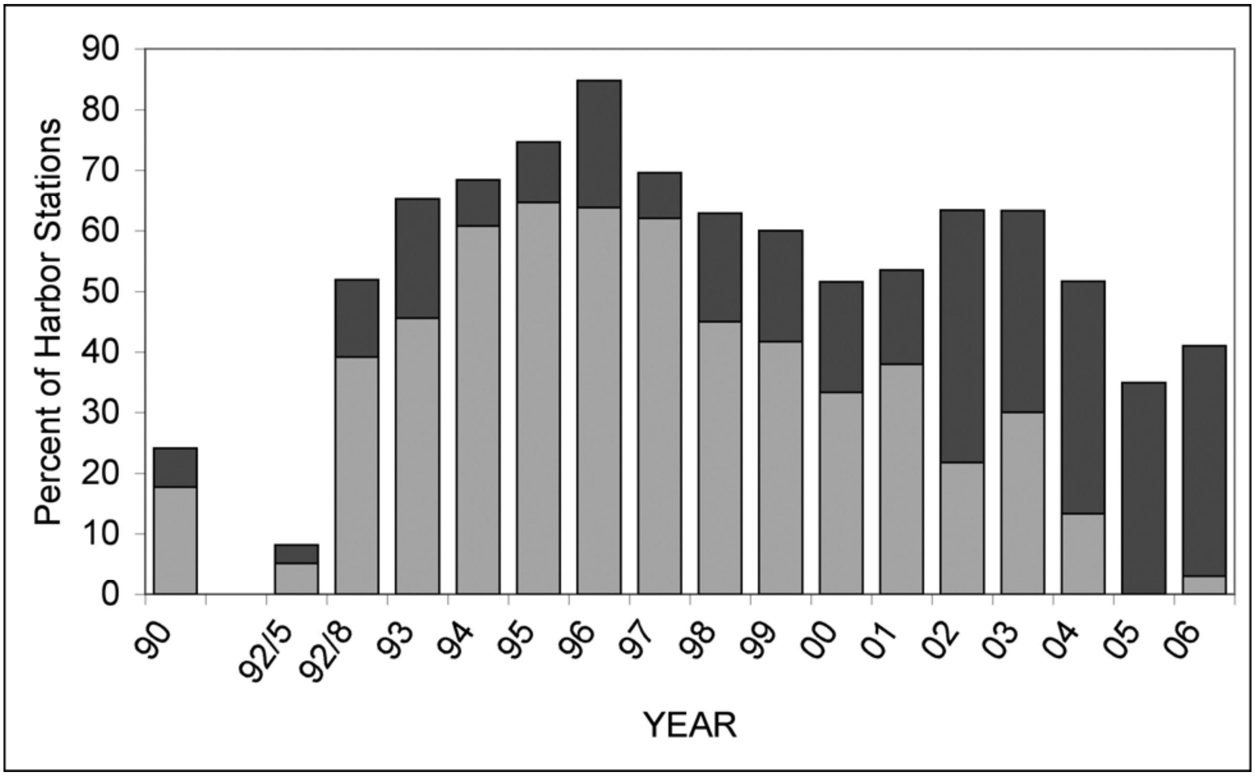


Figure 3-2. Histogram showing the percentage of stations with *Ampelisca* spp. tube mats >50 tubes/image, (light gray) and the total percentage of stations with *Ampelisca* spp. tubes. Data prior to 1993 are from SAIC (1992) and Blake *et al.* (1993).

At some time from 1990 to 1992 there appeared to be an increase in the occurrence of *Ampelisca* spp. tube mats. About 20% of images from 1990 had mat densities of *Ampelisca* spp. (SAIC 1992). In 1992, mats increased to about 40% of stations (Blake *et al.* 1993) and continued to increase with peaks at 60 to 65% from 1994 to 1997. Mat densities of *Ampelisca* spp. declined starting in 1998 to 45% and were 13% by 2004 with no tube mats observed in SPI in 2005 (Figure 3-2). In 2006, tube mats were present at two stations, R30 in Hingham Bay and R21 in Nantasket Roads, both of which had *Ampelisca* spp. tubes present all year and at mat densities 78% and 93% of the years, respectively. The total number of stations with *Ampelisca* spp. tubes at any density, from a few tubes to mat densities, also followed a similar pattern (Figure 3-2).

In addition to *Ampelisca* spp. tubes, other types of tubes and feeding structures were common biogenic features observed at the sediment surface and appeared to structure surficial sediments at many stations. Starting in 1998, information on the processes structuring surficial sediments was assessed from SPI. It appeared that 27% of all year-station combinations from 1998 to 2006 were dominated by biological processes as evidenced by the widespread biogenic activity associated with more mature successional stage infauna (Rosenberg 2001). At 44% of year-station combinations, it appeared that both biological and physical processes were active in structuring bed roughness and physical processes dominating at the remaining 29% of the year-station combinations. There was a significant decline in the odds of a station having a biologically dominated sediment surface through time (data for 1998 to 2006), even when accounting for the declining trend in *Ampelisca* spp. tubes and sediment type (Repeated measure GEE, sediment effect on odds 1.4, $p = <0.001$, *Ampelisca* spp. effect on odds 39.5, $p = <0.001$; year effect on odds 0.61, $p = 0.010$). This trend may be related to the shifts in proportion of infaunal feeding types away from sediment surface feeding species to burrowing and subsurface feeding species that produce fewer surficial biogenic structures.

It also appeared that stations classified as having biologically dominated surface sediments had higher infaunal biogenic activity (infaunal organisms, burrows, feeding voids). The number of infaunal organisms per image was significantly higher at stations with biologically or biologically and physically dominated surfaces (2.2±0.14 and 2.0±0.14 infauna/image, mean±SE) relative to physically dominated surfaces (0.8±0.09 infauna/image) (Welch ANOVA, df = 2, F = 41.7, $p = <0.001$). Similarly significant patterns of higher mean values at biologically dominated stations were observed for number of burrows and feeding voids per image. Gas-filled voids, indicative of high rates of methanogenesis, were not related to year or processes structuring surficial sediments but were related to TOC. Station T04, which had gas voids 64% of the years also had the highest TOC of all T stations.

The high degree of biogenic sediment reworking observed at many stations was consistent with the presence of a more mature infaunal community. Evidence of equilibrium successional Stage III fauna, the presence of feeding voids (oxic and anaerobic), was observed at 73% of year-station combinations for 1993–1994 and 1998–2005; the presence of voids was not recorded from 1995 to 1997. There was a significant increase in the odds of a station having feeding voids, which implies an increasing trend in the presence of deeper subsurface feeding species even when controlling for tube mats and sediment type (Repeated measure GEE, sediment effect on odds 1.8, $p = <0.001$, *Ampelisca* spp. effect on odds 1.0, $p = 0.934$; year effect on odds 1.3, $p = <0.001$). Recruitment by small (<1 mm diameter) tube building species, likely pioneering successional Stage I fauna, was evident at 76% of year-station combinations, with the odds of small tubes being present increasing with time when controlling for the effects of sediment type, amphipod tubes, and surface processes (Repeated measure GEE, sediment effect on odds 0.9, $p = 0.339$, *Ampelisca* spp. effect on odds 0.1, $p = <0.001$; year effect on odds 1.1, $p = <0.001$). Much of the increase in odds of small tubes being present appeared due to the decline in numerical dominance of *Ampelisca* spp., which may have discouraged settlement of tube builders through its high levels of bioturbation and filter feeding. The shift from amphipod dominance to small-tube species was likely related to the temporal patterns in organic inputs: a shift from a sewage based alloctononus carbon system to a detrital and phytoplankton dominated autonctonus carbon system.

3.3.2 Trends Linked to Changes in Loadings from Wastewater

In 1990 and 1991 about 40,000 mt of particulate organic carbon (POC) entered Boston Harbor annually with over 95% associated with sewage discharges (Taylor 2006). At this time, sludge discharge from primary wastewater treatment accounted for about 25% of this carbon loading (Werme and Hunt 2004) but ended late in 1991. The cessation of sludge discharge reduced POC by about 40% from 1992 to 1994. Additional improvements in treatment further reduced carbon loading from 1995 to 1998 to about 17,000 mt C annually. When the discharge was moved offshore in 2000 allochthonous carbon loading to the harbor was reduced to about 2,000 mt and was from river and nonpoint source inputs (Taylor 2006). During the SPI monitoring, which started in 1993, two major changes occurred in wastewater discharge. One change was in June 1998 when discharges near Nut Island in Quincy Bay were transferred to Deer Island at the mouth of the harbor and treatment was upgraded to secondary. A second change occurred in September 2000 when all wastewater discharges were transferred to the new ocean outfall.

To look for patterns relative to changes in wastewater discharges and loading to the harbor, the SPI data were grouped into the three periods based on Taylor's (2006) summary of major patterns in freshwater flows and loadings of total nitrogen (TN), total phosphorus (TP), total suspended solids (TSS), and particulate organic carbon (POC) to Boston Harbor between 1990 and 2005. Taylor period I was the two years of highest carbon loadings (1990 and 1991). Period II was from 1992 through mid-1998 when wastewater was discharged in Quincy Bay off Nut Island. During period II, the harbor received elevated freshwater flows and high loadings of TN, TP, TSS, and POC. On average, wastewater flows were 39% (SD = 20%) of the 1.85 x 106 m3 d-1 (SD = 1.3) river flows. Period III was from mid-1998 to 2000 when the Nut Island discharges were transferred to off Deer Island and secondary treatment was improved. Freshwater flows, at 1.7 x 106 m^3 d-1 (SD = 1.2), remained moderately elevated above the long-term average, but loadings of TSS and POC, and to a lesser extent TN and TP, decreased. During summer low flows within Periods II and III, wastewater accounted for almost half of all freshwater entering the harbor (Taylor 2006). Period IV was post-transfer of the Deer Island discharge offshore in 2000. Loadings of TSS and POC were further reduced, but the largest decrease was observed for TN and TP. River flows declined during period III to an average of 1.3 x 106 m^3 d-1 (SD = 1.1), but the largest decline in freshwater flows was primarily due to moving wastewater discharge offshore. The changes in wastewater discharge in 1998 and again in 2000 resulted in about a 90% decrease in loadings to Boston Harbor. For TSS and POC, most of the decreases occurred between periods I, II, and III, in response to the transfer of the Nut Island discharge to Deer Island and treatment upgrade. For TN and TP, most of the decreases occurred between periods III and IV, in response to transfer of the discharge offshore (Taylor 2006). SPI data from 1993 to 1998 were grouped for period II. Period III was SPI data for 1999 and 2000, and 2001 to 2006 for period IV.

Had the reductions in loadings associated with reduced wastewater discharge and improved treatment affected benthic habitat quality for infauna within the harbor, the largest effects should have been observed at stations closest to the outfalls. Based on this hypothesis of localized wastewater discharge impacts, stations nearest Nut Island (within 2 km: R18, R22, R23, R24, and T06; within 4 km: R21, R38, R39, and T07) and Deer Island (within 2 km: R02, R03, R07, R47, T01, and T05A; across channel: R06, R45, and T03) outfalls should have shown the greatest change relative to relocation of discharges and improved treatment (Figure 2-1). Based on the results of harbor-wide trends, which indicated that sediment type and presence of *Ampelisca* spp. tube mats controlled many of the SPI parameter associations, GEE models were constructed controlling for these variables to determine effects of proximity to an outfall (<2 km and <4 km) and Taylor periods (II, III, and IV).

For Nut Island, there was no significant effect of proximity to outfalls for any of the SPI parameters examined (Table 3-3). At Deer Island, there were significant differences in burrows, an indicator of subsurface biogenic activity, with the odds of burrows being present greater further away from the outfalls. For the Nut Island stations, the odds of an *Ampelisca* spp. tube mat occurring declined from period II to III to IV. For Deer Island, most of the decline in the odds of tube mats being present occurred from period II to III. There was no significant difference between periods III and IV (Figure 3-3). The harbor-wide decline in tube mats was consistent with reduced loadings from 1992 to 2000. There were no significant patterns in the depth of the apparent color RPD (aRPD) layer related to Taylor periods except that when amphipod tube mats were present the aRPD was deeper. Patterns in biogenic activity relative to Taylor periods was mixed. The number of infauna and voids, both oxic and anaerobic, observed in SPI was significantly higher in period IV for both Nut and Deer Islands, but the odds of burrows and tubes being present declined for period IV only for Deer Island (Table 3-3). At Nut Island the patterns for burrows and tubes were not significant.

The patterns of biological change observed in SPI, the most obvious being the reduction in *Ampelisca* spp. tube mats, may be related to changes in organic matter stored in the sediment. With the reductions in loadings to the harbor, benthos may have relied on inventories of organic matter stored in the sediment for maintaining large populations. Measurements of TOC at T02 (flux station BH02) and T03 (BH03) found TOC was less variable and declined slightly in periods II and III relative to period IV. For station T03, the decline in TOC for periods III and IV was more pronounced (Tucker *et al.* 2006). The significant decline in the odds of a tube mat being present at a station from periods II to IV would also be consistent with reduction of sediment organic inventories as large amounts of organic matter are needed to sustain mat densities of *Ampelisca* spp., which McCall (1977) considered to be an opportunistic r-strategist. High densities of *Ampelisca abdita*, up to 94,000 m^2, in Jamaica Bay, New York, were sustained by large amounts of particulate organic carbon—much of which was contributed indirectly from wastewater effluents and incorporated into sediments (Franz and Tanacredi 1992). To estimate the amount of organic matter needed to support mat densities, we assumed that *Ampelisca* spp. in Boston Harbor had a life history to similar *A. abdita* in Jamaica Bay. Franz and Tanacredi (1992) estimated mat densities of *A. abdita* to produce at 25 to 47 g dry wt/m^2/year or 12 to 24 g C/m^2/yr. Assuming a 10% trophic level transfer efficiency, then 120 to 240 g C/m^2/yr are needed to support populations at mat densities. Based on carbon inputs to Boston Harbor, it then seems that *Ampelisca* spp. consumed or participated in the remineralization via redox cycling (see Aller 1994) of 7% to 18% of the total carbon depending on the Taylor period (Table 3-4). While the total annual carbon budget for Boston Harbor should be sufficient to support high densities of *Ampelisca* in any one year, the increases and declines observed from 1993 to 2005 appear related to shifts from wastewater to phytoplankton-derived carbon, all of which was not available for the amphipods to directly utilize.

Table 3-3. Summary of longitudinal analyses for SPI variables from stations near the location of either Deer or Nut Island outfalls. Taylor (2006) II, III, and IV refer to periods of loading reductions to Boston Harbor. II-IV is the effect between periods II and IV, and III-IV is the effect of period III to IV. Negative estimates indicate an increase in the variable going toward period IV. Near vs. Far contrasts stations <2 km (Near) to stations <4 km (Far) of the outfalls. A positive estimate indicates an increase at <2 km stations. Sediment class and *Ampelisca* spp. tube mats were included as covariates, with negative estimates indicating a decline in the variable as sediments became finer and mats increased.

	Deer Island			**Nut Island**		
***Ampelisca* spp. Tube Mat**						
Parameter	Estimate	SE	P	Estimate	SE	P
Intercept	-3.14	1.51	0.038	-1.83	1.29	0.157
Sediment	0.53	0.25	0.032	0.13	0.16	0.436
Taylor II-IV	-1.91	0.47	<0.001	-2.55	0.39	<0.001
Taylor III-IV	-0.78	0.49	0.115	-1.31	0.44	0.003
Near vs. Far	0.59	0.55	0.283	-0.55	0.85	0.520
aRPD Thickness						
Parameter	Estimate	SE	P	Estimate	SE	P
Intercept	2.93	0.68	<0.001	3.65	0.67	<0.001
Sediment	0.19	0.10	0.058	0.00	0.11	0.995
Ampelisca Mat	0.73	0.34	0.033	1.38	0.41	0.001
Taylor II-IV	-0.90	0.63	0.154	-0.27	0.45	0.553
Taylor III-IV	-0.64	0.43	0.134	-0.39	0.33	0.233
Near vs. Far	-0.06	0.41	0.879	-0.06	0.43	0.885
Infauna per Image						
Parameter	Estimate	SE	P	Estimate	SE	P
Intercept	0.06	0.86	0.940	1.00	1.22	0.415
Sediment	0.44	0.15	0.004	0.37	0.16	0.017
Ampelisca Mat	-0.40	0.63	0.523	0.59	0.49	0.229
Taylor II-IV	-1.49	0.36	<0.001	-1.58	0.57	0.006
Taylor III-IV	-1.33	0.40	0.001	-0.91	0.39	0.021
Near vs. Far	0.89	0.58	0.122	-0.11	0.67	0.869
Oxic & Anaerobic Voids per Image						
Parameter	Estimate	SE	P	Estimate	SE	P
Intercept	-2.42	1.24	0.052	-2.40	0.76	0.002
Sediment	0.74	0.19	<0.001	1.06	0.13	<0.001
Ampelisca Mat	0.14	0.80	0.862	0.73	0.39	0.065
Taylor II-IV	-2.85	0.42	<0.001	-3.18	0.67	<0.001
Taylor III-IV	-0.29	0.70	0.677	0.41	1.63	0.802
Near vs. Far	1.07	0.74	0.147	-0.23	0.30	0.436
Burrows present/absent						
Parameter	Estimate	SE	P	Estimate	SE	P
Intercept	-3.06	1.81	0.090	0.32	1.43	0.823
Sediment	1.08	0.28	<0.001	0.74	0.15	<0.001
Ampelisca Mat	0.65	1.08	0.549	1.18	0.58	0.040
Taylor II-IV	-2.22	0.48	<0.001	-1.89	0.53	0.000
Taylor III-IV	-0.44	0.60	0.457	-0.56	0.83	0.498
Tubes present/absent						
Parameter	Estimate	SE	P	Estimate	SE	P
Intercept	-1.09	1.37	0.428	1.97	1.97	0.318
Sediment	0.21	0.22	0.334	-0.33	0.30	0.270
Ampelisca Mat	-4.06	1.28	0.002	-4.10	0.87	<0.001
Taylor II-IV	-2.13	0.86	0.013	-1.45	0.69	0.036
Taylor III-IV	-1.54	0.82	0.061	-1.27	0.78	0.104
Near vs. Far	-0.18	0.39	0.651	0.31	0.90	0.726

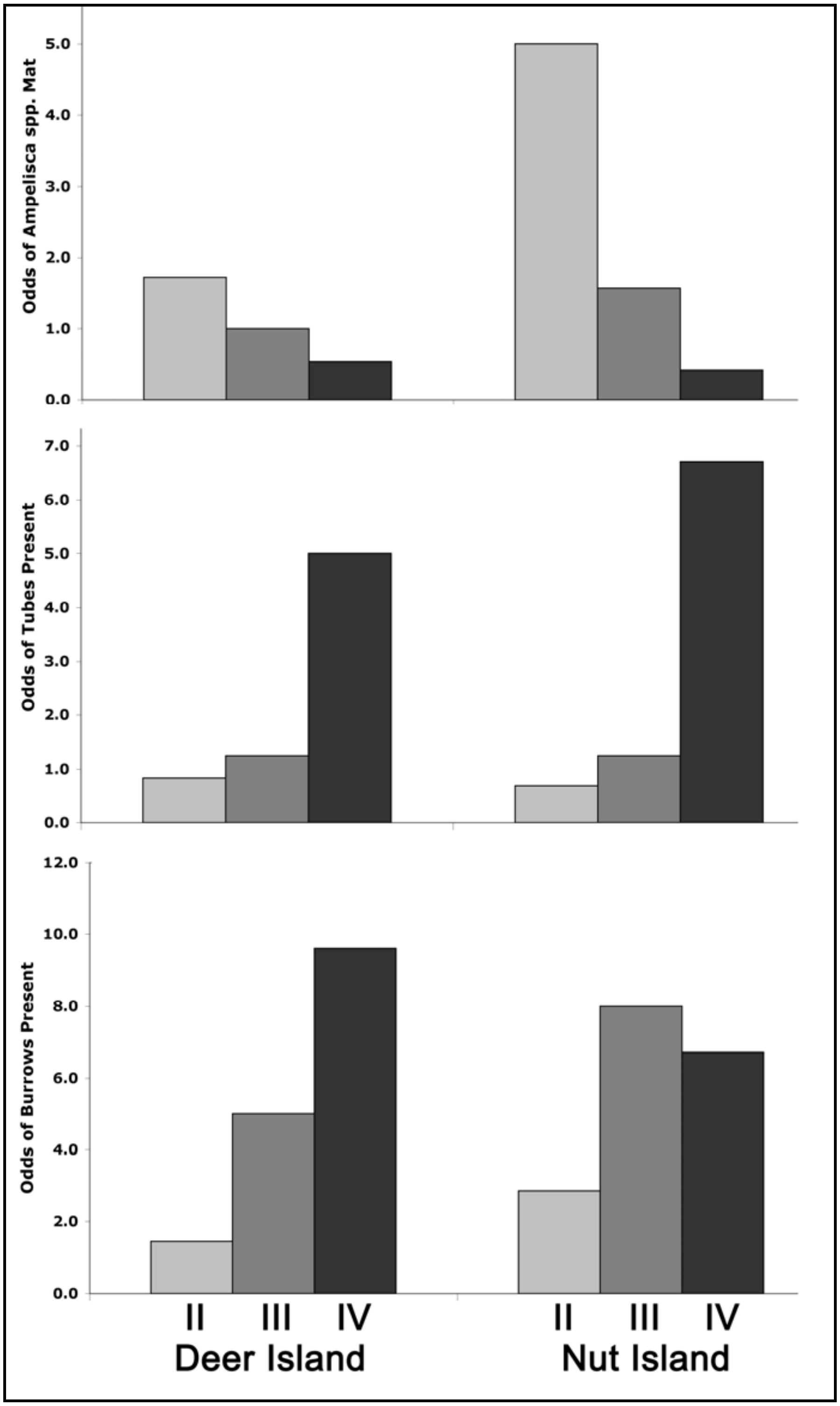


Figure 3-3. Histograms depicting the change in odds for *Ampelisca* spp. tube mats, other tubes, and burrows for Taylor (2006) periods II (light gray), III (medium gray), and IV (dark gray) for each of the harbor outfall areas (Deer Island and Nut Island).

Table 3-4. Estimated organic carbon inputs to Boston Harbor and percentage of carbon flowing through Ampelisca spp. over time blocked by Taylor periods. Wastewater carbon estimates were derived from Taylor (2006), primary production (PP) was estimated from Keller *et al.* (2001) and Oviatt (pers. comm.), and *Ampelisca* production from Franz and Tanacredi (1992).

Taylor Period	Time	Rivers & Wastewater g C/m^2/yr*	PP g C/m^2/yr	Total C g C/m^2/yr	Total C Wastewater %	Total C PP %	*Ampelisca* 120 gC/m^2/yr	*Ampelisca* 240 gC/m^2/yr
II	1992–mid1998	92	700	790	12%	88%	15%	30%
III	mid1998–2000	32	460	490	6%	94%	24%	49%
IV	2001–2005	9	430	440	2%	98%	27%	55%
IV/05–06***	2005–2006	9	251****	260	3%	97%	46%	92%

Taylor Period	Mat % stations	Wastewater mt C/yr	PP mt C/yr	Total mt C/yr	Mat Area km^2	C to support *Ampelisca* at Mat Densities:			
						mt C @ 120 gC/m^2	% of C	mt C @ 240 gC/m^2	% of C
II	0.59	11450	87500	98950	68	8160	8	16320	16
III	0.38	4000	57500	79000	47	5620	9	11250	18
IV	0.26	1150	53700	44900	22	2660	5	5310	10
IV/05–06	0.015	1150	31380	32520	2	225	<1	450	1

* 125 km^2 used as area of Boston Harbor (Signell *et al.* 2000)
** From Oviatt *et al.* 2007
*** Only 2005 and 2006
**** Only PP for 2005

3.3.3 Benthic Habitat Quality

Benthic habitat quality for infauna at the Traditional (T) stations for the 1992 to 2006 was assessed using sediment and infaunal data from grab samples (total abundance, Fisher's *alpha*, mean Phi, percent gravel, and TOC; see Chapter 4, this report) and SPI image data (RPD, amphipod tube mats, and estimated successional stage). Based on the patterns of association between the sediment, infauna, and SPI variables as determined from principle components analysis (77% of variance in first three axes) a cline of relative habitat quality was detected from lowest quality at station T04, progressing to intermediate habitat quality for T01, T02, T03, and T07, and highest habitat quality at T06, T05A, and T08 (Figure 3-4).

Among the sediment variables, mean Phi and TOC were positively correlated (Table 3-5). Percent gravel and mean Phi were negatively correlated and indicated that gravel tended to occur as grain-size coarsened. For the infauna variables, total species and *alpha* were correlated with sediment and SPI variables. The inverse relationships of species and *alpha* with TOC and Phi were expected as TOC is directly related to sediment grain-size, here expressed as mean Phi. Interestingly, the apparent color RPD layer depth was not correlated to any of the sediment variables. This likely reflects the contribution of bioturbation, which was independent of the range of sediment grain-size at the eight traditional stations, to deepening the RPD. Even though station T04 consistently had the shallowest RPD, highest TOC, and limited evidence of bioturbation, the amount of biogenic activity at the other seven stations consistently deepened the RPD beyond what would be expected by diffusional processes alone (Jørgensen and Revsbech 1985). It is also well documented that higher levels of TOC tend to depress community structure and successional stage (Pearson and Rosenberg 1978). However, the range of TOC measured at the T stations does not appear to be sufficient to alone account for the range in habitat quality documented. Station T04 had the highest TOC annually (mean from 1992 to 2003 of 4.3%, 1.5% SD) and also the lowest habitat quality, while station T03 had higher habitat quality and consistently the second highest TOC annually (mean 3.2%, 0.4% SD). It is likely that sediment contamination, which is also strongly associated with sediment grain-size (Olsen *et al.* 1982), plays an important role in determining benthic habitat quality at muddy sites within Boston Harbor and that contaminated sediments remain a "lingering legacy of the long history of contaminant discharge" (Bothner *et al.* 1998), particularly at T04, which is located near a storm-water outfall.

The positive significant relationships between infaunal and SPI variables reflect the integrative nature of biological processes. The direction in the relationships between variables is seen in the biplot based on PCA on station means for the eight variables (Figure 3-4). Station T04 had the finest sediments with highest TOC and lowest values for community structure and SPI variables. Stations T05A and T08 were the opposite of T04, with lower TOC and higher community structure and SPI variables. Stations T01 and T07 were separated from the other stations primarily because of low total and *Ampelisca* spp. abundance, and shallower RPD layer depths. Stations T03 and T06 had the highest abundances and deepest RPD layers. Station T02 was near the ordination centroid with variable values that were close to the grand mean of all stations from 1992 to 2006.

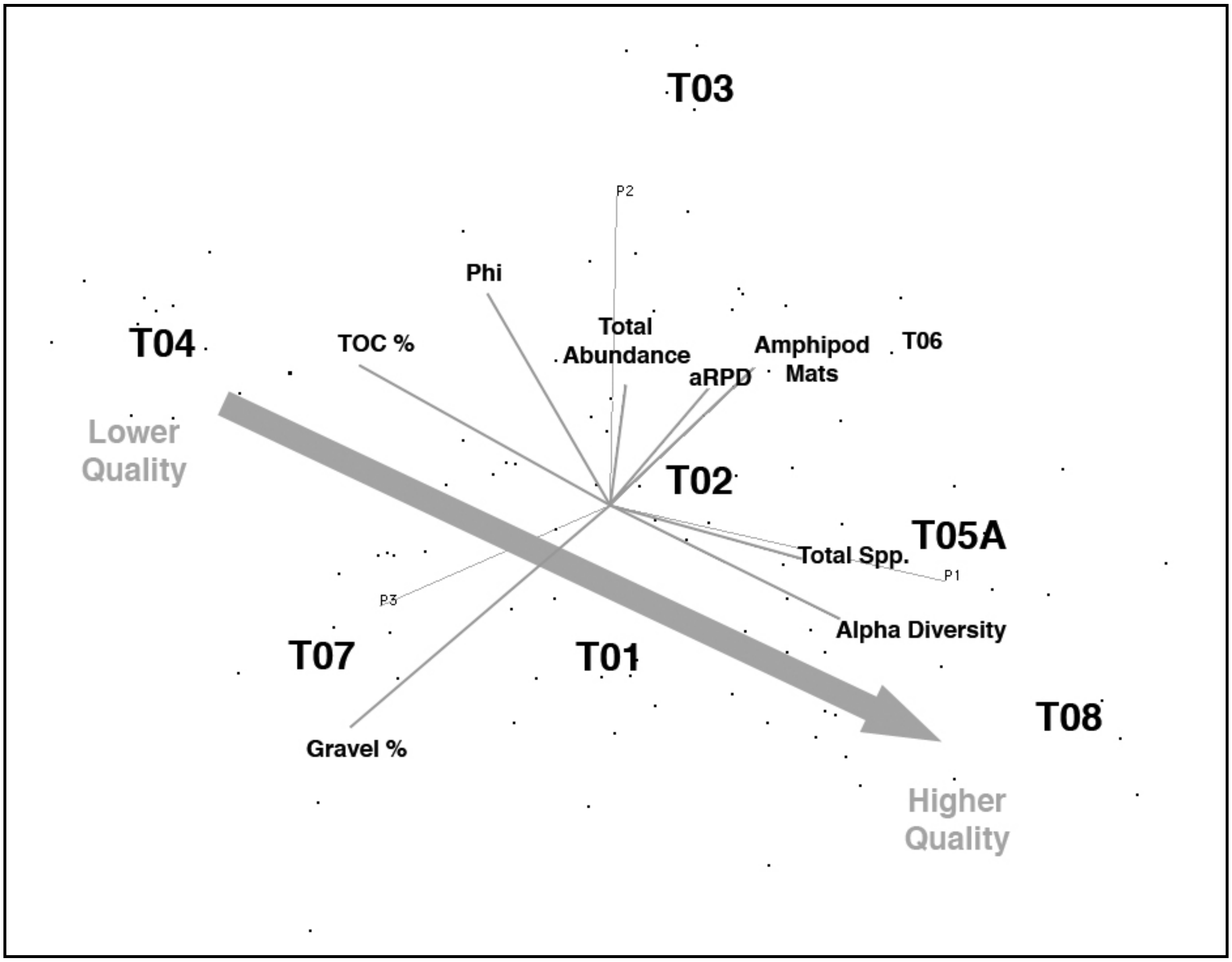


Figure 3-4. Biplot of eight sediment, infauna, and SPI variables from PCA of station-averaged data. Plot is arranged looking down on the first three principle component axes (P1, P2, and P3) at about a 45° angle. Arrow indicates general cline of habitat quality from lower at T04 to higher at T08.

Table 3-5. Significant correlations between selected sediment, SPI, and infauna variables.

Variable	Variable	N	Correlation	Prob.
Alpha	Amphipod Mats	109	0.30	0.002
Alpha	Phi	111	-0.54	<0.001
Alpha	RPD	105	0.24	0.016
Alpha	TOC %	112	-0.69	<0.001
Alpha	Total Species	112	0.86	<0.001
Total Species	Abundance	112	0.49	<0.001
Total Species	Amphipod Mats	109	0.48	<0.001
Total Species	Phi	111	-0.42	<0.001
Total Species	RPD	105	0.36	<0.001
Total Species	TOC %	112	-0.57	<0.001
Amphipod Mats	Abundance	109	0.55	<0.001
Amphipod Mats	Gravel %	117	-0.21	0.025
Amphipod Mats	RPD	110	0.42	<0.001
Gravel %	Phi	119	-0.26	0.004
TOC %	Phi	119	0.66	<0.001
Abundance	RPD	105	0.42	<0.001

3.4 Discussion

From 1991 to the start of outfall operation in 2000, a series of regional events transpired that influenced all of Boston Harbor. Climatologically, severe storms passed over the region in October 1991 and May 2005 representing the highest and second highest bottom stress on record, respectively (Butman *et al*. In Preparation). Freshwater flow was elevated for much of the study period except for 1995, which was a low-flow year (Taylor 2006). 1991 was also the year sludge dumping within Boston Harbor ended (Taylor 2006). 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 down to about 4,000 mt C/yr from a high of about 11,400 mt C/yr. Starting in late 2000, the offshore discharge went into operation and diverted about an additional 2,800 mt C/yr out of the harbor (Taylor 2006). Overall, the changes in wastewater discharge and improved treatment from 1995 to 2000 resulted in about a 90% decrease in loadings to Boston Harbor to about 1,200 mt C/yr.

It is possible that the major climatological event and cessation of primary discharges in the early 1990s set the stage for harbor benthic conditions prior to the start of our study. The most apparent change in harbor benthos was the widespread increase in *Ampelisca* spp. that took place in 1992 (Figure 3-2). The tube-building amphipods in the genus *Ampelisca*, which seem to have a life history that reflects a combination of opportunism in responding to organic matter (McCall 1977) and sensitivity to pollutants (Wolfe *et al.* 1996) could be considered an indicator of improving benthic habitat quality and intermediate along a path of community maturation (Rhoads and Germano 1986). *Ampelisca* spp. seem to thrive in high organic input areas with good water quality (Stickney and Stringer 1957). Based on grab-sample data, *Ampelisca* spp. tube mats were not broadly distributed in Boston Harbor prior to mid-1992 (Hilbig *et al.* 1997). Organic loads were high prior to 1992 but water quality may have also been poor and hindered *Ampelisca* spp. settlement. Periods of low dissolved oxygen were observed in the inner harbor in the 1980s

(Neponset River Watershed Association *et al.* 2004). In late 1992, there was about a doubling of stations with *Ampelisca* spp. tube mats from <20% to about 40%. From 1993 to 1995, the spatial distribution of tube mats increased to >60% of stations and remained at >60% until 1998 when the distribution of tube mats started to contract and dropped to about 20% by 2000. In 2003, there was a rebound to about 30% and then a decline in 2004 to 13%. In 2005, which had the lowest primary production of the last 14 years (Oviatt *et al.* 2007), *Ampelisca* spp. tubes did not occur at mat densities at any of the 60 monitoring stations. Based on energetics, large amounts of organic matter are required to maintain mat densities of *Ampelisca* spp., because of their high productivity and turnover ratio (Robertson 1979, Franz and Tanacredi 1992), and there may not have been sufficient amounts of carbon available to the amphipods. This progression of higher percentages of stations with tube mats in the 1990s and generally declining percentages from 2000 is consistent with the declining organic loading to the harbor and a lagged response of *Ampelisca* spp. As stores of organic carbon in the sediments were depleted, amphipod densities declined with the combined bioturbation activity of lower densities of *Ampelisca* spp. and deeper dwelling infauna continuing to contribute to organic matter remineralization and shifting sediments back to a more aerobic state (Aller 1994, Tucker *et al.* 2006). In 2006, tube mats were observed again at stations R21 in Nantasket Roads and R30 in Hingham Bay. Station R21 had amphipods at mat densities all years from 1993 to 2006 except 2005. Station R30 had mats all years except three.

As seen in Table 3-1, it appears that regionally within Boston Harbor, it appears that from 1993 to 2006 sedimentary habitat conditions as measured by SPI did not change appreciably. Throughout this period, stations in Nantasket Roads, Hingham Bay, Deer Island Flats, and off Long Island tended to be sandier than stations in Dorchester Bay, Quincy Bay, or Charles River.

The relatively constant sediment types suggest that causes other than sediment transport and deposition are implicated in the substantive changes observed in other parameters monitored using SPI. As mentioned previously, the most obvious changes were related to amphipod mats as previously described, but there was also a long-term increase in what appeared to be reddish-brown geochemically oxidized sediments (Jørgensen and Revsbech 1985), thickness of the apparent color RPD layer (aRPD) in SPI, which would be consistent with reductions in organic loading and/or increases in bioturbation. Secondary succesional species like *Ampelisca* spp. render sediments inhabitable by mature succesional species such as deep-dwelling maldanid polychaetes by burning off excess organic matter. The increase in aRPD thickness was a harbor-wide trend, even controlling for regions within the harbor and presence of *Ampelisca* spp. tube mats. The thinnest aRPD layers occurred in Dorchester Bay, which also had the stations with the poorest habitat quality. Poor habitat quality stations tended to be mud stations in Dorchester Bay (T04 and R43), which exhibited little evidence of surface or subsurface biogenic activity. Station T04 appeared to be the most highly stressed soft-bottom benthic habitat in the harbor, likely from a combination of high TOC (range of 3.1 to 8.9%) and poor water quality. This level of TOC is highly correlated with altered community structure and reduced benthic habitat quality for infauna (Pearson and Rosenberg 1978, Hyland *et al.* 2005). Infauna at station T04 consistently had the lowest community structure statistics of all stations sampled within the Harbor and was dominated by surface-dwelling spionid polychaetes (Maciolek *et al.* 2006, this report). Conversely, Stations T03 along the western side of Long Island consistently had good benthic habitat quality and infaunal communities despite the fact that it was across the channel from the Deer Island outfall and had TOC that ranged from 2.5% to 3.8% over the years sampled. This is an indication that habitat quality cannot be determined solely by the quantity of organic matter. Other factors such as quality of the organic matter (Marsh and Tenore 1990) and hydrodynamics (Nowell and Jumars 1984) may be more important determinants of benthic habitat quality.

The functioning state of a marine coastal ecosystem is dependent on a complex of biological and geochemical processes, many of which are related to the sediment, infauna, and SPI variables measured. For example, bioturbation is a primary determinant of sediment oxidation state, which in turn influences biomass, the rate of organic matter remineralization, and regeneration of nutrients (Giblin *et al.* 1997, Nowicki *et al.* 1997, Aller and Aller 1998). The magnitude and importance of bioturbation is primarily a function of biodiversity, species life histories, and abundance patterns (Diaz and Schaffner 1990, Solan *et al.* 2004). Bioturbation by larger, deeper-dwelling species found in succesionally mature communities is key to keeping organic matter from building up in the sediments through microbial gardening, which maintains a balance between flux of compounds in and out of the sediments and enhances benthic habitat quality (Yingst and Rhoads 1979). Sediment grain size and hydrodynamic processes are also important in determining the relative importance of biogenic to physical mixing processes and can modify habitat quality in either positive or negative ways.

Based on the patterns of association between the sediment, infauna, and SPI variables, a cline of relative habitat quality emerged, from lower habitat quality at station T04 to higher habitat quality at T08 (Figure 3-4). At higher levels of organic carbon, as seen at station T04, the benthic habitat appears characterized by anaerobic processes and carbon accumulation. At lower carbon levels, as seen at station T08, the benthic habitat appears more aerobic with little carbon accumulation. The tipping point between these two habitat states appears to occur between 2% to 3% TOC with the state set by processes that control bioturbation and organic accumulation rates. The improvements in wastewater treatment and moving the outfall offshore have tipped the balance back to good benthic habitats within Boston Harbor by favoring processes that enhance bioturbation rates. The exception remains portions of the inner harbor that have not had sufficient time to burn off stores of organic matter.

3.5 Conclusions

From 1992 to 2006, there is strong evidence that benthic habitats within Boston Harbor have shifted from a more anaerobic state to a more aerobic state and that these changes are directly related to changes in carbon loading associated with outfall placement and improvements in wastewater treatment. Over the period 1992–2000, when the ocean outfall started to operate, there was >90% reduction in organic loadings to Boston Harbor from 11,400 to 1,200 mt C/yr. There were also corresponding decreases in primary production due to reduced nutrient loadings

The tipping point for recovery of the benthic system appears to be when organic carbon loading rates dropped below 350–630 g C/m^2/yr, corresponding to increased development of *Ampelisca* spp. tube mats and associated deepening of the apparent RPD. The optimal organic loading rate for maintaining large areas of amphipod tube mats appears to be ca. 500 g C /m^2/yr. Above and below this rate, tube mats in Boston Harbor declined. The concept of a range of critical loading rates for organic carbon was proposed by Rhoads (1998). This paradigm was developed to predict changes in benthic community structure at the Massachusetts Bay site following outfall diversion. However, the model can also be used to evaluate benthic responses to reduction of organic loading within the harbor. The quantitative basis for the model was a review of carbon loading in experimental tanks and observations of intensive mariculture operations. The critical organic carbon loading rates quoted from these sources range from ca. 300 to 550 g C/m^2/yr with most values falling around 300 g C/m^2/yr. At or below this value, the benthos facilitate aerobic recycling of labile organic matter by deep and intensive bioturbational mixing; a natural analog to tertiary sewage treatment. Above this critical rate, sediments increasingly become storage systems of labile carbon and associated reduced metabolites overwhelming the ability of the infauna to aerobically recycle carbon. This predictive model seems to be supported by long-term monitoring observations and lends support to the assertion that one of the most sensitive indicators of the critical loading rate is widespread and dense aggregations of *Ampelisca* spp.

4. 2006 SOFT-BOTTOM INFAUNAL COMMUNITIES

by Nancy J. Maciolek

4.1 Introduction

Nine stations in Boston Harbor were sampled in August 2006 for soft-bottom benthic infauna. Seven of these stations have been sampled consistently since September 1991; the eighth, T05A, replaced T05 in 1993. A ninth station, C019, was added in 2004 to monitor changes that may occur during upgrading of the combined sewer overflow (CSO) system. Station locations are indicated in Figure 2-1 (Chapter 2, this report).

In the early years of sampling in Boston Harbor, stations in the northern part of the harbor, particularly those near Deer Island flats, were characterized as polluted, with low species richness, diversity, and evenness (Blake and Maciolek 1990, Maciolek *et al.* 2004). Stations in the southern harbor, *i.e.*, Quincy, Hingham, and Hull Bays, were noticeably different, with a richer, more diverse fauna. As changes in terms of the character and amount of sewage dumped into the harbor have been implemented, the stations in the northern part of the harbor have exhibited more changes in the number of species and diversity of the benthic fauna than have the stations in the southern part.

4.2 Methods

4.2.1 Laboratory Analyses

Samples were preserved with formalin in the field (see Chapter 2), and in the laboratory were rinsed with fresh water 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. After the samples were sorted, the organisms were identified to the lowest practical taxonomic category, usually species. Voucher specimens of any species newly identified from the harbor samples were kept as part of the MWRA reference collection.

4.2.2 Data Analysis

Preliminary Data Treatment—Prior to performing any analyses, several modifications were made to the database (Appendix C1). These modifications were generally similar to those performed in previous years as given in the standard operating procedure (SOP) for this project (Williams *et al.* 2005). 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, cluster and principle components analysis) included only those taxa identified to species level, or those treated as such (see Appendix C1).

Statistical Analysis—Initial inspection of the benthic data included production of summaries of species densities by sample, tables of species dominance, and lists 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, univariate and multivariate methods were used to assess community patterns and structure.

Univariate Measures —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.

A PRIMER routine was also used to calculate a species-area curve for the 16-year monitoring period. Gallagher’s program *rarefyl* was used to construct rarefaction curves for the same period.

Multivariate Measures —**Similarity analysis** was performed using both CNESS (chord-normalized expected species shared) (Trueblood *et al.* 1994) and the Bray-Curtis index (Bray and Curtis 1957). For the analysis of the 1991–2006 samples, replicates were pooled to one sample per year (*i.e.*, all samples from all stations pooled to one annual sample). All similarity matrices were clustered using a hierarchical agglomerative clustering technique, with group average sorting.

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 annual data and 20 for multiyear comparisons. CNESS is included in the COMPAH96 package, 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).

The Bray-Curtis similarity analyses were based on a fourth-root transformation of the data (performed in order to diminish the impact of numerically dominant species) and were carried out in PRIMER v.5 (Clarke and Gorley 2001).

The PRIMER routine ANOSIM (analysis of similarities) was used to test the null hypothesis that there are no differences in harbor communities, either within 2006 or between years. This test is based on the matrix generated by a similarity test, in this case, Bray-Curtis. Clarke and Gorley (2001) discuss the use of this test as a replacement for ANOVA, and interpretation of R values is discussed in Chapman and Underwood (1999).

Ordination techniques used to visualize distances among samples include Principal Components Analysis of hypergeometric probabilities (PCA-H) applied to the CNESS results (see Trueblood *et al.* 1994 for details), and non-metric multidimensional scaling (NMDS) applied to the Bray-Curtis results (Clarke and Gorley 2001).

The PCA-H method is a multistep analysis that produces a metric scaling of the samples in multidimensional space, as well as a Euclidean distance biplot (Gabriel 1971) of the major sources of CNESS variation, *i.e.*, the species that contribute the most to the distances among samples. These species are determined using matrix methods adapted from Greenacre's correspondence analysis (Greenacre 1984) and are plotted as vectors in the Euclidean distance biplot. PCA-H analysis was performed using MATLAB as an operating platform and programs written by Dr. E.D. Gallagher.

NMDS (Kruskal and Wish 1978, Kenkel and Orloci 1986, Clarke and Gorley 2001) also produces a two (or more)-dimensional map that demonstrates the relative distances between samples. This ordination technique is recommended over typical PCA procedures (other than PCA-H discussed above), since it is better at preserving sample distances and makes few assumptions about the nature of the data (Clarke and Gorley 2001).

4.3 Results and Discussion

4.3.1 Species Composition of 2006 Samples and 1991–2006 Taxonomic Summary

In August 2006, 132 species of benthic infauna occurred in the samples. Three species, the polychaete *Sphaerosyllis brevifrons*, the isopod *Politolana polita*, and the bivalve *Yoldia myalis* were added to the Boston Harbor database. Of these three, the first two have been recorded previously from samples taken in Massachusetts Bay, and *Y. myalis* is new to the combined Massachusetts Bay/Boston Harbor database. For the period 1991–2006, 263 identified species have been recorded in the summer samples (Appendix C2). Some species recorded in previous years have been renamed or merged based on new taxonomic work (Table 4-1)

Table 4-1. Comparison of old and new designations for species reported from the Boston Harbor samples.

Old Name	New Name	Reference
Polychaeta		
Caulleriella sp B	*Caulleriella venefica*	Doner and Blake 2006
Chaetozone sp. Mass Bay	*Chaetozone anasimus*	Doner and Blake 2006
Chaetozone sp. BH	*Chaetozone hystricus*	Doner and Blake 2006
Polygordius sp. A	*Polygordius jouinae*	Ramey *et al.* 2006
Oligochaeta		
Enchytraeidae sp. 1	*Marionina welchi* Lasserre, 1971	reevaluated by R. Winchell
Tubificidae sp. 2 & *Tubificoides* nr. *pseudogaster* Dahl, 1960	*Limnodriloides medioporus* Cook, 1969	reevaluated by R. Winchell

Ampelisca spp. Two species of *Ampelisca* are found in Boston Harbor: *A. abdita* and *A. vadorum*; the former is associated with fine sand to muddy substrates, and the latter with coarse sand (Mills 1967). Early populations of *A. vadorum* have largely been replaced by *A. abdita*, which has accounted for nearly 97% of the *Ampelisca* identified since 1995. The two species have often co-occurred at T06 and T08. In the early years of the monitoring program, the taxonomic team did not discriminate between different species of *Ampelisca*, therefore both species are combined with juveniles and otherwise unidentifiable individuals to the taxon *Ampelisca* spp. for report purposes. Maciolek *et al.* (2004a) investigated the effect of this "lumping" procedure on results obtained for diversity parameters, and concluded that there was no significant effect.

Because members of this genus are considered (by some) to be indicative of clean environments, population levels of *Ampelisca* have been considered key in following the status of the infaunal community of the harbor. Reish and Barnard (1979) found that slight increases in organic matter resulted in increased amphipod abundance, but beyond a certain level, amphipod numbers decreased. The possible relationship of *Ampelisca* abundances in Boston Harbor to carbon loading is examined in further detail in Chapter 3 (this report).

Maciolek *et al*. (2006) reported the virtual elimination of *Ampelisca* populations in the harbor in 2005, following a major peak in numbers in 2003 (Figure 4-1). While increases in ampeliscid populations in the harbor through the 1990s have been partly explained as a response to cleaner sediments, the recent decline in numbers is most likely the result of severe storms in December 2003, December 2004, and May 2005, which affected the bottom substrate, altering the sediment texture (see Chapter 3 in Maciolek *et al.* 2006) and bottom habitats. A small increase in numbers of *Ampelisca* was seen in the 2006 samples compared with 2005 (Figure 4-1), with the majority found at T03. Other species of amphipods have also been recorded in low numbers for the past two years (Tables 4-2 and 4-3). A shift from wastewater to phytoplankton-derived carbon, not all of which was available for the amphipods to directly utilize, may account for the slow recovery of amphipod populations (see Chapter 3, this report).

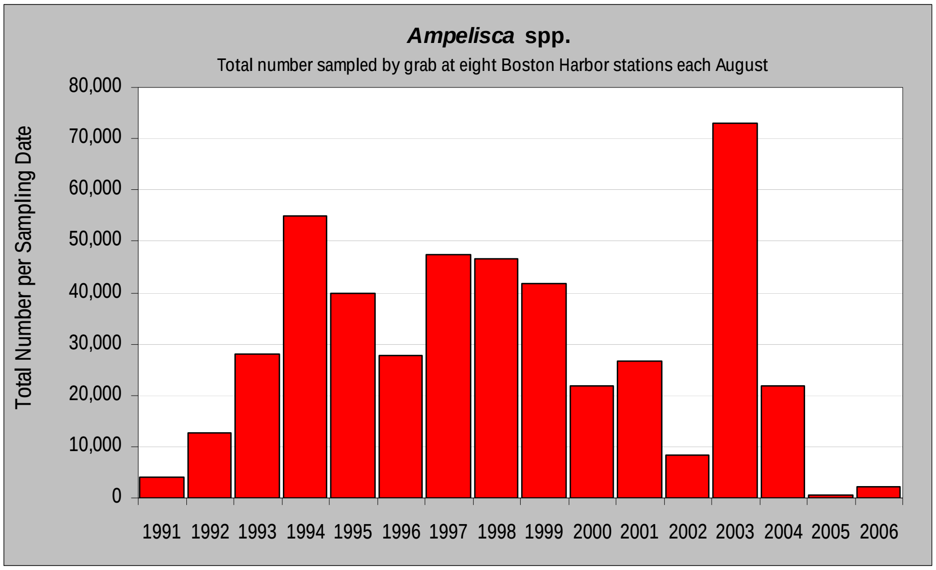


Figure 4-1. *Ampelisca* spp. at eight Boston Harbor stations.

Table 4-2. Total abundance of amphipod species present in Boston Harbor grab samples taken at eight traditional stations in August 2003–2006.

Amphipod Species	2003	2004	2005	2006
Ampelisca spp.	73,112	21,728	614	2,131
Leptocheirus pinguis	4,735	1,734	97	220
Unciola irrorata	3,841	756	18	93
Crassicorophium bonnelli	2,148	9	1	5
Photis pollex	2,108	1,677	100	219
Orchomenella minuta	1,194	1,230	21	54
Dyopedos monacanthus	1,029	1		3
Phoxocephalus holbolli	96	153		1
Microdeutopus anomalus	39	3	2	
Crassicorophium crassicorne	17	11		5
Ischyrocerus anguipes	9	2		
Pontogeneia inermis	9	1		
Jassa marmorata	2	1		
Harpinia propinqua	1			
Metopella angusta	1	3		
Ameroculodes sp. 1				8
Argissa hamatipes				6
Monocorophium acherusicum				1
Monocorophium inisdiosum				1
Totals	88,341	27,309	853	2,747

Table 4-3. Summary of amphipod population status in Boston Harbor as determined by grab sampling (see Table 4-1 for species).

Year	Amphipod Population Status
late 1970s–1980s	several stations with *Ampelisca*, other species; variable between sampling years (high organic load to harbor)
1991	Sept 91 – *Ampelisca* present (severe storms in June, October)
1992–2001	amphipod populations grow, fluctuate (TOC reduced when sludge dumping stops, no bad storms)
2002	low numbers of amphipods
2003	highest levels of *Ampelisca* and other species
2004	major decline in amphipod populations
2005	essentially no *Ampelisca* or other amphipods (major storm in May)

2006	small increase in *Ampelisca*, overall amphipod populations still an order of magnitude smaller compared with 2003.

4.3.2 Benthic Community Analysis for 2006

With the exception of total infaunal abundance at a few stations, values of all parameters were essentially the same in 2006 as in 2005. As in previous years, each station exhibited a slightly different trend.

Density, Species Richness, Diversity, and Evenness—Community parameters for the grab samples collected in 2006 at the nine harbor stations are shown in Figure 4-2 and Table 4-4. For comparison with the last sampling date, data for 2005 are included in Figure 4-2.

Density—Total abundances were significantly higher at harbor stations T01, T03, and T06, where amphipods recovered to some extent from the low numbers in 2005. Mean densities at T01 increased by a factor of three, from 802 organisms per sample in 2005 to 2306 organisms per sample in 2006; and nearly doubled at T03 and T06 (from 2844 to 4948 organisms per sample at T03 and from 1391 to 2539 organisms per sample at T06). Mean density also doubled at T04, from 650 organisms per sample in 2005 to 1213 organisms per sample in 2005, but this was the result of one of the three replicates having densities five times that of the other two, resulting in a large standard deviation around the mean (Table 4-4) and a lack of significant difference between the two years. Mean densities in 2006 were minimally higher at T07, slightly lower at T02 and C019, and essentially identical at T05A and T08 compared with those recorded in 2005.

Species Richness —The mean number of species per sample was nearly identical in 2006 as in 2005) at most stations, except T05A, where it was slightly lower, and T06 where it was higher (Figure 4-2). CO19 and T04 had the lowest species richness of all harbor stations, with 14.0±1.0 species per sample at CO19 and 14.0±6.0 at T04. Station T03 had the highest species richness, with 51.0±9.6 species per sample, an increase of 4.3 species over 2005.

Diversity —Compared with 2005 values, mean Shannon diversity declined most noticeably at T01 and T06; was slightly higher at T03, T04, and C019; and nearly identical at T02, T05A, T07, and T08 (Figure 4-2, Table 4-4). Mean Shannon diversity was lowest at CO19 (0.64±0.02) and highest at T08 (3.72±0.3), a pattern similar to that recorded in previous years. Before CO19 was sampled, T04 usually exhibited the lowest Shannon diversity among the harbor stations; in 2006, diversities calculated for T02 were actually lower than those at T04 (0.96±0.2 at T02 and 1.12±0.2 at T04; Table 4-4).

Diversity as measured by Fisher's log-series *alpha* (Figure 4-2) declined significantly at T01 compared with 2005 diversity; slightly at T02, T04, and T05A; was identical at T03, T07, and CO19; and was slightly higher at T08. Earlier station patterns were repeated in 2006: the lowest mean values were recorded at CO19 (2.37±0.20) and T04 (2.32±0.89) and the highest at T05A (8.50±1.04) and T08 (11.23±2.33).

Evenness—Evenness values in 2006 compared with 2005 were significantly lower at T01 and T06; slightly lower or identical at T02, T05A, T07 and T08; and slightly higher at T03, T04, and CO19 (Figure 4-2).

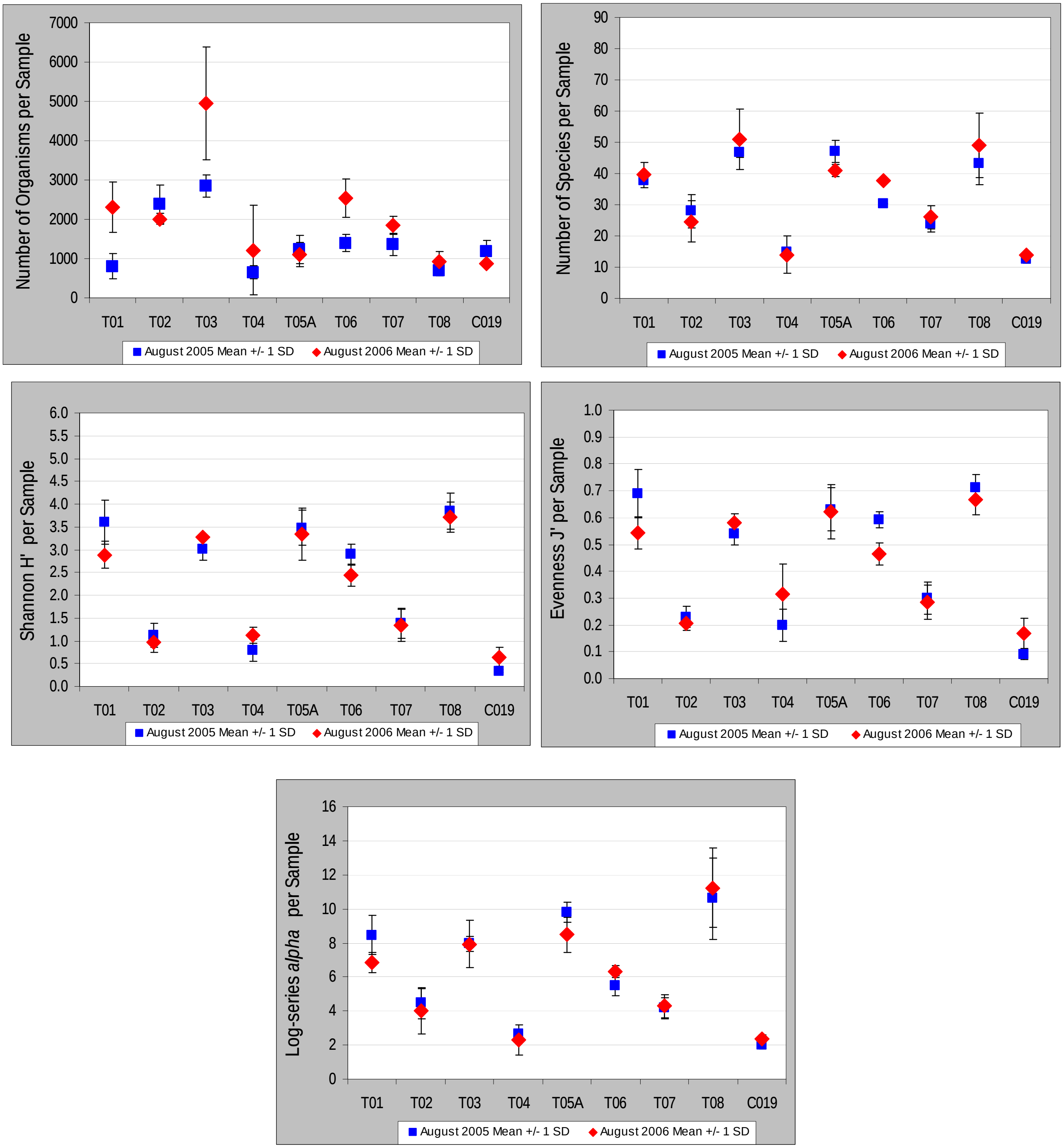


Figure 4-2. Mean ± 1SD of five benthic infaunal community parameters for the Boston Harbor stations sampled by grab in August 2006. The 2005 values are included for comparison.

Table 4-4. Benthic community parameters for samples taken at Boston Harbor traditional stations in August 2006.

Station	Replicate	Total Abundance	No. Species	H′ (base 2)	J′	Log-series *alpha*
T01	1	2556	44	2.99	0.55	7.55
	2	1587	36	3.12	0.60	6.57
	3	2777	39	2.55	0.48	6.42
	Mean ± SD	2306.7±633.0	39.7±4.0	2.89±0.3	0.54±0.06	6.85±0.61
T02	1	2136	19	0.79	0.19	2.9
	2	2029	23	0.91	0.20	3.64
	3	1872	32	1.19	0.24	5.49
	Mean ± SD	2012.3±132.8	24.7±6.7	0.96±0.2	0.21±0.03	4.00±1.34
T03	1	6433	58	3.28	0.56	8.80
	2	3542	40	3.30	0.62	6.3
	3	4871	55	3.26	0.56	8.69
	Mean ± SD	4948.7±1447.1	51.0±9.6	3.28±0.02	0.58±0.03	7.94±1.40
T04	1	2529	20	0.94	0.22	2.96
	2	522	14	1.12	0.29	2.69
	3	588	8	1.31	0.44	1.3
	Mean ± SD	1213.0±1140.2	14.0±6.0	1.12±0.2	0.32±0.11	2.32±0.89
T05A	1	896	43	3.49	0.64	9.44
	2	976	41	3.82	0.71	8.67
	3	1457	39	2.71	0.51	7.39
	Mean ± SD	1109.7±303.4	41.0±2.0	3.34±0.6	0.62±0.10	8.50±1.04
T06	1	2034	38	2.66	0.51	6.6
	2	2563	38	2.42	0.46	6.33
	3	3020	37	2.21	0.42	5.94
	Mean ± SD	2539.0±493.4	37.7±0.6	2.43±0.2	0.46±0.04	6.31±0.35
T07	1	1884	30	1.68	0.34	5.07
	2	1607	23	0.97	0.22	3.8
	3	2067	25	1.37	0.30	4.00
	Mean ± SD	1852.7±231.6	26.0±3.6	1.34±0.4	0.28±0.06	4.29±0.68
T08	1	1131	61	3.93	0.66	13.88
	2	613	42	3.90	0.72	10.25
	3	993	44	3.34	0.61	9.5
	Mean ± SD	912.3±268.3	49.0±6.0	3.72±0.3	0.67±0.06	11.23±2.33
CO19	1	847	13	0.81	0.22	2.19
	2	874	15	0.71	0.18	2.58
	3	912	14	0.40	0.11	2.3
	Mean ± SD	877.7±32.6	14.0±1.0	0.64±0.2	0.17±0.06	2.37±0.20

Dominant Species **—**The numerically dominant species and their percent contribution to the fauna at each harbor station in August 2006 are given in Appendix C3. As discussed above, the density of *Ampelisca* spp. had declined significantly in 2005 compared with 2003 and 2004, and had not recovered in 2006. However, in 2005 and again in 2006, this taxon was recorded among the numerically common species at several stations, although it was not the numerical dominant at any station. At most stations where it did occur, it accounted for less than 1 % of the fauna (*e.g*., 0.3% at T07, 0.5% at T01 and T06, and 0.7% at T02). It was most numerous at T03, where mean densities were 617 ±202.2 per sample, and the taxon contributed 12.5% of the infauna.

For the third consecutive year, the polychaete species, *Nephtys cornuta*, a small jawed omnivore, was a numerical dominant at several stations. In 2006, it was present in densities far exceeding those recorded in 2004 and 2005 (Figure 4-3, Table 4-5). It accounted for as much as 90% of the fauna at CO19 and was the numerical dominant at T01 (ca. 39%), T02 (ca. 87%), T06 (ca. 51%) and T07 (ca.78%). At all of these stations, its abundance and proportion of the fauna increased compared with previous years. In addition, *N. cornuta* was found in large numbers in one of the three replicates at T04, resulting in it accounting for ca. 12% of the organisms and being the second-most numerous species at that station in 2006. Overall, in 2006, it accounted for 37.8% of the organisms collected in the harbor. Although this is a small-bodied species, the animals found in these samples were not juveniles and included sexually mature specimens (R.E. Ruff and T. Morris, project taxonomists, pers. comm. October 2006). The population irruption of this species coincided with the decline of the large amphipod populations in 2004, and it is likely that it is fueled by the detrital remnants of the crustaceans and/or other organisms exposed by the storms in subsequent seasons. It is possible that it is feeding on *Streblospio* at T04 (see paragraph below), having intruded into that part of the harbor. It is likely that the *N. cornuta* population will soon crash throughout the harbor, as resource items are consumed to the point that the numbers cannot be sustained.

The community at T04 remained less species rich compared with the infauna at all other traditional stations in August 2006, as in most previous years. The overwhelming numerical dominant was *Streblospio benedicti* (72.0% of the fauna), although it was found in widely varying densities in the three replicates (2145, 391, and 85 specimens, respectively), as was *Nephtys cornuta* (7, 2, and 431 specimens, respectively).

Station CO19, although sampled in 2004 for the first time in this program, had been sampled in 1989 as part of the Sediment-Water Exchange (SWEX) study (Gallagher and Keay 1998). At that time, 94–96 % of the fauna was comprised of *Streblospio benedicti* and a cirratulid identified as *Chaetozone setosa*; only a few individuals of four additional taxa were identified from the samples (oligochaetes, *Polydora* sp., *Mya arenaria*, and *Pectinaria gouldii*). In 2006, as in 2004 and 2005, the fauna at this station was overwhelmingly dominated by *Nephtys cornuta* (89.7%), although 20 additional taxa were also found there (an increase of two taxa over 2005). *Polydora cornuta* accounted for 4%, and *Tharyx* spp. for 0.2% of the organisms at CO19 in 2006, but *Streblospio benedicti, Mya arenaria*, and *Pectinaria gouldii* were not recorded from that station.

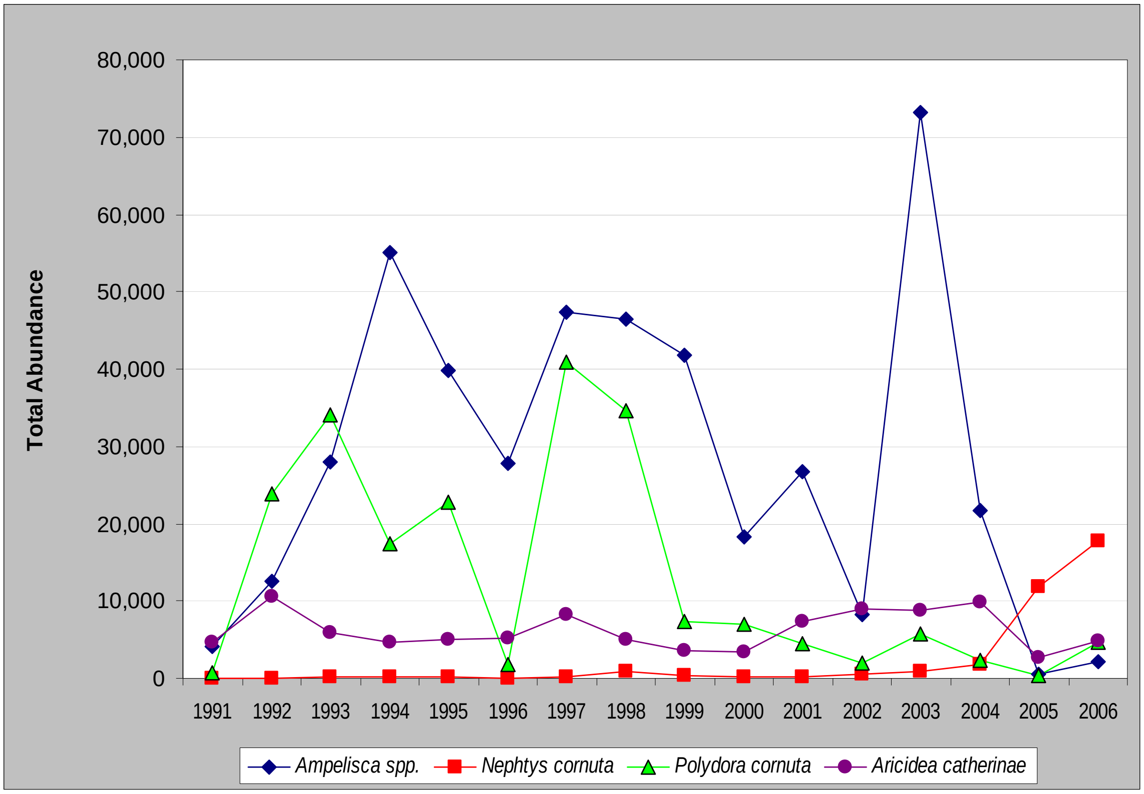


Figure 4-3. Total densities of four common species at Boston Harbor traditional stations.

Table 4-5. Total annual abundance of *Nephtys cornuta* at eight stations in Boston Harbor.

Year	*Nephtys cornuta* (total individuals)
1991	0
1992	0
1993	258
1994	221
1995	112
1996	12
1997	99
1998	936
1999	321
2000	188
2001	215
2002	573
2003	910
2004	1838
2005	11,825
2006	17,670

4.3.3 Multivariate Community Analysis of the 2006 Data

Similarity and Ordination Analysis with CNESS—The CNESS analysis of the 27 samples taken at nine stations in August 2006 showed high within-station similarity, with all replicates from a station clustering together before joining replicates from any other station Figure 4-4). Within-station similarity was highest at T03 and T06, and lowest within T04, where one replicate differed considerably from the other two. That sample (replicate 3) contained 431 individuals of the small polychaete *Nephtys cornuta*, whereas the other two replicates had only seven and two individuals, respectively, of that species.

The high number of *N. cornuta* in that single replicate is most likely also the reason that, for the first time, T04 was not the most dissimilar station. Cluster group 3, which includes T05A and T08, joined the remaining samples at a slightly lower level of similarity than T04. All six replicates of T05A and T08 also had very few *N. cornuta* (mean of 2.3 and 1.3 individuals per sample, respectively), whereas all other samples had hundreds or thousands of specimens.

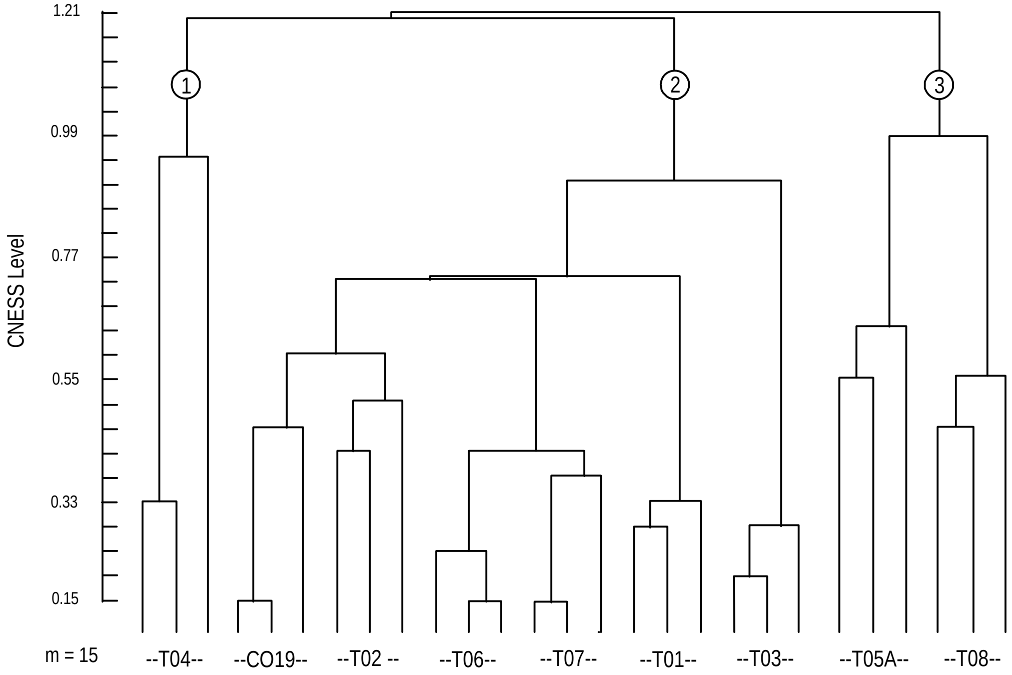


Figure 4-4. Cluster dendrogram of the 27 samples collected at the eight Boston Harbor traditional stations and C019 in 2006; based on CNESS similarity with *m* set at 15 and group average sorting.

PCA-H Analysis—The metric scaling of the 2006 samples on the first two PCA-H axes, which accounted for 57% of the CNESS variation in the communities, is shown in Figure 4-5. The clear separation along axis 2 of the two of the T04 samples is apparent in this diagram; these two samples lacked the high numbers of *Nephtys cornuta*. Axis 2 likely represents carbon loading and perhaps sediment grain size. The high similarity of stations T05A and T08, which lacked *N. cornuta*, the dissimilarity of T03, where the highest numbers of *Ampelisca* spp. were found, and the grouping of the remaining stations as indicated by the CNESS analysis are also apparent. Stations other than T04 separated along axis 1, which most likely reflect some measure of sediment texture.

The next step of the PCA-H analysis indicated which of the 132 species in the samples were responsible for the relationships among samples as reflected in the metric scaling. With CNESS (*m*=15), 11 species contributed 2% or more of the total variation on PCA-H axes 1, 2, and 3 (Table 4-6). The Gabriel Euclidean distance biplots for axes 1 v. 2, 1 v. 3, and 2 v. 3 (Figure 4-6) show those species superimposed over the metric scaling of the stations.

The polychaete *Nephtys cornuta,* which had not been especially abundant in the harbor before 2004 (see Table 4-5), was identified by the PCA-H analysis as the most important species in structuring the fauna in 2006 (Table 4-6), as it was in the two previous years. In particular, *N. cornuta* influenced the CNESS distances of one replicate from T04. The polychaete *Streblospio benedicti* distinguished the remaining two T04 samples from the other stations. The polychaete *Spiophanes bombyx*, typically found in sandy environments from shallow to continental shelf depths, was responsible for differentiating T05A and T08 from the remaining stations.

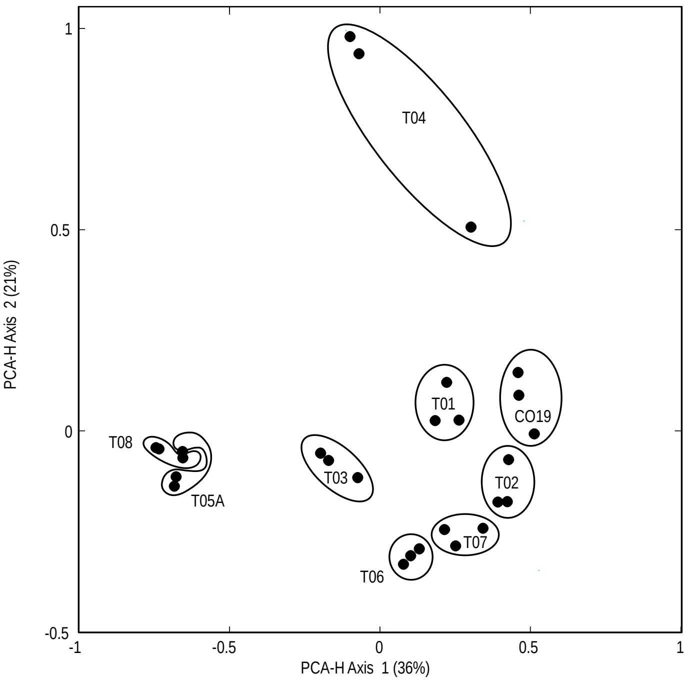


Figure 4-5. Metric scaling of the 2006 Boston Harbor samples, axis 1 v. axis 2, based on CNESS *m* set at 15.

Table 4-6. Contributions to PCA-H axes by species accounting for at least 2% of the CNESS variation among the infaunal samples collected in Boston Harbor 2006 (see Figure 4-6).

Important species: Axis 1 vs. 2

PCA-H Rank	Species	Contr.[a]	Total Contr.	Axis 1	Axis 2
1	*Nephtys cornuta*	37	37	53	9
2	*Streblospio benedicti*	13	50	0	36
3	*Spiophanes bombyx*	13	63	20	1
4	*Tubificoides apectinatus*	7	71	3	15
5	*Limnodriloides medioporus*	6	76	0	15
6	*Tubificoides* sp. 2	5	81	0	13
7	*Polydora cornuta*	4	85	3	5

Important species: Axis 1 vs. 3

PCA-H Rank	Species	Contr.[a]	Total Contr.	Axis 1	Axis 3
1	*Nephtys cornuta*	42	42	53	4
2	*Spiophanes bombyx*	18	59	20	10
3	*Polydora cornuta*	7	67	3	21
4	*Tubificoides apectinatus*	7	74	3	20
5	*Aricidea catherinae*	5	78	3	11
6	*Ampelisca* spp.	4	82	2	8
7	*Exogone hebes*	3	85	2	7

Important species: Axis 2 vs. 3

PCA-H Rank	Species	Contr.[a]	Total Contr.	Axis 2	Axis 3
1	*Streblospio benedicti*	23	23	36	0
2	*Tubificoides apectinatus*	16	40	15	20
3	*Polydora cornuta*	11	50	5	21
4	*Limnodriloides medioporus*	10	60	15	0
5	*Tubificoides* sp. 2	9	69	13	0
6	*Nephtys cornuta*	8	77	9	4
7	*Aricidea catherinae*	4	81	1	11
8	*Spiophanes bombyx*	4	85	1	10
9	*Tharyx* spp.	3	88	2	6
10	*Ampelisca* spp.	3	92	1	8
11	*Exogone hebes*	2	94	0	7

[a] Percent contributions are rounded up to the nearest whole number by the computer program.

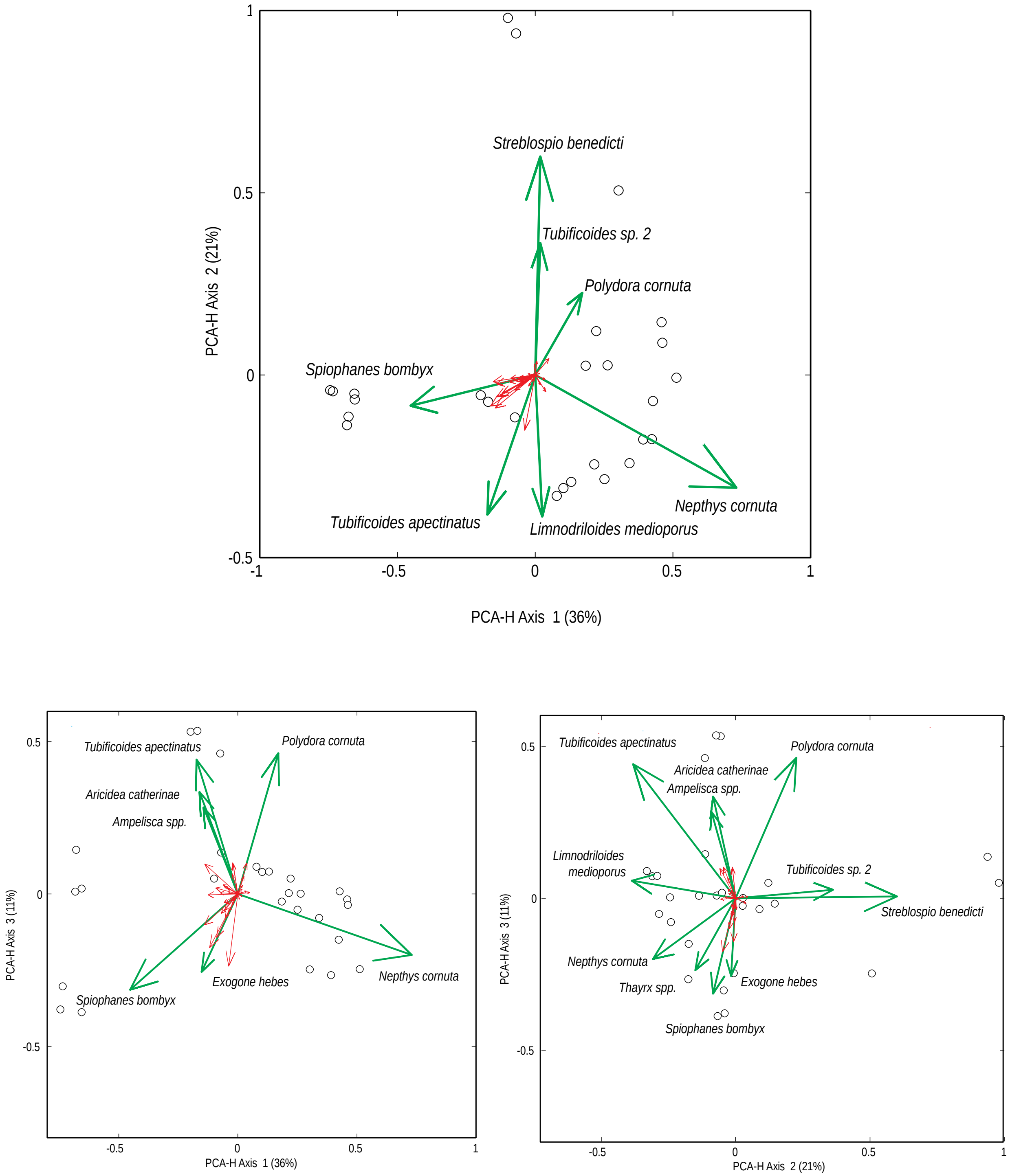


Figure 4-6. Gabriel Euclidean distance biplots of the 2006 Boston Harbor samples based on CNESS *m* set at 15. Species that account for at least 2% of the variation are labeled (see Table 4-6).

***Similarity and Ordination Analysis with Bray-Curtis*—**Figure 4-7 shows the results of a similarity analysis using the Bray-Curtis algorithm, after a fourth-root transformation of the data. This data transformation compensates for the overwhelming numbers of *N. cornuta* in most of the 2006 samples, resulting in a pattern that differs from the CNESS evaluation presented above.

As with CNESS, within-station similarity is very high, with the exception of one replicate from T07 that joins a group of samples including T02 and T07 (rather than being similar only to other replicates from T07, as in 2005 (Maciolek *et al.* 2006c)). However, T04 has very low similarity to the remaining stations, as has been seen in previous years. Three main groups can be identified from the dendrogram, as follows:

Cluster 1. T04
Cluster 2. CO19
Cluster 3. subgroup a: T05A and T08
subgroup b: T01, T06, T03 and T02, T07

These groups differ from those seen for the 2005 data in that T02 and T07 are less similar to CO19, and more similar to T01, T03 and T06 than in 2005, and T08 clusters with T05A rather than by itself.

Ordination of these samples by non-metric multidimensional scaling (NMDS) is shown in Figure 4-8. The low stress level (0.09) indicates that this sample map is a good representation of the multidimensional space occupied by the 27 samples, and indicates relative distances better than portrayed by the dendrogram. Thus, the three replicates from T04, while forming a unique station cluster, are seen to differ from (have low similarity with) each other; the two stations forming cluster 3a (T05A and T08) form two unique station groups; and the replicates from T06 have greater similarity to each other than do replicates within other station groups.

The ANOSIM statistic was applied to test the null hypothesis that there is no significant difference between stations. The resultant statistic (global R) was R= 0.92 with a significance level of 0.1%. An R value of 1 indicates that all replicates within a site are more similar to each other that to any replicates from different sites. The result of this test suggests that there are significant differences among stations, but does not indicate which ones. The test was repeated using selected stations pairs (CO19 v. T01, T02 v. T07, T05A v. T08, T03 v. T05, T01 v. T06, and T01 v. T08). For four of these five tests, the global R=1, indicating highly significant differences between stations (significance level = 10%). For the comparison of similarities between T02 and T07, R= 0.741, which was also significant at the 10% level. Thus, as was found for a similar analysis with the 2005 data (Maciolek *et al*., 2006c), each site within the harbor can be considered to be significantly different from the others.

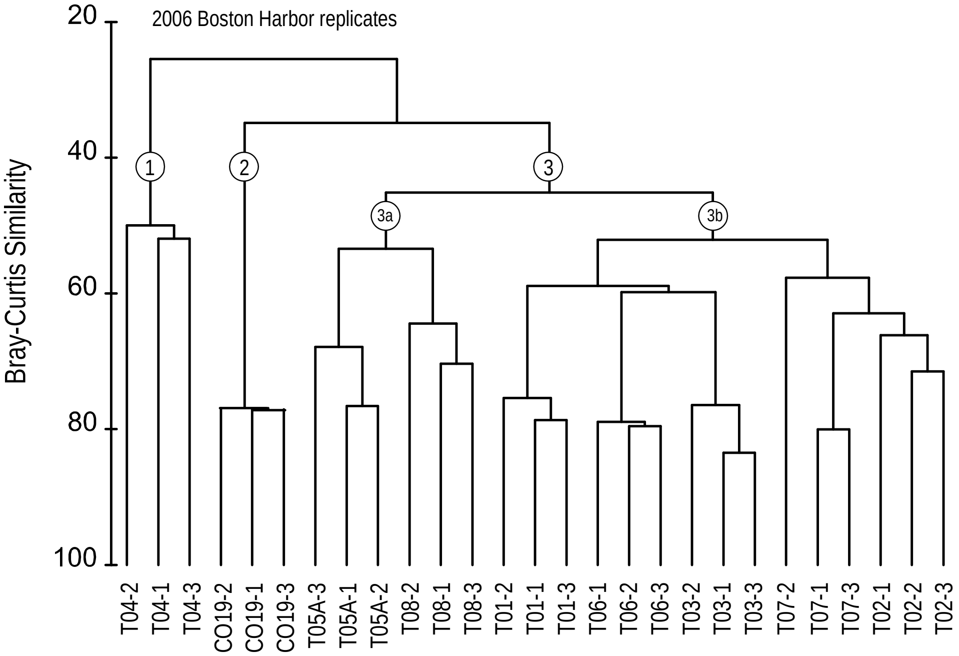


Figure 4-7. Cluster dendrogram of the 27 samples collected in 2006 at nine Boston Harbor stations. The analysis is based on a fourth-root transformation of the data, Bray-Curtis similarity, and group average sorting.

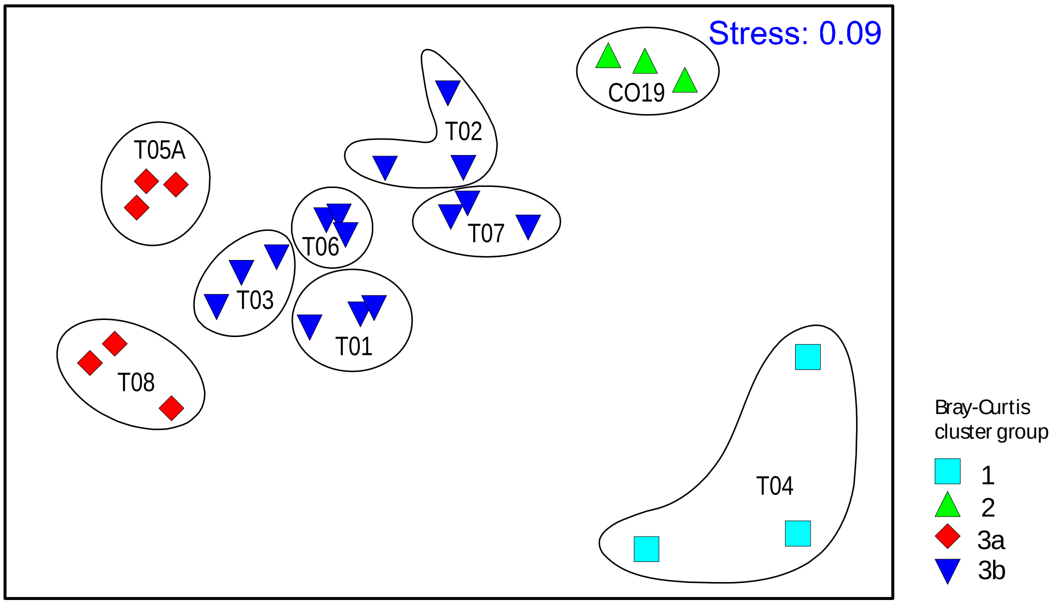


Figure 4-8. NMDS diagram of the 2006 clusters, derived from the similarity matrix based on a fourth-root transformation of the data, Bray-Curtis similarity, and group average sorting.

4.3.4 Long-term Monitoring (1991–2006): Annual Harborwide Changes

Monitoring at eight harbor stations has now continued for 16 years, during which time the pollutant load to the harbor has been significantly reduced. Additionally, severe weather events, including spring and winter nor'easters and heavy rainfalls have impacted the harbor. These factors are integrated by the benthic populations, and, combined with the natural expansion and reduction of biological populations, have resulted in the community patterns that have been recorded to date.

Parameters calculated for each replicate and then averaged for each year are shown in Figure 4-9. In general, all parameters except abundance trended upward over time, particularly after the diversion of the outfall offshore in 2000, suggesting an increase in diversity throughout the harbor. This trend continued through 2004, when it was reversed after the major storms that impacted the harbor and the concomitant loss of the dense populations of ampeliscid amphipods. In 2005, all parameters showed a significant decline compared with previous years, and values in 2006 were essentially identical to those recorded for 2005.

The Shannon diversity index H′ ranged from a low of 2.11 in 1992 to a high of 3.00 in 2004 (Figure 4-9), with the 2006 value of 2.39 being the fifth lowest of the 16 years. Although the SE around each mean suggests that these values may not all be significantly different from each other, mean values were higher in years after the outfall diversion (2000) compared with earlier ones, suggesting higher species diversity after the diversion. The typical range of this index is from 1.5 to 3.5 (Magurran 1988), and it is unlikely that changes in H′ will provide detailed insight into trends over time for averaged harbor stations. The associated evenness index, J′, was lower in the early years of monitoring, indicating higher dominance by fewer species during those years (Figure 4-9).

The average number of species per sample, the most direct measure of species richness, ranged from 18.4 in 1991 to 50.9 in 2003, with a subsequent drop to 34.0 in 2005 (Figure 4-9). This value rose slightly to 35.4 in 2006. The years 1992–2002 evidenced few real changes in this measure, with a low of 29.0 in 1996 and a high of 40.8 in 1998 and an average of 34.3 species per sample for the period. Log-series *alpha* exhibited the strongest upward trend over time, from low values in the early 1990s to higher values in recent years, with 2003 and 2004 in particular having higher mean values than in all previous years (Figure 4-9). The subsequent drop in 2005 was not reversed on 2006, when the mean value (6.43) was only slightly higher than that recorded in 1998 (6.31).

In order to examine the overall change in harbor benthic communities, samples were pooled to one sample per year (*i.e.*, all samples from all stations were pooled to one annual harbor-wide sample, resulting in 16 harbor samples) to examine harbor-wide averages. The analyses of these pooled samples included data from T05 rather than T05A for 1991 and 1992; these samples were included to provide an equal number of samples in each year before pooling. In addition, in order to have three samples for each year, the missing replicate from T03, 2000, was constructed by taking the average of the other two replicates. Pooling across stations is probably not entirely valid because of the wide differences among stations in terms of sediment type and environmental conditions (*e.g.*, water circulation patterns, depth, etc.). However, because differences were seen at individual stations, both in terms of infaunal community structure, SPI, and sediment characteristics, averaged annual differences were investigated in order to determine if there were any apparent annual patterns as well. As discussed below, some analyses were more informative than others.

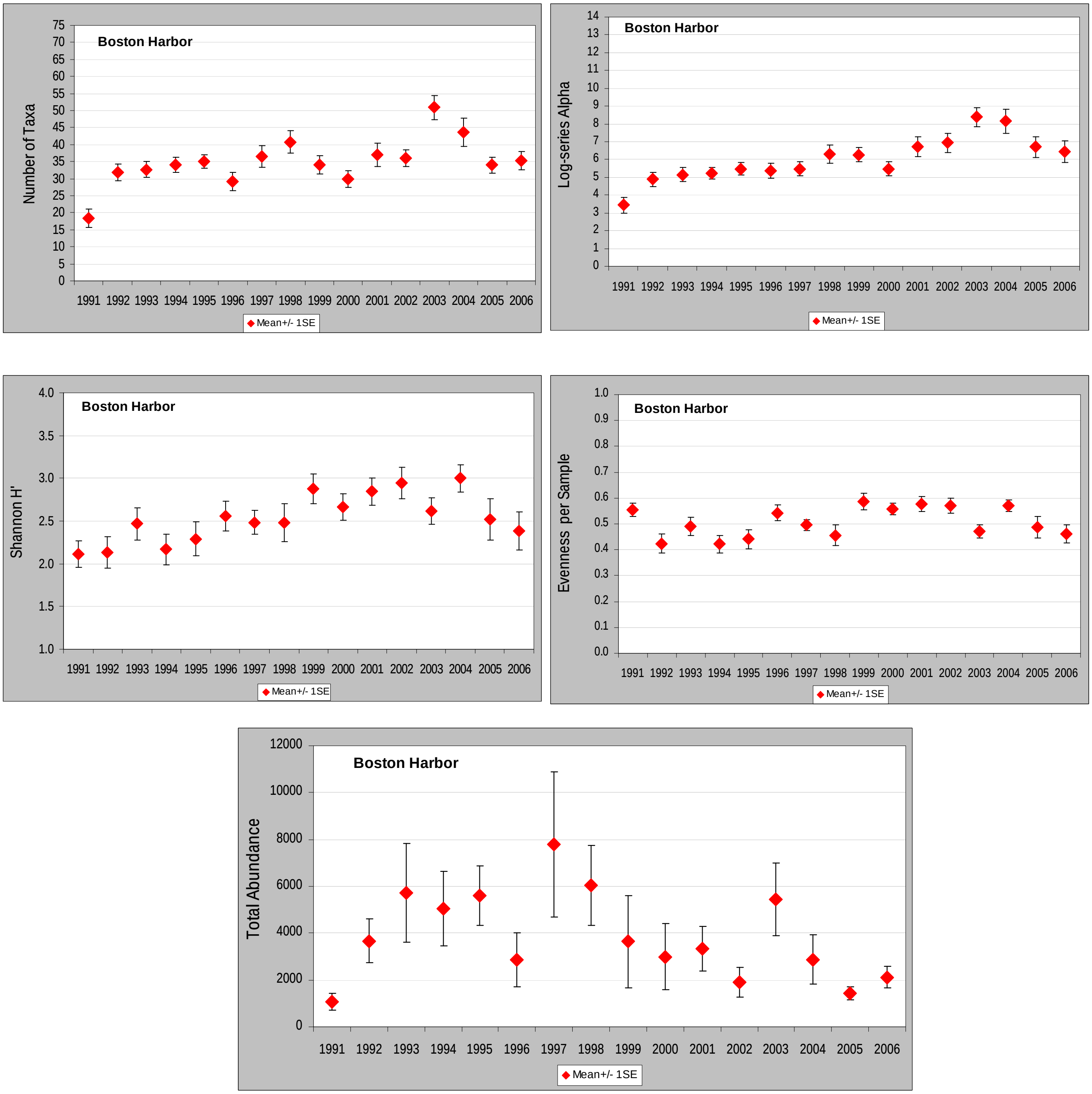


Figure 4-9. Benthic community parameters for Boston Harbor stations for each August (or September) sampling event from 1991–2006.

***Rarefaction Analysis*—** Rarefaction analysis is essentially a measure of species richness, with loss of information about the relative abundances of each species (Magurran 1988). However, it is useful as a way to compare the overall diversity in the harbor for each year of the sampling program. The results indicate an increase in diversity since the early 1990s, with a clear increase after 1991, when sludge was no longer dumped into the harbor, and after 2000, when the discharge was routed offshore (Figure 4-10). The curve for 2004 (Figure 4-10) is the highest reported to date; diversity as measured by this method was slightly lower in 2006 than in 2005, but still higher than the curves for 1991–2003.

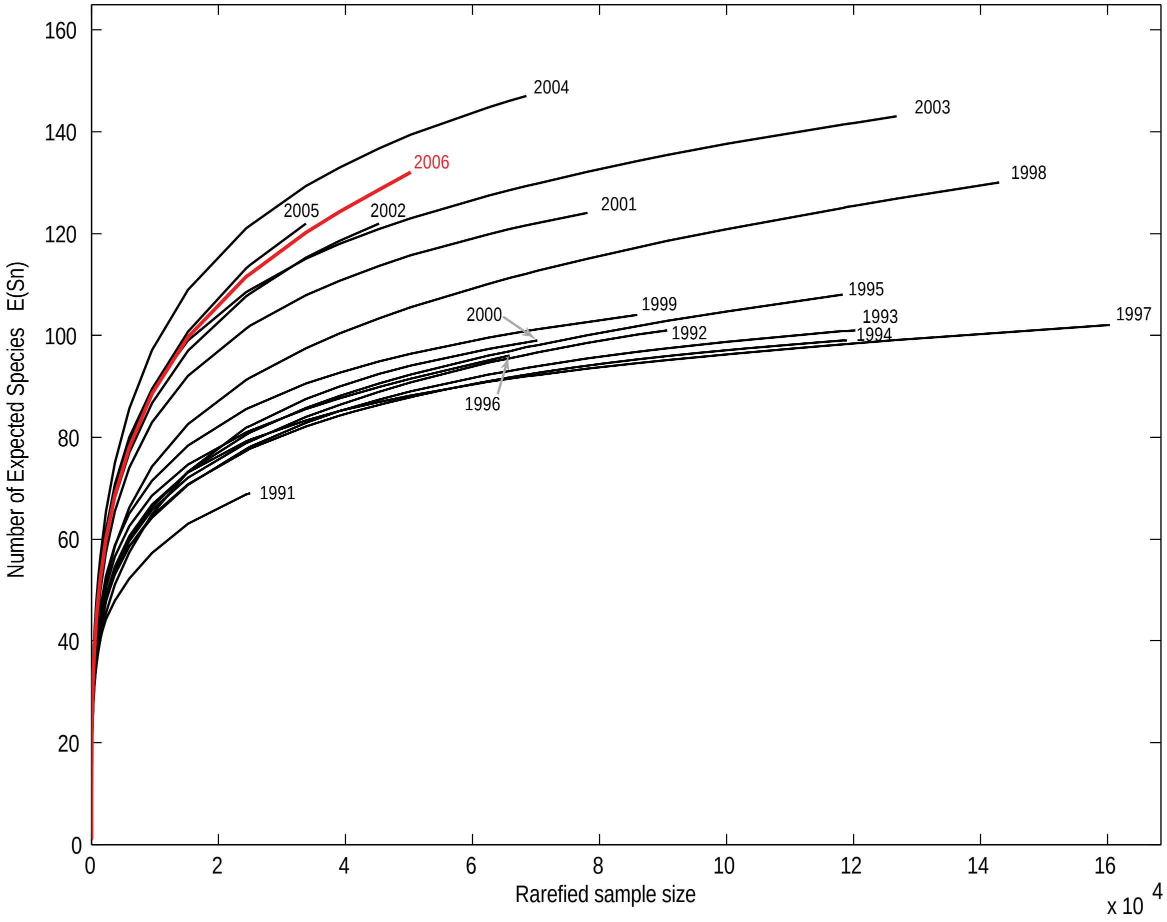
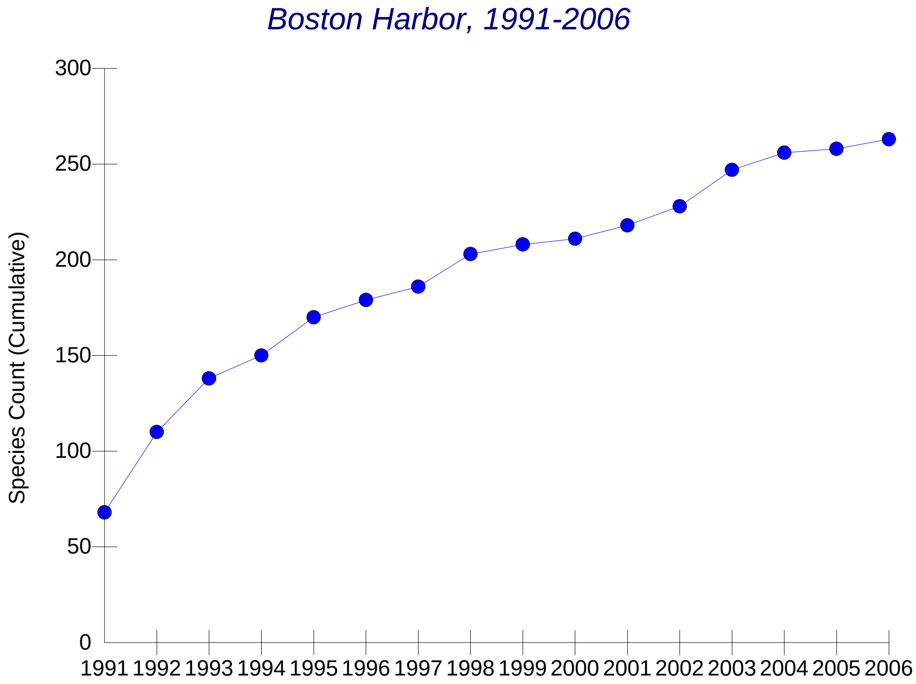


Figure 4-10. Rarefaction curves for August samples taken in Boston Harbor each year from 1991 through 2006; all samples pooled within each year.

Species–Area Curve**—**The species-area curve (Figure 4-11) indicates the accumulation of new species as samples (and therefore area sampled) are added each year. The slope of the curve is steeper in the very early years of the program, with other smaller "spurts" in 1995, 1998, and 2003. New species are added each year, with the steepest increases corresponding to major cleanup events (see Introduction) and to recovery from winter storms.



Year	No. Species
1991	68
1992	110
1993	138
1994	150
1995	170
1996	179
1997	186
1998	203
1999	208
2000	211
2001	218
2002	228
2003	247
2004	256
2005	258
2006	263

Figure 4-11. Cumulative plot of the number of different species recorded in Boston Harbor as each year's samples are added, from 1991 through 2006.

Similarity and Ordination Analysis with CNESS—The dendrogram based on the CNESS similarity analysis indicated four major groups or clusters of annual samples (Figure 4-12). The highest possible CNESS dissimilarity value is √2 (1.41) (Trueblood *et al.*, 1994), therefore many years can be considered fairly similar to one another. However, using a criterion level of 0.60, four groups can be distinguished. A group (labeled '4' in the diagram) that includes 2005 and 2006 has the lowest similarity to the remaining years (Figure 4-12). The rest of the dendrogram is identical to that presented last year (Maciolek *et al.* 2006c): cluster group 1 includes years 1992–1998 (except 1996), group 2 comprises only 1991, and group 3 includes 1996 plus 1999–2004.

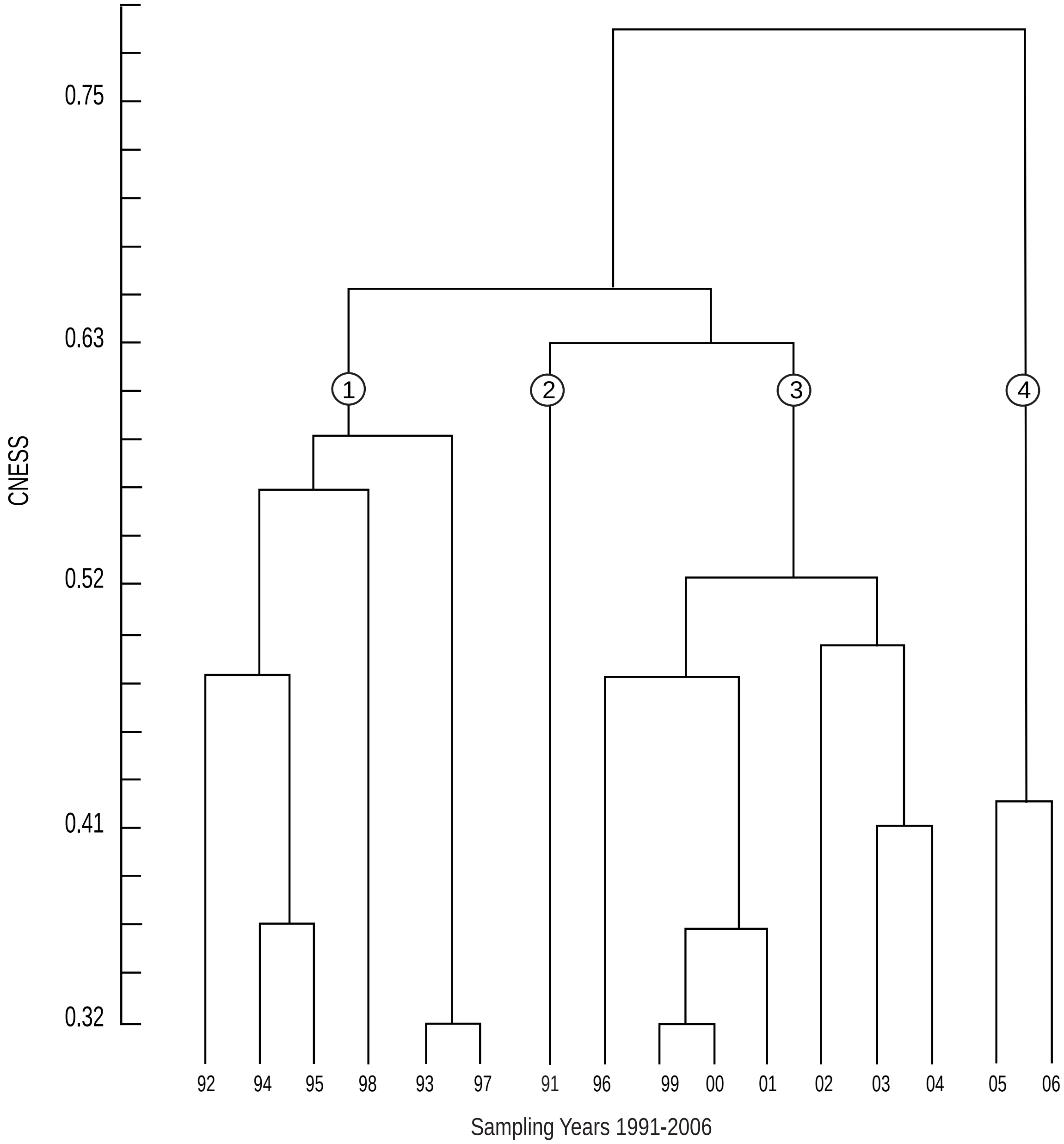


Figure 4-12. Cluster diagram for Boston Harbor 1991–2006 infauna. The lower the CNESS number, the more similar the years. CNESS *m* = 20 and group average sorting were used. 263 taxa and 16 pooled annual samples were included.

PCA-H Analysis—The metric scaling of the 16 annual samples on the first two PCA-H axes accounted for 56% of the CNESS variation (Figure 4-13). The contribution of species to the PCA-H axes (Table 4-7) indicated that three species in particular influenced the metric scaling of the samples: the polychaetes *Nephtys cornuta* and *Streblospio benedicti* and the oligochaete *Tubificoides apectinatus*. In 2006, *N. cornuta* accounted for 11% of the total variation, whereas in 2005 it represented 7% (Maciolek *et al*. 2006c); its increased importance is due to the larger numbers found at several stations in 2006. Although *S. benedicti* continues to be found in high numbers at T04, it was also common at other stations (*e.g.*, T01, T02, T07) during the early years of monitoring. In both 2005 and 2006, it accounted for 10% of the variation. The oligochaete *T. apectinatus* was slightly less important in 2006 than in 2005, with a contribution of 10% in 2006 compared with 11% in 2005.The Gabriel Euclidean distance biplot (Figure 4-14) shows these species superimposed over the metric scaling of the stations. With CNESS (*m*=20), 12 species contributed 2% or more of the total variation on PCA-H axes 1 and 2 (Table 4-8).

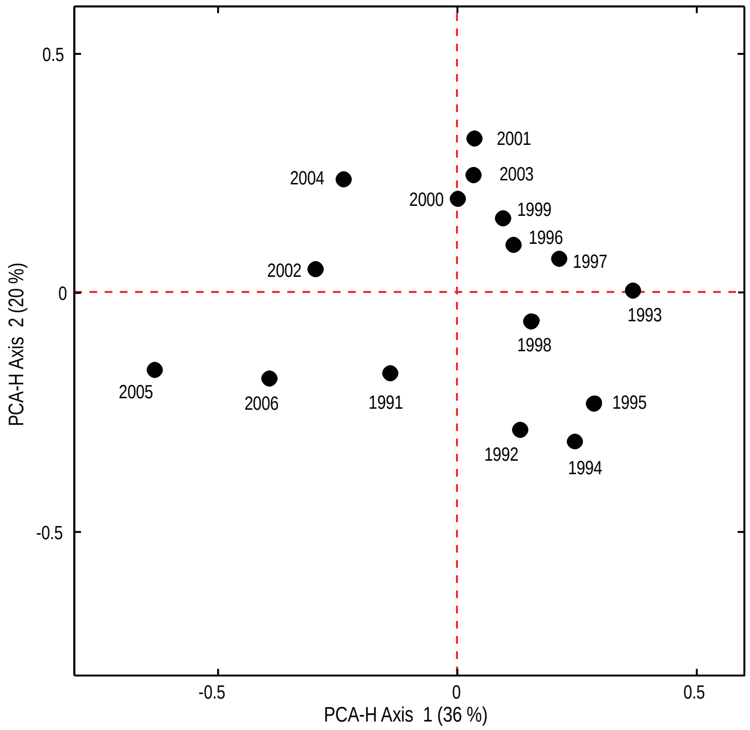


Figure 4-13. Metric scaling of 16 pooled samples taken in Boston Harbor from September 1991 through August 2006.

Table 4-7. Important species, their relative and cumulative contributions to PCA-H axes 1–7 of the metric scaling of CNESS distances of Boston Harbor samples within each year (see Figure 4-13).

PCA-H Rank	Species	% Contr.[a]	Cum. Contr.	Ax.1	Ax.2	Ax.3	Ax.4	Ax.5	Ax.6	Ax.7
1	*Nephtys cornuta*	11	11	21	2	14	7	2	8	0
2	*Tubificoides apectinatus*	10	21	19	14	0	0	2	3	2
3	*Streblospio benedicti*	10	31	0	45	0	4	0	1	0
4	*Crassicorophium bonelli*	9	40	7	2	35	5	14	2	15
5	*Polydora cornuta*	7	46	11	1	2	17	5	2	6
6	*Phoxocephalus holbolli*	6	52	5	4	8	0	10	32	2
7	*Leptocheirus pinguis*	5	57	3	5	1	5	33	5	5
8	*Capitella capitata* complex	5	63	1	2	5	35	2	6	25
9	*Ampelisca* spp.	5	67	7	3	3	0	1	9	8
10	*Unciola irrorata*	4	71	6	4	4	1	0	0	1
11	*Prionospio steenstrupi*	3	74	5	0	2	0	0	0	0
12	*Chaetozone vivipara*	3	77	2	3	2	0	3	1	20
13	*Limnodriloides medioporus*	2	80	1	0	10	2	2	1	0
14	*Photis pollex*	2	82	1	5	1	7	3	0	1
15	*Aricidea catherinae*	2	84	2	0	1	7	1	5	2
16	*Spio thulini*	2	86	2	0	0	1	7	5	2
17	*Tharyx* sp. B	2	88	1	0	0	1	1	5	0
18	*Orchomenella minuta*	2	90	0	5	0	0	1	0	0
19	*Nucula delphinodonta*	1	91	0	1	1	1	2	5	0
20	*Phyllodoce mucosa*	1	92	0	1	0	0	2	1	0
21	*Nephtys ciliata*	1	93	2	0	1	0	0	0	0
22	*Polygordius jouinae*	1	93	0	0	2	1	0	1	0
23	*Microphthalmus pettiboneae*	1	94	0	0	2	0	1	0	1
24	*Pholoe minuta/tecta*	1	95	1	0	1	1	0	1	0

[a] Percent contributions are rounded up to the nearest whole number by the computer program.

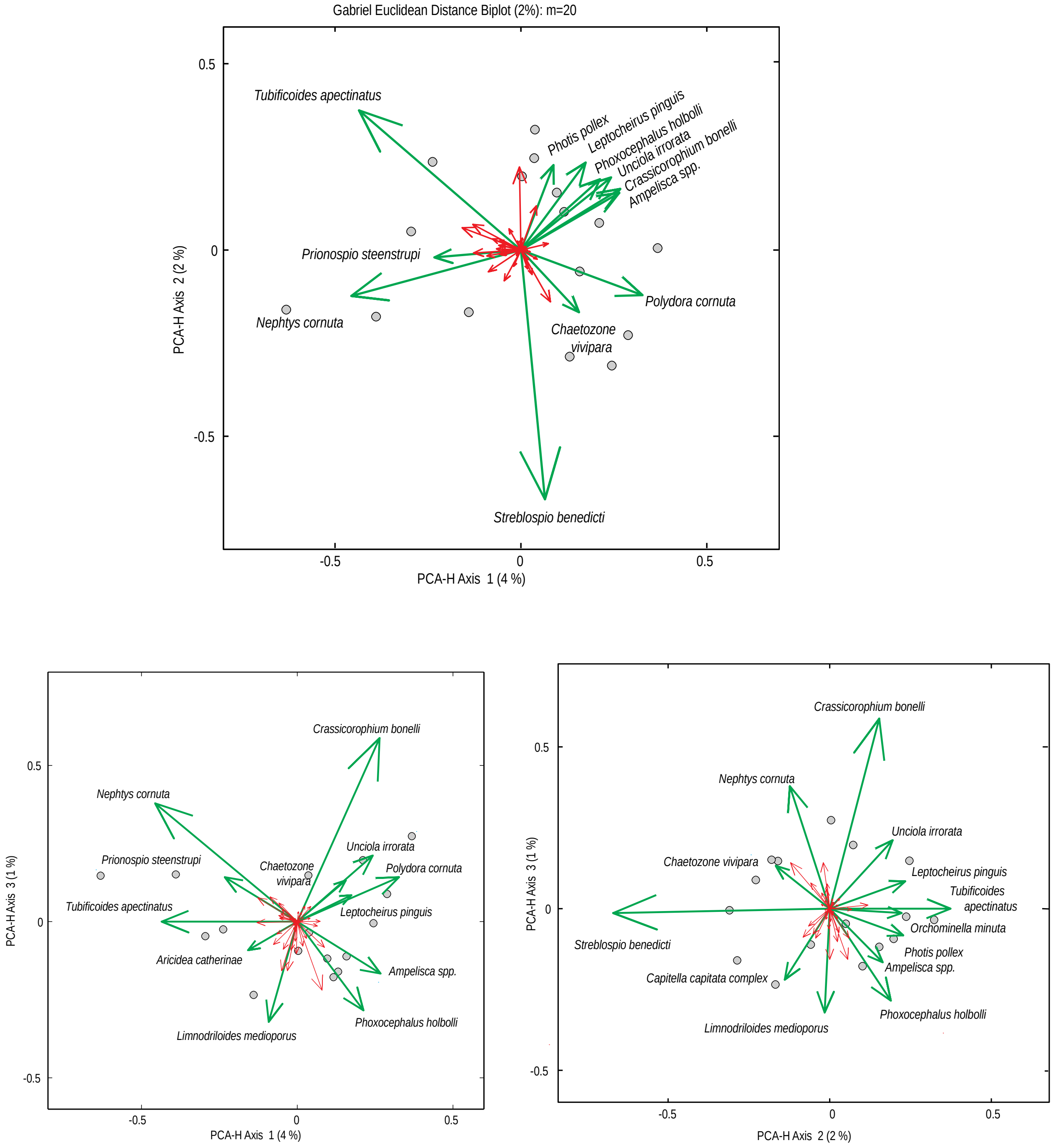


Figure 4-14. Gabriel Euclidean biplot of 16 annual pooled samples. Species vectors accounting for >2% of plot variation in green; other species vectors plotted in red and unlabeled.

Table 4-8. Contribution to PCA-H axes 1, 2, and 3 of the species accounting for at least 2% of the annual community variation at the Boston Harbor stations when samples are pooled to one per year for each of 16 years (see Euclidean Distance Biplot, Figure 4-14).

Important species: Axis 1 vs. 2

PCA-H Rank	Species	Contr.[a]	Total Contr.	Axis 1	Axis 2
1	*Tubificoides apectinatus*	17	17	19	14
2	*Streblospio benedicti*	16	34	0	45
3	*Nephtys cornuta*	14	47	21	2
4	*Polydora cornuta*	7	55	11	1
5	*Ampelisca spp.*	6	60	7	3
6	*Crassicorophium bonelli*	5	66	7	2
7	*Unciola irrorata*	5	71	6	4
8	*Phoxocephalus holbolli*	4	75	5	4
9	*Leptocheirus pinguis*	4	79	3	5
10	*Prionospio steenstrupi*	3	82	5	0
11	*Chaetozone vivipara*	3	85	2	3
12	*Photis pollex*	2	87	1	5

Important species: Axis 1 vs. 3

PCA-H Rank	Species	Contr.[a]	Total Contr.	Axis 1	Axis 3
1	*Nephtys cornuta*	19	19	21	14
2	*Tubificoides apectinatus*	14	34	19	0
3	*Crassicorophium bonelli*	14	47	7	35
4	*Polydora cornuta*	9	56	11	2
5	*Ampelisca* spp.	6	62	7	3
6	*Unciola irrorata*	6	68	6	4
7	*Phoxocephalus holbolli*	5	73	5	8
8	*Prionospio steenstrupi*	5	78	5	2
9	*Limnodriloides medioporus*	3	81	1	10
10	*Leptocheirus pinguis*	2	83	3	1
11	*Chaetozone vivipara*	2	85	2	2
12	*Aricidea catherinae*	2	88	2	1

Important species: Axis 2 vs. 3

PCA-H Rank	Species	Contr.[a]	Total Contr.	Axis 2	Axis 3
1	*Streblospio benedicti*	29	29	45	0
2	*Crassicorophium bonelli*	14	43	2	35
3	*Tubificoides apectinatus*	9	52	14	0
4	*Nephtys cornuta*	6	58	2	14
5	*Phoxocephalus holbolli*	5	63	4	8
6	*Unciola irrorata*	4	67	4	4
7	*Leptocheirus pinguis*	4	71	5	1
8	*Limnodriloides medioporus*	4	74	0	10
9	*Photis pollex*	4	78	5	1
10	*Orchomenella minuta*	3	81	5	0
11	*Capitella capitata* complex	3	84	2	5
12	*Ampelisca* spp.	3	87	3	3
13	*Chaetozone vivipara*	2	89	3	2

[a] Percent contributions are rounded up to the nearest whole number by the computer program.

Similarity and Ordination Analysis with Bray-Curtis**—**The Bray-Curtis similarity analysis returned results that at first appear somewhat different than with CNESS. When the data were fourth-root-transformed prior to analysis, the abundant species such as *Nephtys cornuta* were severely down-weighted and the similarity values better reflect the uncommon species in the samples. In this analysis, as last year, three groups of years are evident (Figure 4-15), with the samples from the current year 2006 being most similar to 2005:

Cluster 1. 1991
Cluster 2. 1992–2001
Cluster 3. 2002–2006

With CNESS (Figure 4-12), a group comprised of 2005 and 2006 was the most dissimilar group, whereas with Bray-Curtis, it is 1991. Both Bray-Curtis and CNESS indicate a high similarity between years 2002 through 2004, and differentiate these from earlier years. In the Bray-Curtis analysis, years 2005 and 2006 are more similar to 2002–2004 than they are with CNESS. The Bray-Curtis analysis suggests a dichotomy between the years prior to moving the outfall offshore and those after the move.

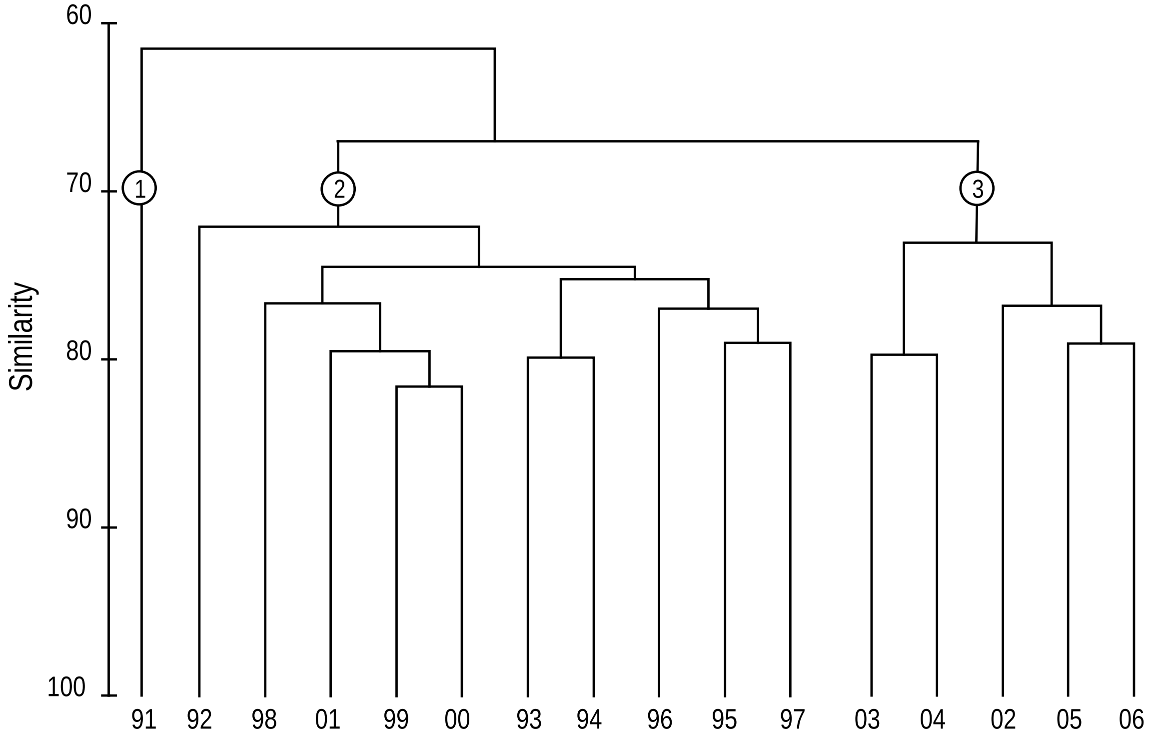


Figure 4-15. Cluster dendrogram based on the Bray-Curtis similarity analysis of Boston Harbor 1991–2006 infaunal data, after fourth-root-transformation of the data and group average clustering.

Ordination of these samples by non-metric multidimensional scaling (NMDS) is shown in Figure 4-16. The low stress level (0.07) indicates that this sample map is a good representation of the multidimensional space occupied by the annual samples. Because this map indicates relative distances among samples better than is portrayed by the dendrogram, it can be seen that with Bray-Curtis 1991 in particular occupies a different multidimensional space than the remaining samples, and that the early years are separated from the most recent years.

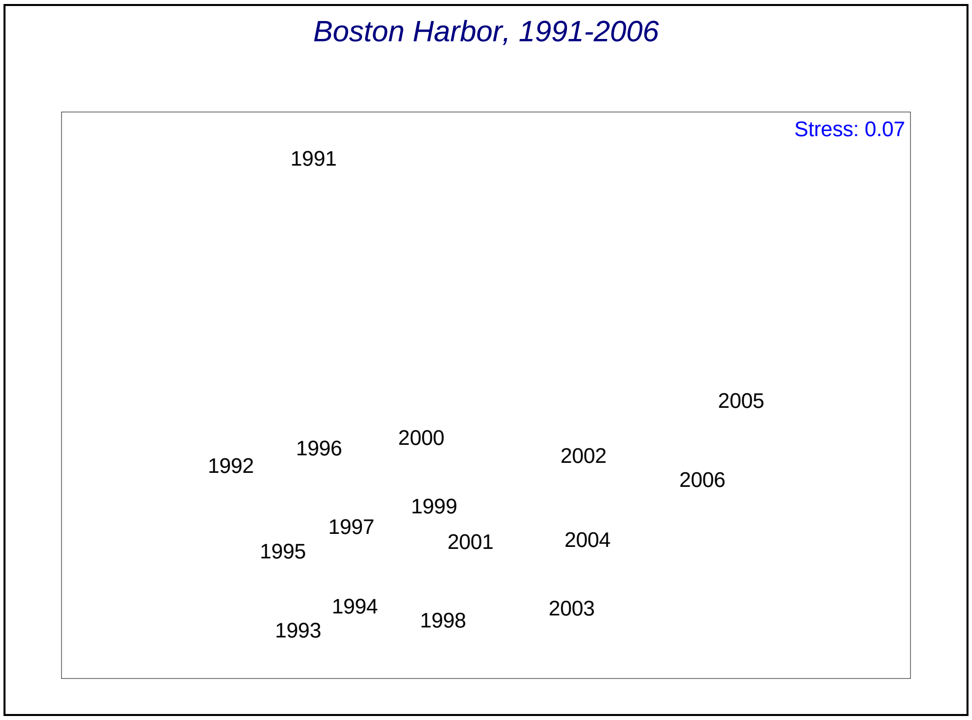


Figure 4-16. NMDS based on the Bray-Curtis similarity analysis of Boston Harbor 1991–2006 infaunal data, after fourth-root-transformation of the data.

Relative abundances of the 12 species that were identified in the PCA-H Euclidean distance analysis as contributing the most to the variation among samples (Table 4-8) are shown as overlays to the NMDS result in Figures 4-17–4-19.

Differences in species composition among years are obvious from these plots; *e.g.*, *Phoxocephalus holbolli*, *Polydora cornuta, Streblospio benedicti*, and *Unciola irrorata* were abundant in early years while other species, such *Tubificoides apectinatus* were common more recently. Some species occurred only in a particular year (*Capitella capitata*, 1998; *Crassicorophium bonelli*, 1993 and 1997. The large increase in numbers of *Nephtys cornuta* in 2005 and 2006 is also very noticeable.

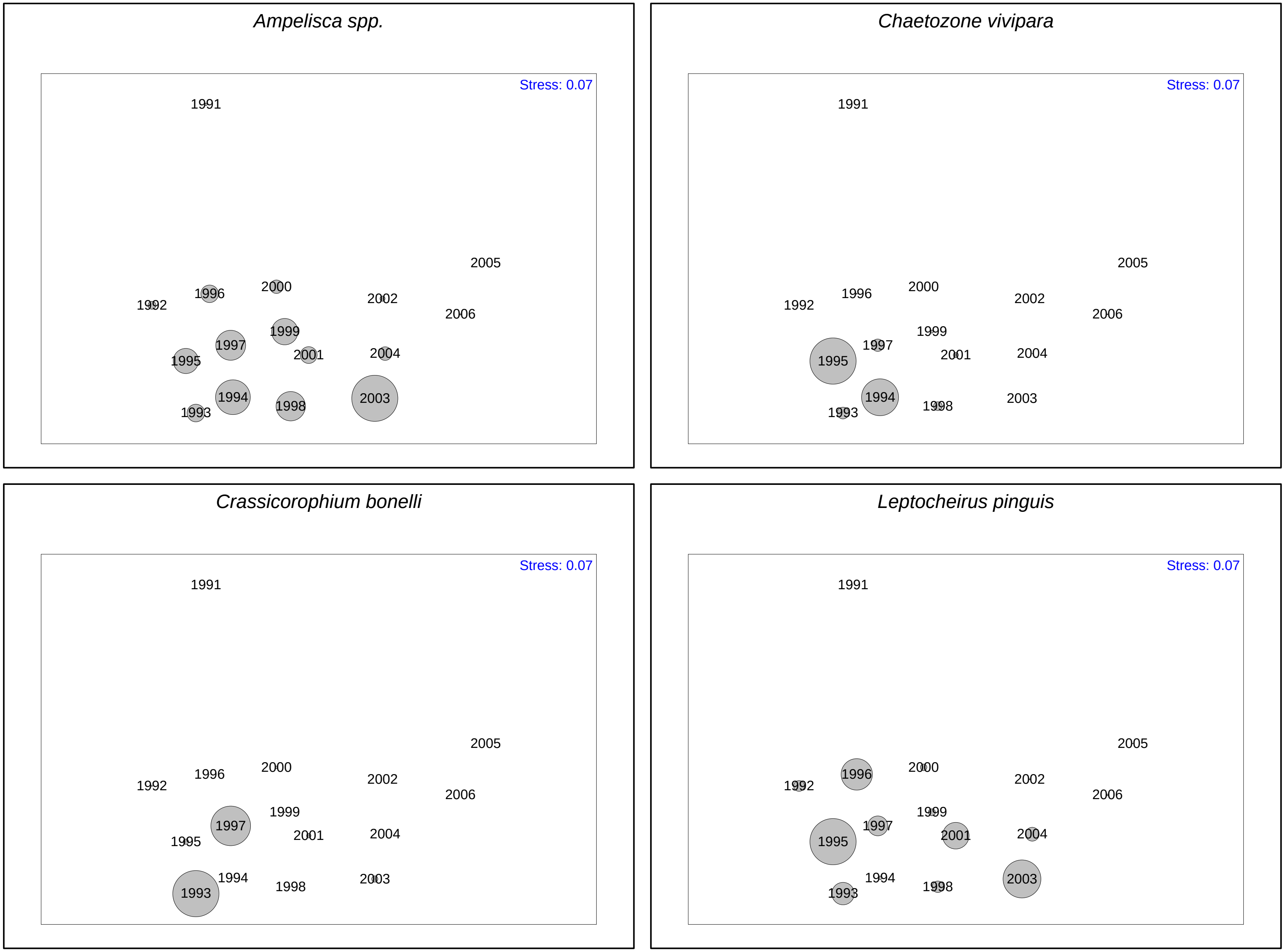


Figure 4-17. NMDS based on the Bray-Curtis similarity analysis of Boston Harbor 1991-2006 infaunal data, after fourth-root-transformation of the data. Relative abundances of individual species are indicated by the size of the bubble for each year.

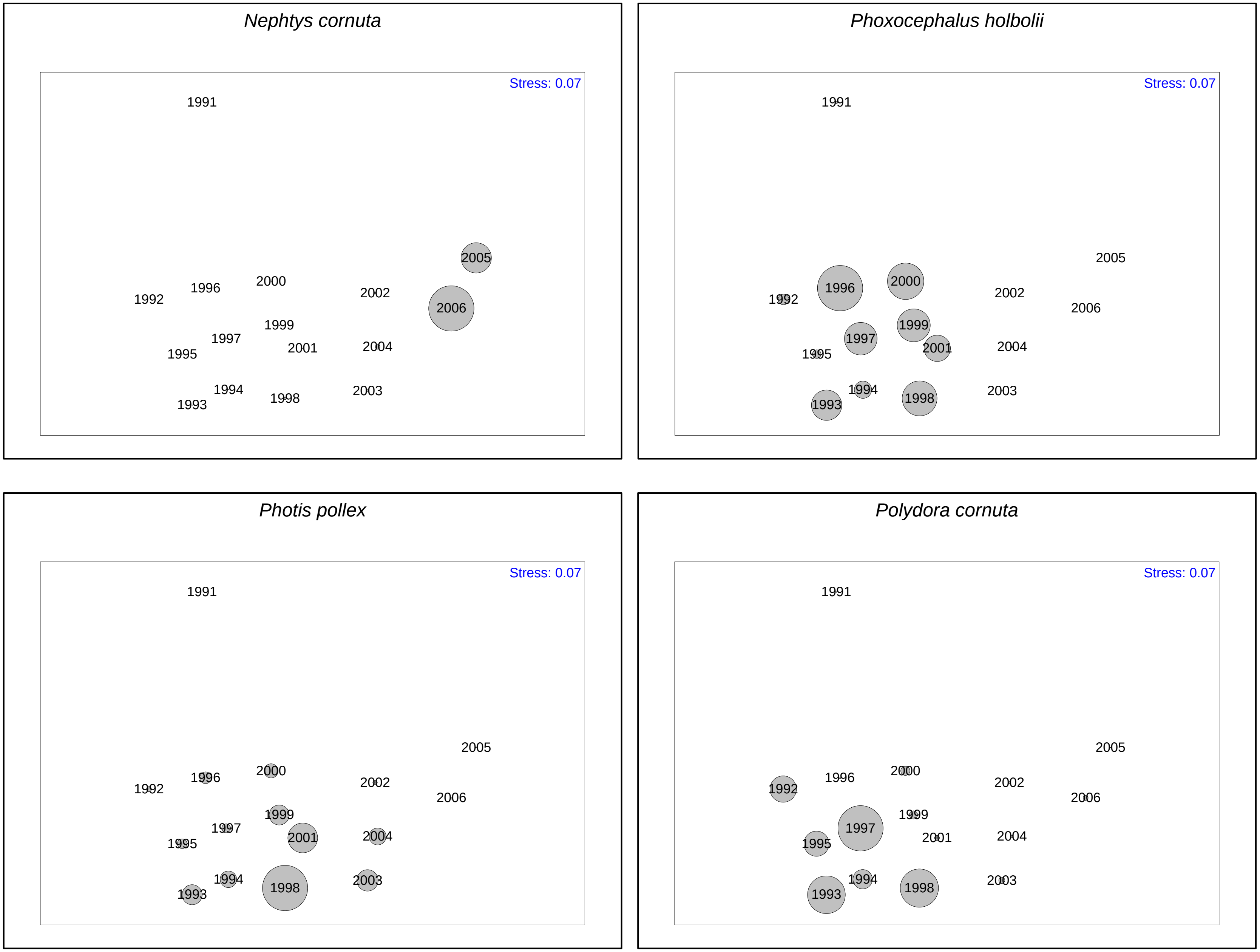
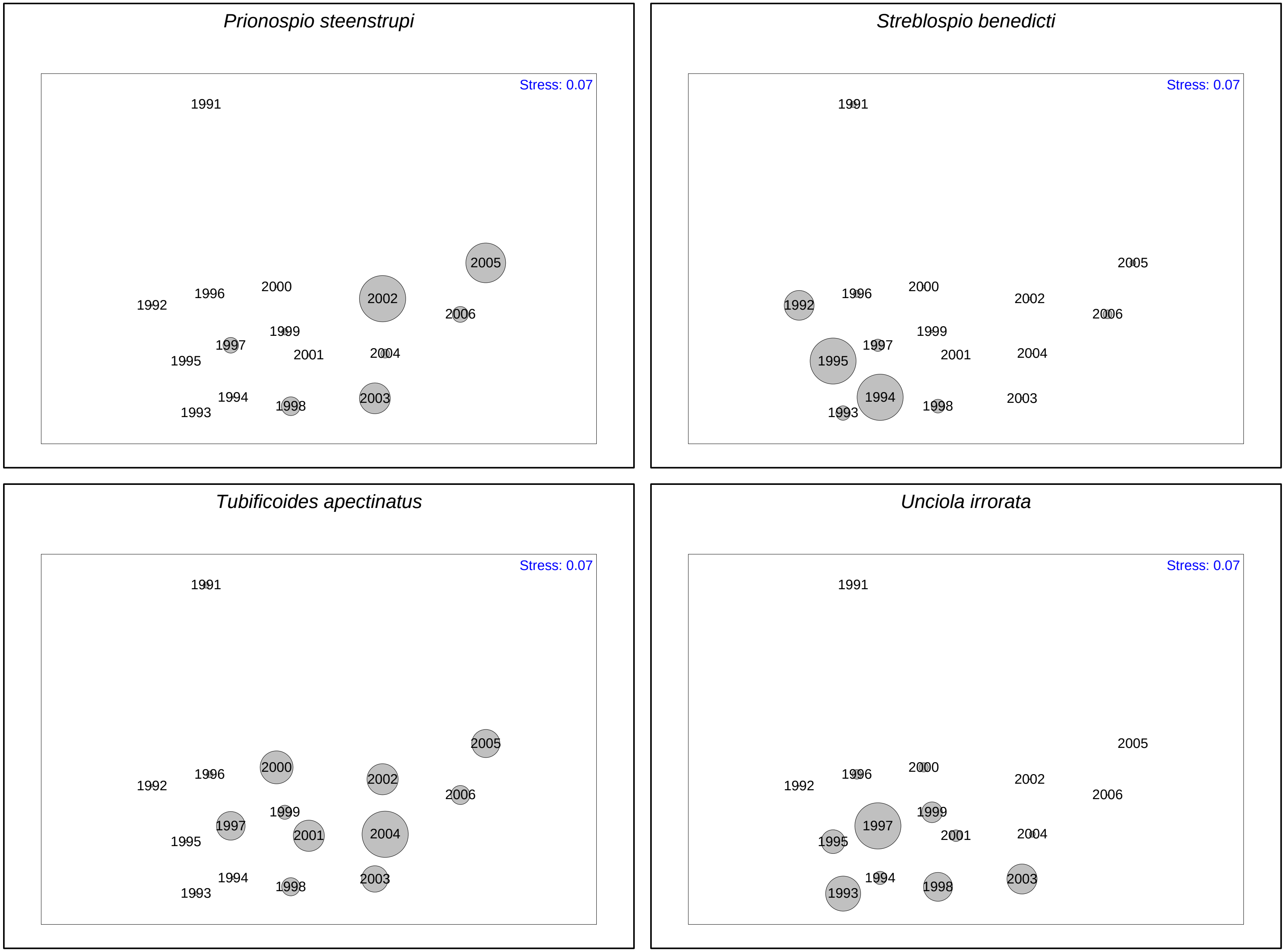


Figure 4-18. NMDS based on the Bray-Curtis similarity analysis of Boston Harbor 1991-2006 infaunal data, after fourth-root-transformation of the data. Relative abundances of individual species are indicated by the size of the bubble for each year.



Prionospio steenstrupi

Streblospio benedicti

Tubificoides apectinatus

Unciola irrorata

Figure 4-19. NMDS based on the Bray-Curtis similarity analysis of Boston Harbor 1991-2006 infaunal data, after fourth-root-transformation of the data. Relative abundances of individual species are indicated by the size of the bubble for each year.

4.3.5 Long-term Changes in the Infaunal Communities

Early studies—Benthic communities in Boston Harbor were clearly impacted by decades of pollutant discharge. The early studies of benthic communities in Boston Harbor (1978, 1979, and 1982) indicated distinct groupings of stations that corresponded to (1) a progression from higher saline oceanic conditions in the outer harbor to estuarine conditions in the inner harbor and (2) known areas of pollution (Blake and Maciolek 1990, Maciolek *et al*. 2004). A distinct outer harbor assemblage that included species with close affinities to faunal communities in Massachusetts Bay changed in the middle of the harbor to one that included estuarine species and elements of so-called pollution indicators or stress-tolerant taxa.

All stations in the outer harbor assemblage had more species and higher species diversity values regardless of differences in sample size or analytical technique. Stations having high infaunal densities were found throughout the station array, but opportunistic species such as *Streblospio benedicti* were found only at the stations in the middle of the harbor. The early data also clearly indicated an obvious north/south pattern in the benthic communities, with stations near the northern Deer Island outfall being distinctly different from those near Nut Island in Hingham Bay in the southern part of the harbor. Tidal exchange through President Roads and Broad Sound appeared to be sufficient to maintain benthic assemblages that were only moderately stressed despite their proximity to the sewage and sludge outfalls. In contrast, shallow sites to the east and west of the outfall had low diversities and high densities of opportunistic stress-tolerant species.

Pollution abatement and sediment characteristics—Discharge of sludge into the harbor ended in 1991 and in 1998 all effluent discharge from Nut Island was discontinued and full secondary treatment of the effluent was implemented. On September 6, 2000, all wastewater discharges were diverted to the new outfall in Massachusetts Bay, and in early 2001, the final battery of secondary treatment became operational. Taylor (2005, 2006) summarized the major patterns in freshwater flows and loadings of total nitrogen (TN), total phosphorus (TP), total suspended solids (TSS), and particulate organic carbon (POC) to Boston Harbor between 1995 and 2003. He elucidated four periods, as outlined in Chapter 1(this report) and discussed in relation to the SPI results (Chapter 3, this report.) The changes in wastewater discharge from 1991 to 2005 resulted in an 80–95% decrease in loadings to Boston Harbor. Annual average loadings of TSS and POC showed a progressive decrease, starting in 1991/1992 and proceeding through 2001, after which the average loadings remained low and similar between years. For TN and TP, loadings showed some decrease with the end of sludge discharge, but remained elevated through 1998, when Nut Island flows were discharged closer to the mouth of the harbor, resulting in decreased inputs to the harbor. TN and TP showed additional, larger decreases with the transfer of the effluent discharge offshore in 2000 (Taylor 2006).

TOC content increased in 2006 compared with 2005 values at all harbor stations except T05A (Appendix B); this increase was not surprising considering that TOC content measured in 2005 were among the lowest, or the lowest, measured values during the monitoring program (1991–2006). The unusually low values in 2005 were attributed to sediment bed disturbance from the May 2005 nor'easters, which contributed to a coarsening of grain size at some harbor stations (Maciolek *et al.* 2006c). However, the trend of decreasing TOC observed since 1992 at T01 and T03 continued to be apparent, suggesting a reduction in carbon loading to the northern harbor consistent with the improvements to wastewater treatment practices. Decreasing levels of *Clostridium perfringens*, the sewage tracer, continued at all stations except CO19 and T08 in 2006 (Appendix B, this report).

Temporal changes in sediment environments at the harbor stations have been difficult to discern because of the high variability among the data over time (Appendix B, this report). Harbor stations include locations with dissimilar grain-size characteristics: T01, T05A, and T08 generally have coarse-grained sediments; T04 and CO19 have fine-grained (silty) sediment; and T02, T03, T06, and T07 have been comprised of sediments with roughly equal parts coarse- and fine-grained material (Maciolek *et al.* 2006c). Grain-size composition has been the most consistent at T07 over the years of the monitoring program (1991–2006).

Recovery of benthic communities—Recovery of areas degraded by the long-term disposal of sludge and effluents may involve a transitional stage of undetermined length before an equilibrium community is established. This intermediate stage can involve the sequential appearance and decline of a diverse assemblage of tube-dwelling amphipods, mollusks, and polychaetes. As noted earlier, *Ampelisca* spp. can thrive in areas within a certain range of organic input and good water quality (Stickney and Stringer 1957). Beginning in 1993, the *Ampelisca* spp. population in the harbor spread and in 2003 the populations of this and other species of amphipods accounted for 75 % of the sampled fauna, the second highest density since 1998. In 2004, the amphipod populations had declined and by 2005 this major faunal component, which had dominated much of the harbor benthos over the 15 years of this study, was almost entirely absent. The reduction in *Ampelisca* spp. and high-density tube mats may be related to depletion of the organic matter stored in the sediment, as well as to the impact of the severe storms in recent winters. While the total annual carbon budget for Boston Harbor should be sufficient to support high densities of *Ampelisca* in any one year, a shift from wastewater- to phytoplankton-derived carbon, all of which may not have been available to the amphipods, may have resulted in the apparently slow recovery of this species in 2006.

Given the physical and oceanographic attributes of the study area (*i.e.*, a near-coastal environment that is relatively shallow compared with offshore areas, and a continuing pollutant load, albeit reduced, from CSOs or other industrial sources), it is probable that the harbor benthos will continue to evidence episodic irruptions and declines of populations of amphipods and other species, such as the polychaete *Nephtys cornuta* that has been increasingly common over the past three years.

Individual stations —When stations are evaluated individually (Maciolek *et al*. 2006a,c), it is clear that the communities present in the harbor today differ from those present before the major reduction in pollutant loads, and that species richness and diversity (as measured by log-series *alpha*) have increased at each of the eight traditional harbor stations over the 16-year time period. T01 is an example of a harbor station that has changed noticeably since it was first sampled in the late 1970s and early 1980s. At that time, this station, located off the Deer Island flats, exhibited the poor physical environment and low diversity of a severely stressed station. Over the course of the past 16 years, with the increasing removal of the pollutant load, the species composition of the station has changed, concomitant with a steady increase in diversity and species richness.

Mean community parameters— Mean community parameters for the harbor overall were summarized for Taylor (2006) time periods, offset by one year to allow for any lag time in the response of benthic populations to decreased pollutant loads (Table 4-9). Periods II and III appear the most similar for all parameters. Fisher's *alpha* shows a steady increase through all time periods, whereas the mean values of other parameters appear identical or decline between subsequent periods (*e.g.*, number of species, periods II and III; Shannon diversity, periods III and IV).

Lines of evidence from other components of this monitoring program suggest that, when taken as a whole, the harbor has not changed significantly over the past decade. For example, using the OSI index as a surrogate for habitat quality, no station has shown a monotonic trend of either improvement or decline (Maciolek *et al*., 2005). However, detailed analyses of the infaunal communities at the traditional stations, as well as other lines of evidence, such as the continuing decrease in levels of the sewage marker *Clostridium perfringens* (Appendix B, this report) support a different conclusion: that the benthic environment in the harbor is indeed recovering from years of pollutant input.

Table 4-9. Characteristics of Boston Harbor traditional stations summarized by time periods defined by Taylor (2006).

Parameter	**Period**			
	I **before Dec. 1991**	**II** **Dec 1991–mid-1998**	**III** **mid-1998–Sep. 2000**	**IV** **after Sep. 2000** ***(after outfall diversion)***
Groupings offset by one year	***n*= 48** **(1991–1992)**	***n* = 144** **(1993–1998)**	***n*= 71** **(1999–2001)**	***n* = 120** **(2002–2006)**
Number of Species	25.1 ± 14.25	34.7 ± 13.6	33.7 ±14.2	41.9 ± 17.5
H′	2.12 ± 0.81	2.41 ± 0.90	2.80 ±0.78	2.79 ± 0.89
log-series *alpha*	4.17 ± 2.14	5.50 ± 2.00	6.16 ± 2.25	7.61 ± 3.01
Rarefaction curves	1991 lowest	low	intermediate	highest
Fauna	highest abundances of opportunistic species such as *Streblospio benedicti* and *Polydora cornuta*	declining abundances of opportunistic species, some amphipod species numerous	fewer opportunists, more oligochaetes, some amphipod species numerous	some species from Massachusetts Bay, rise and decline of amphipods, increase in *Nephtys*.

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Massachusetts Water Resources Authority
Charlestown Navy Yard
100 First Avenue
Boston, MA 02129
(617) 242-6000
http://www.mwra.state.ma.us