Boston Harbor Benthic Monitoring Report: 2016 Results

Massachusetts Water Resources Authority

Environmental Quality Department
Report 2017-10

Citation:

Pembroke, AE, Diaz RJ, Nestler EC. 2016. ***Boston Harbor Benthic Monitoring Report: 2016 Results.*** Boston: Massachusetts Water Resources Authority. Report 2017-10. 45 pages.

Boston Harbor Benthic Monitoring Report:
2015 Results

Submitted to

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

prepared by

Ann E. Pembroke[1]
Robert J. Diaz[2]
Eric C. Nestler[1]

[1]Normandeau Associates, Inc.
25 Nashua Road
Bedford, NH 30110

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

September 2017
Report No. 2017-10

EXECUTIVE SUMMARY

Boston Harbor was once considered among the most degraded urban estuaries in the country. Direct discharge of wastewater with limited treatment into the harbor had affected both water quality and biological conditions. Both the EPA and the Federal Court prevailed upon the Commonwealth of Massachusetts to take actions to improve these conditions substantially and the Massachusetts Water Resources Authority (MWRA) was created in response. In 1985, MWRA initiated a multi-faceted plan to meet these mandates, most significantly including an upgrade to secondary treatment, elimination of sludge disposal into the harbor, and relocation of wastewater discharge through an offshore diffuser located 9.3 miles off Deer Island in Massachusetts Bay. Subsequently, improvements have been made to numerous Combined Sewer Overflows (CSOs) reducing another source of water quality concern.

Conditions in the sediments and the associated benthic infaunal community reflect cumulative water quality exposures. In order to evaluate changes to the ecosystem, particularly the benthic community, resulting from reductions in contaminated discharges over time, MWRA has conducted benthic monitoring in Boston Harbor on an ongoing basis since 1991. This report provides a summary of the results of the benthic surveys that were conducted in 2016. These include sediment conditions, benthic infauna, and sediment profile imagery.

Overall, the improvements in wastewater treatment and moving the outfall offshore have led to improvements in water quality and benthic habitat quality within Boston Harbor by reducing organic and nutrient loading. These reductions have enabled processes that enhance bioturbation or the mixing of sediment by organisms to predominate. At one time, the sediment organic matter in Boston Harbor was derived primarily from sewage but once changes in wastewater treatment and disposal were initiated, marine-derived organic material has become prevalent in the sediment. The infaunal community has responded to this change and subsequent biological activity has led to more aerobic and ‘healthy’ sediment conditions. Physical and biological properties of the soft substrate in Boston Harbor in 2016 exhibited minor changes from recent years but were consistent with longer-term trends (Pembroke et al. 2016). Concentrations of both TOC and *Clostridium perfringens*, indicators of organic enrichment and deposition from municipal wastewater discharge, have remained low compared to the levels occurring prior to the offshore diversion.

Community structure measures also continue to point to improving benthic conditions. As municipal wastewater and sludge discharges were eliminated from the harbor, total abundance has trended downward, particularly for opportunistic species such as *Capitella capitata*, reaching a fairly stable level for about the last decade. Species richness, while variable, has trended upward as did evenness (J’), Shannon diversity (H’), and log series alpha diversity. Although abundances of individual taxa, such as the dominants *Ampelisca* spp., *Aricidea catherinae,* and *Polydora cornuta* have varied over time, the infaunal community structure and evidence from sediment profile imaging suggest that these changes relate more to normal physical disturbances than organic stress in the years since wastewater impacts to the Harbor have been reduced. The trends observed in previous years, including reduction of indicators of organic enrichment and increases in species diversity that continued in the 2016 survey are consistent with the recovery of benthic habitats from decades of inadequately treated sewage discharges.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

1. INTRODUCTION

Boston Harbor was once considered among the most degraded urban estuaries in the country. Direct discharge of wastewater with limited treatment into the harbor had affected both water quality and biological conditions. Both the EPA and the Federal Court prevailed upon the Commonwealth of Massachusetts to take actions to improve these conditions substantially and the Massachusetts Water Resources Authority (MWRA) was created in response. In 1985, MWRA initiated a multi-faceted plan to meet these mandates, most significantly including an upgrade to secondary treatment, elimination of sludge disposal into the harbor, and relocation of wastewater discharge through an offshore diffuser located 9.3 mi off Deer Island in Massachusetts Bay. In 2015, MWRA and its member communities completed a series of 35 projects intended to eliminate or minimize the impacts of Combined Sewer Overflows (CSOs) to Boston Harbor and its tributaries (Kubiak et al. 2016).

MWRA has conducted benthic monitoring in Boston Harbor on an ongoing basis since 1991 to evaluate changes to the ecosystem, in particular the benthic community, as contaminated discharges have been reduced over time. This report provides a summary of the results of the benthic surveys that were conducted in 2016. These include sediment conditions, benthic infauna, and sediment profile imagery.

2. METHODS

Benthic monitoring in Boston Harbor continued at the same stations that have been surveyed since 1991. No changes were made to this program in the 2010 revision to the Ambient Monitoring Plan (MWRA 2010). This survey comprises three components: sediment conditions (grain size, total organic carbon, and *Clostridium perfringens*), benthic infauna, and sediment profile imaging (SPI).

Methods used to collect, analyze, and evaluate all sample types remain largely consistent with those reported by Pembroke et al. (2016) for previous monitoring years. Detailed descriptions of the methods are contained in the Quality Assurance Project Plan (QAPP) for Benthic Monitoring (Nestler et al. 2014). A brief overview of methods, focused on information that is not included in the QAPP, is provided in Sections 2.1 to 2.3.

2.1 Field Methods

Sediment and infauna sampling was conducted at 9 stations in August 2016 (Figure 1). Soft-bottom stations were sampled for grain size composition, total organic carbon (TOC), the sewage tracer *Clostridium perfringens*, and benthic infauna. One sediment sample and triplicate infauna samples were collected at each station on August 5, 2016.

SPI samples were collected in triplicate at 61 stations on August 2-4, 2016 (Figure 1).

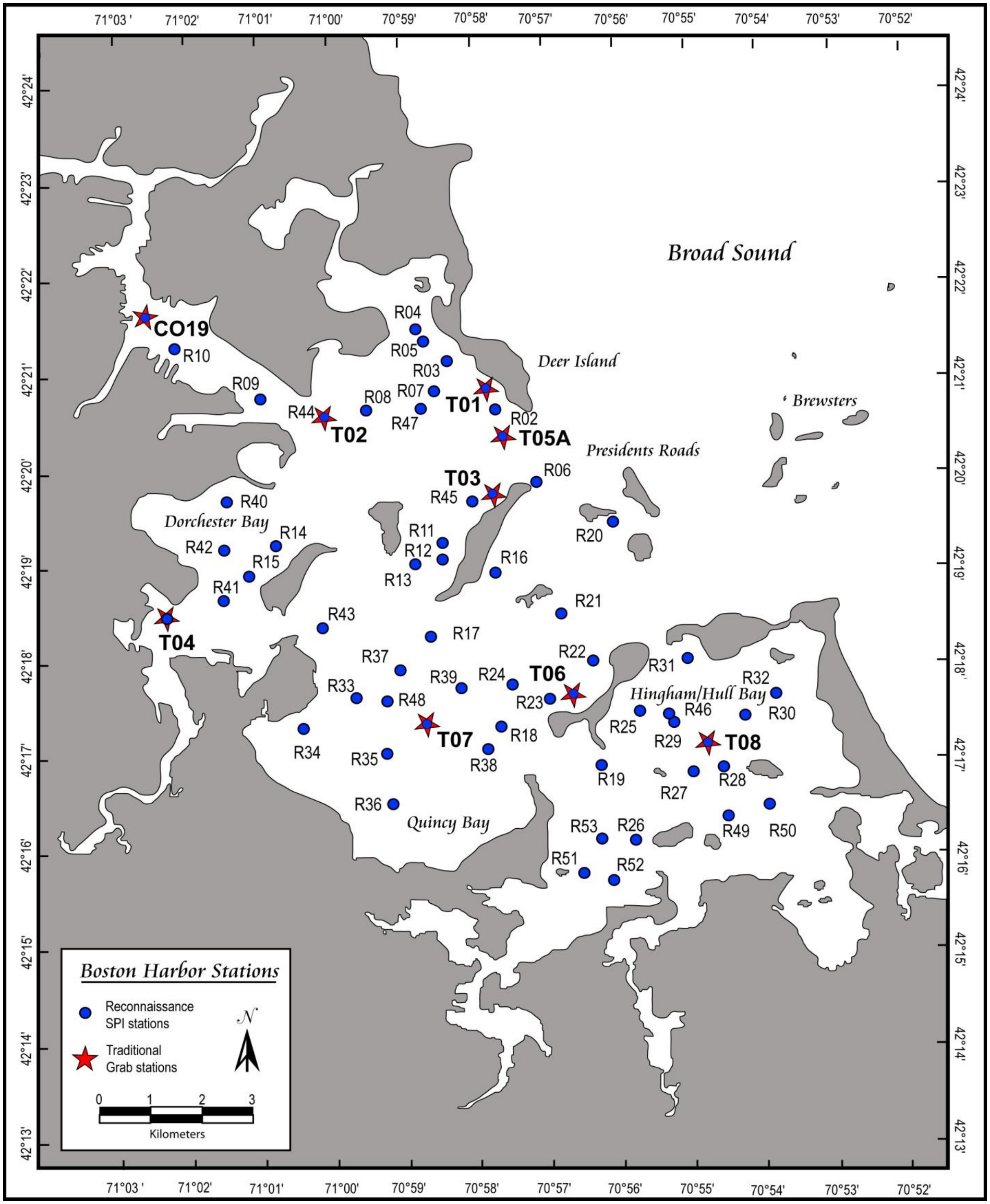

Figure 1. Locations of soft-bottom sampling and sediment profile imaging stations for 2016.

2.2 Laboratory Methods

Laboratory methods for benthic infauna and SPI image analyses were consistent with the QAPP (Nestler et al. 2014). Two of the infauna samples were randomly selected for processing, while the third was archived. Analytical methods for grain size, TOC, and *Clostridium perfringens* are described in (Constantino et al. 2014).

2.3 Data Handling, Reduction, and Analysis

All benthic data were extracted directly from the HOM database and imported into Excel. Data handling, reduction, and graphical presentations were performed in Excel or SAS (version 9.3), as described in the QAPP (Nestler et al. 2014) or in Maciolek et al. (2008). Data are presented graphically as means (averages per station) unless otherwise noted. Shannon-Weiner (H') was calculated using log base 2. Multivariate analyses were performed using PRIMER v6 (Plymouth Routines in Multivariate Ecological Research) software to examine spatial patterns in the overall similarity of benthic assemblages in the survey area (Clarke 1993, Warwick 1993, Clarke and Green 1988). These analyses included classification (cluster analysis) by hierarchical agglomerative clustering with group average linking and ordination by non-metric multidimensional scaling (MDS). Bray-Curtis similarity was used as the basis for both classification and ordination. Prior to analyses, infaunal abundance data were fourth-root transformed to ensure that all taxa, not just the numerical dominants, would contribute to similarity measures.

Cluster analysis produces a dendrogram that represents discrete groupings of samples along a scale of similarity. This representation is most useful when delineating among sites with distinct community structure. MDS ordination produces a plot or "map" in which the distance between samples represents their rank ordered similarities, with closer proximity in the plot representing higher similarity. Ordination provides a more useful representation of patterns in community structure when assemblages vary along a steady gradation of differences among sites. Stress provides a measure of adequacy of the representation of similarities in the MDS ordination plot (Clarke 1993). Stress levels less than 0.05 indicate an excellent representation of relative similarities among samples with no prospect of misinterpretation. Stress less than 0.1 corresponds to a good ordination with no real prospect of a misleading interpretation. Stress less than 0.2 still provides a potentially useful two-dimensional picture, while stress greater than 0.3 indicates that points on the plot are close to being arbitrarily placed. Together, cluster analysis and MDS ordination provide a highly informative representation of patterns of community-level similarity among samples. The "similarity profile test" (SIMPROF) was used to provide statistical support for the identification of faunal assemblages (i.e., selection of cluster groups). SIMPROF is a permutation test of the null hypothesis that the groups identified by cluster analysis (samples included under each node in the dendrogram) do not differ from each other in multivariate structure.

Temporal patterns in the infaunal community and sediment chemistry were evaluated in the context of the four discharge periods described by Taylor (2006) offset by one year to allow for a lag in response time.

3. RESULTS AND DISCUSSION

3.1 Sediment Conditions

Sediment conditions in Boston Harbor were characterized by three parameters measured during 2016 at each of the nine sampling stations: (1) grain size (gravel, sand, silt, and clay), (2) total organic carbon, and (3) *Clostridium perfringens* (Table 1).

Grain Size. Surface sediments at the nine stations sampled during 2015 included a wide range of sediment types (Table 1, Figure 2). Grain size profiles ranged from predominantly sand (e.g., T08, T05A) to almost entirely silt and clay (i.e., C019 and T04). Most stations had mixed sediments. The outer harbor stations (T01, T02, T05A, T06, and T08) generally had more than 50% sand with varying fractions of silt-clay. Outer harbor station T07 had nearly equal proportions of sand and silt-clay. Grain size has been variable at Station T03, in the lee of Long Island, having more fines than sand in 2015 but more sand in 2016. The grain size composition at each station in 2016 generally remained within the ranges reported in prior years although several stations (T01, T03, T04 and T06) exhibited a change in percent fines of about 10% compared to 2015. T01 (just west of Deer Island) and T02 (at the mouth of the Inner Harbor) have exhibited the largest fluctuations in fine sediments over the years and T04 has occasionally exhibited fairly large drops in percent fines (Figure 3).

Total Organic Carbon. Concentrations of total organic carbon (TOC) in 2016 were generally similar to 2015, remaining within the ranges reported in prior years (Figure 4). Concentrations of TOC tend to track closely to percent fine sediments (silt + clay), with higher TOC values generally associated with higher percent fines (Figures 3 and 4). During 2016, Stations T04, T07, and C019 had among the highest concentrations of TOC and also had among the highest proportions of fines (Table 1). T04 and C019 have typically had the highest TOC. The relatively high value at T07 in 2016 was lower than in 2015 consistent with a decrease in percent fines from 48.6 to 41.1%. TOC levels at T03 have been below 3% since 2005 and below 2.5% since 2011; levels in 2016 are consistent with this trend. This pattern has paralleled the proportion of fine grained sediments. As in prior years, the lowest TOC concentrations for 2016 were reported at Station T08.

***Clostridium perfringens*.** Spores of *Clostridium perfringens*, an anaerobic bacterium found in the intestinal tract of mammals, provide a sensitive tracer of effluent solids. Abundances of *C. perfringens* (normalized to percent fines) during 2016 were highest at Stations T08 and T03 in the Outer Harbor and C019 in the Inner Harbor. Lowest values were found at Station T05A (Table 1). Station T08 has the lowest values in 2015; the change in ranking is likely related to the extremely low levels of fine grained sediments at this station in 2016. In the Outer Harbor, abundances have exhibited the highest variability among years at T04, a depositional site in Savin Hill Cove. After a period of decline from 2008-2012, followed by an increase in 2013 and 2014, *C. perfringens* counts decreased again in 2015 and remained at that level in 2016. *C. perfringens* counts at other Harbor stations have remained consistently below historical averages since around 1999 (Figure 5).

Table 1. 2016 monitoring results for sediment condition parameters.

Parameter		C019	T01	T02	T03	T04	T05A	T06	T07	T08
Grain Size	**Gravel (%)**	**0**	**2.0**	**1.2**	**1.8**	**0**	**0.3**	**0.5**	**13.8**	**5.1**
	Sand (%)	**3.1**	**71.8**	**52.1**	**55.2**	**8.9**	**87.1**	**69.3**	**45.1**	**94.8**
	Silt (%)	**61.1**	**21.8**	**33.1**	**29.0**	**65.7**	**9.9**	**20.3**	**27.6**	**0.2**
	Clay (%)	**35.8**	**4.4**	**13.6**	**14.0**	**25.4**	**2.6**	**9.8**	**13.5**	**0.0**
	Percent Fines (Silt + Clay)	**96.9**	**26.3**	**46.7**	**43.0**	**91.1**	**12.6**	**30.1**	**41.1**	**0.2**
Total Organic Carbon	**TOC (%)**	**2.4**	**0.7**	**1.4**	**1.7**	**3.4**	**0.4**	**1.1**	**2.3**	**0.4**
Clostridium perfringens	**not normalized**	**18700**	**448**	**6020**	**6720**	**5140**	**200**	**1510**	**3830**	**54**
	normalized (cfu/g dry/%fines)	**193.0**	**17.1**	**128.8**	**156.4**	**56.4**	**15.9**	**50.1**	**93.2**	**360.0**

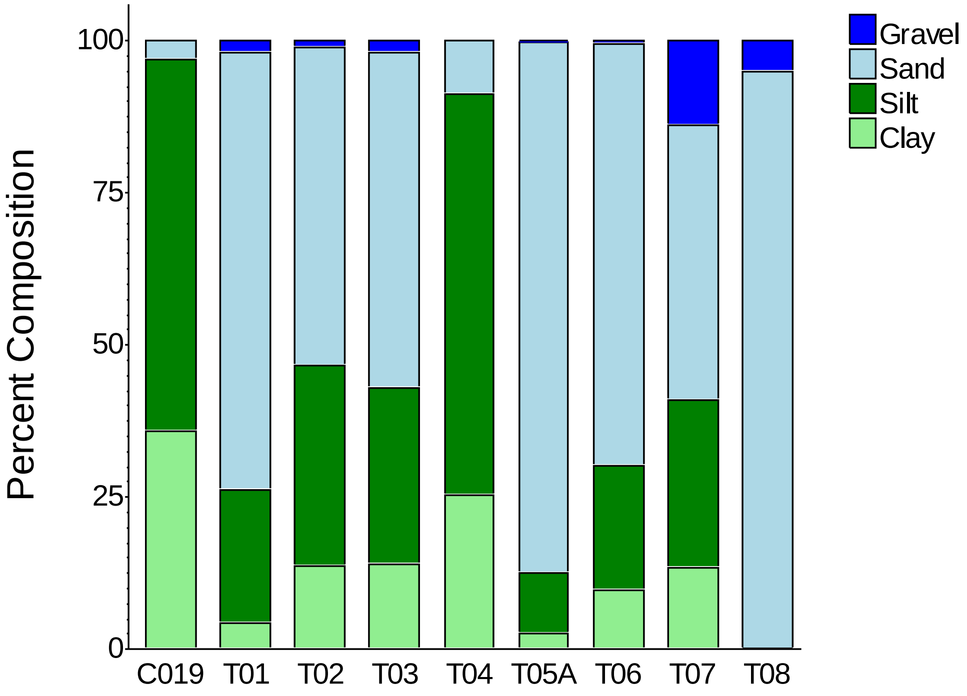

Figure 2. 2016 monitoring results for sediment grain size.

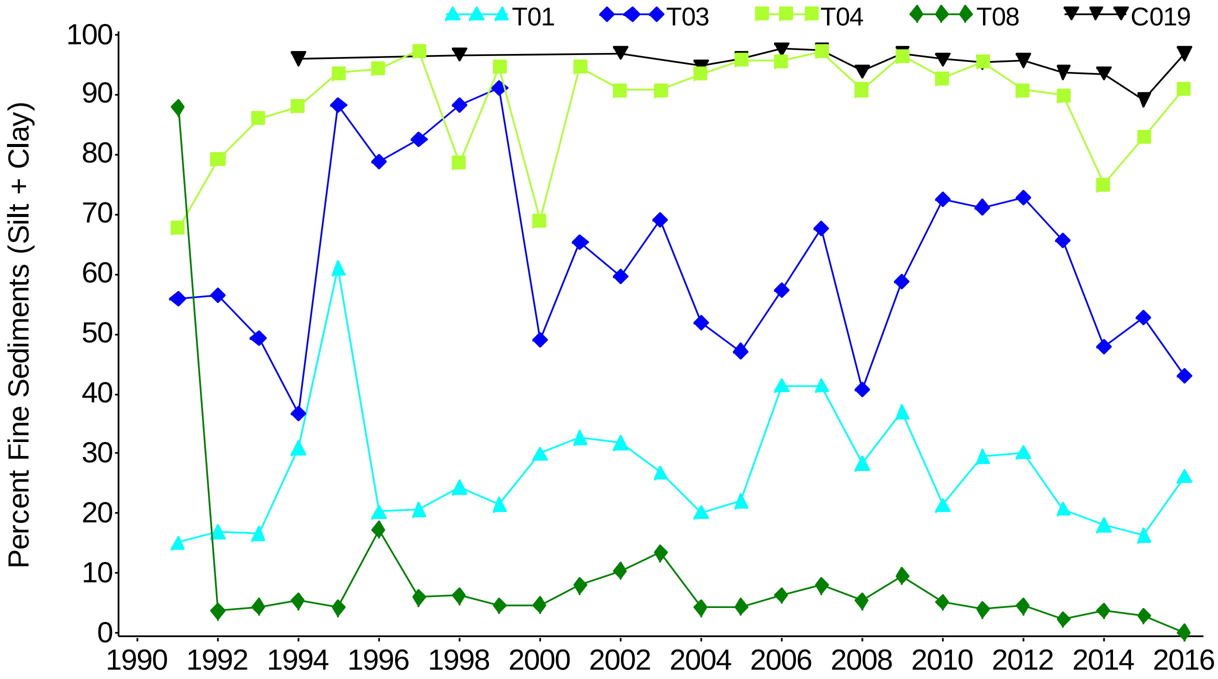

Figure 3. Mean percent fine sediments at five stations in Boston Harbor, 1991 to 2016.

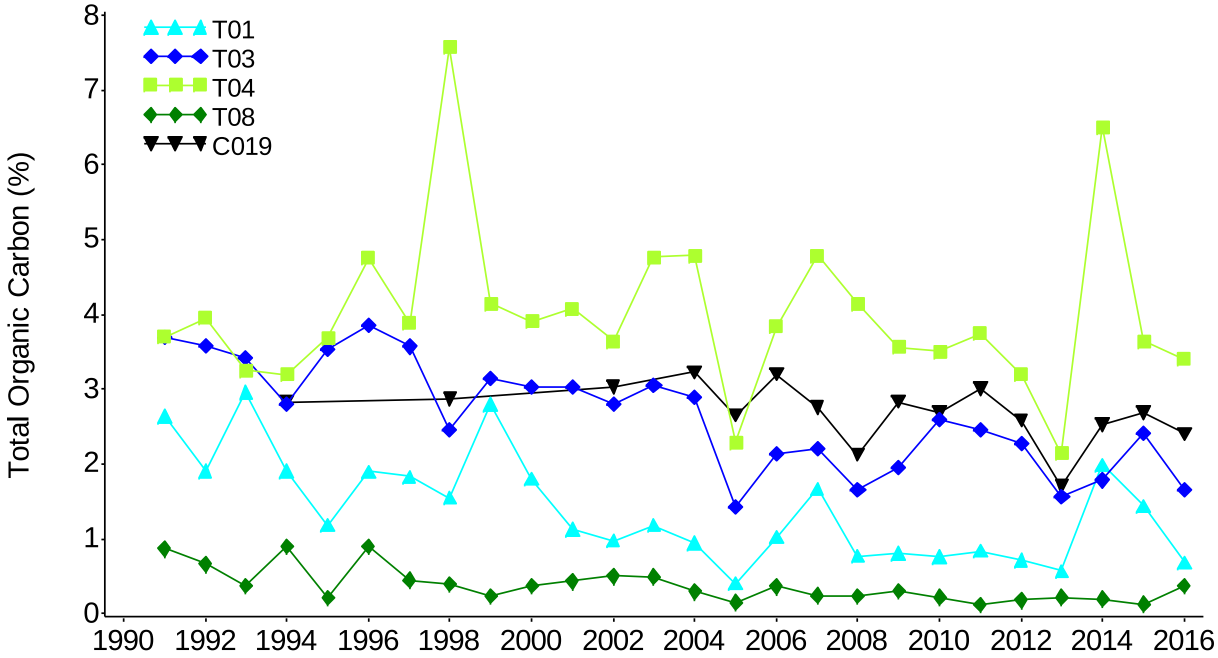

Figure 4. Mean concentrations of TOC at five stations in Boston Harbor, 1991 to 2016.

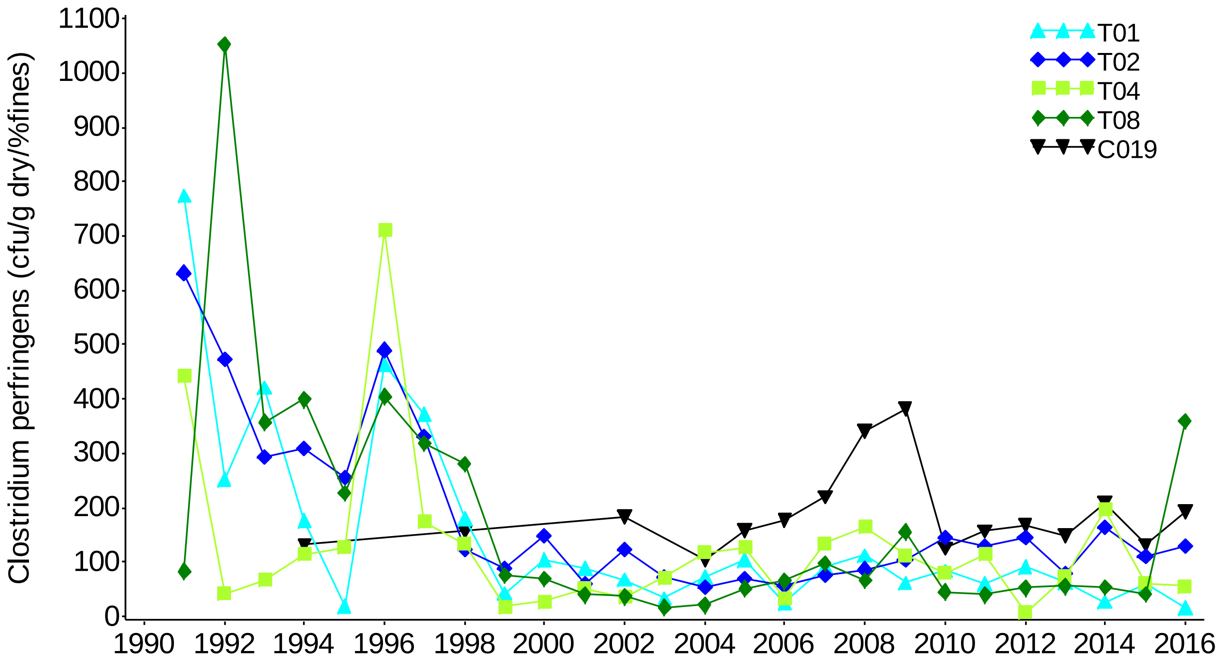

Figure 5. Mean normalized concentrations of *Clostridium perfringens* at five stations in Boston Harbor, 1991 to 2016.

Association with wastewater treatment improvements. Taylor (2006) defined time periods related to various changes in MWRA's management of wastewater and sludge treatment and discharges. Significant events that had a likelihood of affecting the harbor benthic community included ending the discharge of sludge in 1991 (end of Period I); opening of the new primary treatment plant at Deer Island (1995) and its upgrade to secondary treatment between 1997 and 2001 (Period II); implementation of the transfer of wastewater from Nut Island to Deer Island, ending the Nut Island discharge in 1998 (onset of Period III); and implementation of the offshore outfall in 2000 (onset of Period IV).

Results during 2016 for grain size, TOC, and *C. perfringens* in Boston Harbor sediments, are consistent with monitoring results from prior Period IV years (Maciolek et al. 2008, 2011; Pembroke et al. 2012, 2013, 2014, 2015, 2016). Concentrations of both TOC and *C. perfringens* at the traditional harbor stations (T01 to T08) have remained lower during the past decade than those reported during the 1990s (Figures 6 and 7). These findings are consistent with other changes documented in the Harbor following improvements to the collection, treatment and disposal of wastewater as part of the Boston Harbor Project (Maciolek et al. 2008, Taylor 2006).

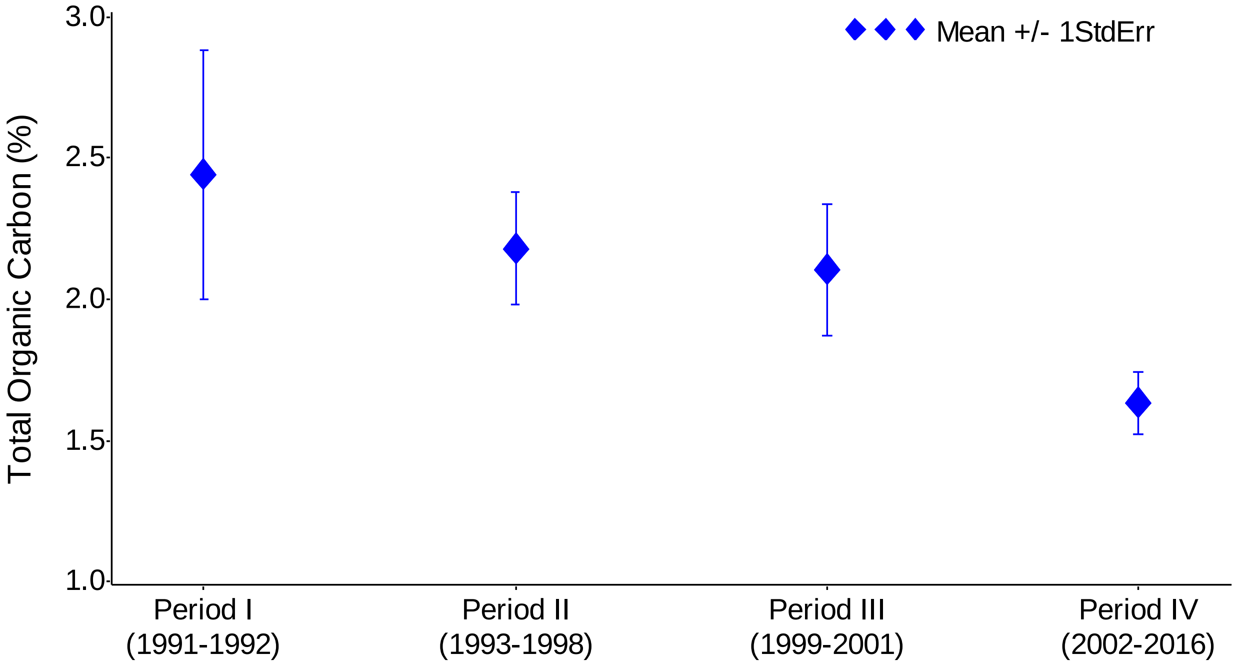

Figure 6. Comparison of TOC across four discharge periods (offset by one year) at Boston Harbor stations (T01-T08) from 1992 to 2016 (1991 excluded).

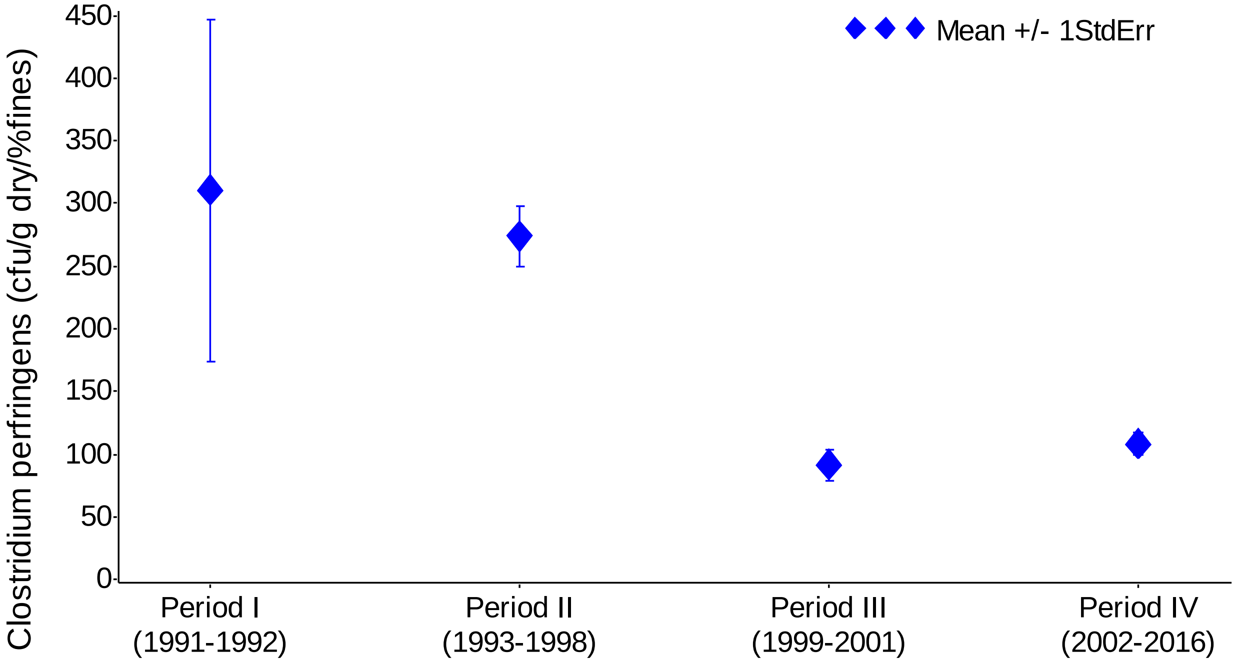

Figure 7. Comparison of *Clostridium perfringens* across four discharge periods (offset by one year) at Boston Harbor stations (T01-T08) from 1992 to 2016 (1991 excluded).

3.2 Benthic Infauna

3.2.1 Community Parameters

A total of 32,348 infaunal organisms were counted from the 18 samples in 2016. Organisms were classified into 134 discrete taxa 125 of which were species-level identifications, including more than 99% of the individuals. Of those not identified to species, all were identified to genus or family. These species richness values are consistent with values observed in the harbor in recent years. Abundance values reported herein reflect the total counts from both species and higher taxonomic groups, while diversity measures are based on the species-level identifications only (Table 2). Data are presented in figures as means (averages per station) unless otherwise noted.

Table 2. 2016 mean infaunal community parameters by station.

Station	Total Abundance	Number of Species	Pielou's Evenness (J')	Shannon-Wiener Diversity (H')	Log-series alpha
C019	937.0	21.0	0.51	2.23	3.83
T01	2020.0	54.0	0.55	3.16	10.24
T02	1860.0	43.5	0.60	3.28	7.99
T03	3053.5	49.0	0.55	3.07	8.38
T04	1398.5	5.5	0.19	0.47	0.87
T05A	1409.0	46.0	0.67	3.72	9.15
T06	4150.0	48.0	0.49	2.70	7.76
T07	967.5	40.5	0.63	3.39	8.65
T08	378.5	38.5	0.75	3.94	11.08

At most stations mean total abundance values reported for 2016 were lower than values in 2015. Decreases in mean abundance were observed at five stations (T01, T02, T03, T05A and T08) and ranged from 27 to 48% (Pembroke et al. 2015). Stations C019, T04 and T07 (that typically have low infaunal abundances) exhibited two to threefold increases in abundance while Station T06 experienced a 50% increase in abundance from 2015 to 2016. With the exception of Station T06, the only stations exhibiting a two to threefold increase in abundance were the typically low abundance stations (C019, T04, and T07). Abundances in 2016 were within the range observed during the post-offshore diversion period but relatively low compared to pre-diversion values (Figure 8). Seven species each contributed at least 2.5% and together they contributed nearly 84% of the total abundance across the eight traditional benthic stations. Most of the species that dominated the infauna at these stations in the past several years continued to do so in 2016 (Table 3) although the rank order changed. Abundances of two taxa (*Mediomastus californiensis* and *Tharyx* spp.) that had been numerical dominants prior to 2013 remained below the 2.5% threshold. The tube-dwelling amphipod *Ampelisca* spp. that rebounded in 2015 remained at similar levels because of high abundances at T03 during both years. Four species of polychaetes and two species of oligochaetes were among the most abundant taxa in 2016. Abundances of two species that achieved dominance status in 2015 based on elevated numbers at a single station, *Clymenella torquata*

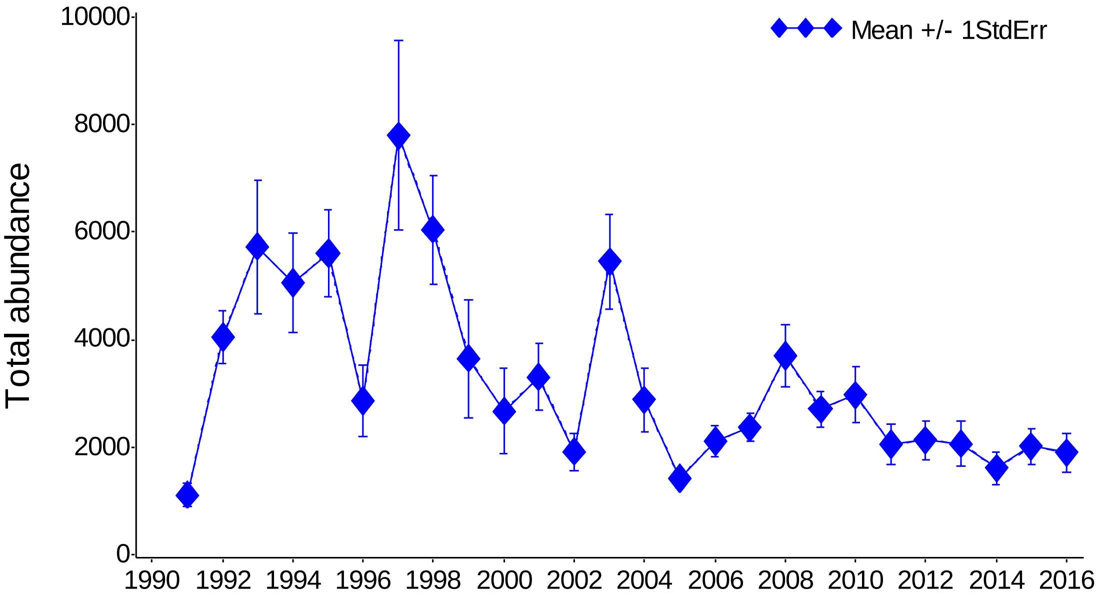

Figure 8. Mean abundance of benthic infauna at eight Boston Harbor stations, 1991-2016.

Table 3. Dominant taxa at eight grab stations in Boston Harbor in August 2016.

Taxon	**Total 2016 Abundance (compared with 2015)[a]**
Aricidea catherinae	6,492 (increase)
Polydora cornuta	5,299 (increase)
Limnodriloides medioporus	3,822 (similar)
Streblospio benedicti	3,713 (increase)
Ampelisca spp.	2,405 (similar)
Tubificoides intermedius[b]	2,048 (decrease)
Scoletoma hebes	1,529 (similar)

[a] increase or decrease indicates ≥25% change from previous year

[b] previously identified as *T. apectinatus*

and Naidinae sp. 1, dropped to well below the 2.5% threshold in 2016. All dominant taxa in 2016 have frequently been among the most abundant in the harbor during previous years. Certain spatial patterns of abundance also appeared to be consistent with previous years; T04, T07 and C019 continued to support low infaunal abundances (Table 2). As previously observed, Station T03 supported among the highest abundances among the harbor stations.

Temporally, benthic infaunal abundance in the harbor has been controlled by a limited number of species (Table 4). Although these dominants have varied somewhat over the course of the surveys, four taxa (*Ampelisca* spp., *Aricidea catherinae*, *Limnodriloides medioporus*, and *Polydora cornuta*) have been among the most abundant organisms during the baseline and subsequent periods. Annual abundances of these species are presented in Figure 9. *Aricidea catherinae* and *Limnodriloides medioporus* have

Table 4. Mean abundance per sample of dominant taxa during four discharge periods at eight Boston Harbor stations (T01-T08), 1992-2016.

Phylum	Higher taxon	Family	Species[a]	Period I	Period II	Period III	Period IV	2016
Annelida	Polychaeta	Capitellidae	*Capitella capitata* complex	65.2	88.8	3.4	6.2	4.1
		Lumbrineridae	*Scoletoma hebes*	3.4	10.5	4.2	69.7	95.6
		Nephtyidae	*Bipalponephtys neotena*[b]	-	11.4	10.3	186.4	16.3
		Paraonidae	*Aricidea catherinae*	325.0	237.4	204.3	228.0	405.8
		Spionidae	*Polydora cornuta*	525.8	1053.0	269.6	257.7	331.2
			Streblospio benedicti	236.0	298.6	27.7	67.9	232.1
	Oligochaeta	Tubificidae	*Limnodriloides medioporus*	484.7	297.9	315.2	243.2	238.9
			Tubificoides intermedius	42.6	101.4	231.2	254.6	128.0
Arthropoda	Amphipoda	Ampeliscidae	*Ampelisca* spp.	354.3	1698.3	1205.9	563.4	150.3
		Corophiidae	Corophiidae spp.	16.1	336.2	23.0	1.4	2.4
			Crassicorophium bonellii	7.9	217.3	37.3	7.7	0.3
			Leptocheirus pinguis	29.0	117.4	66.0	79.5	2.5
		Photidae	*Photis pollex*	11.4	77.0	86.8	31.9	0.6
		Phoxocephalidae	*Phoxocephalus holbolli*	28.0	116.9	125.9	6.5	1.1

[a] Dominants identified as taxa cumulatively composing 75% of total abundance in each period.

[b] previously identified as *Nepthys cornuta.*

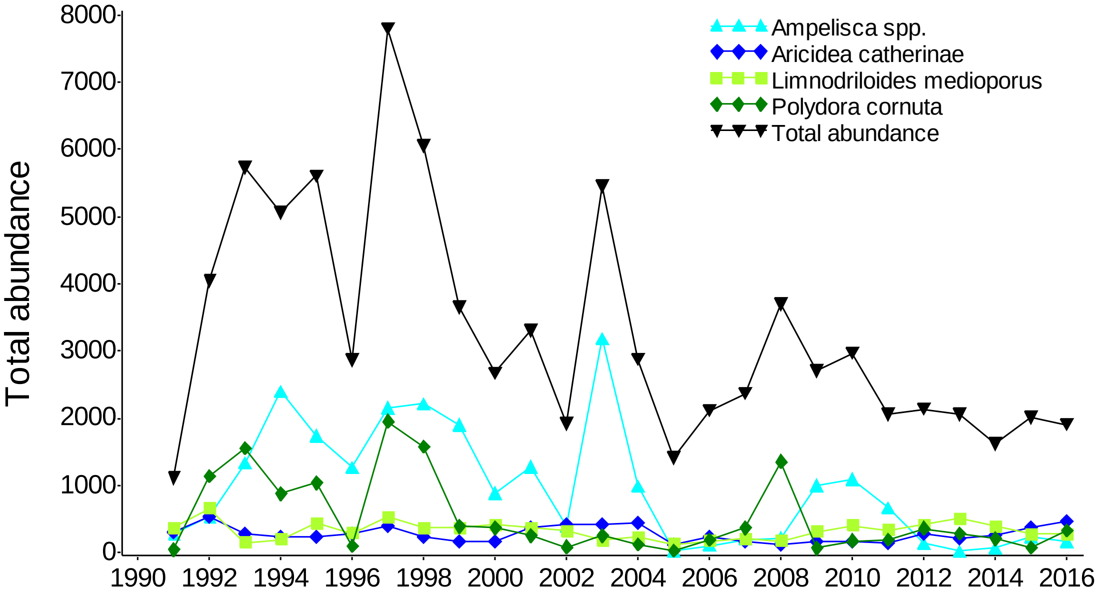

Figure 9. Total abundance of four dominant taxa at eight Boston Harbor stations, 1991-2016.

exhibited little interannual variation in abundance whereas both *Polydora cornuta* and *Ampelisca* spp. have exhibited fluctuations of one to two orders of magnitude and abundances of both species are currently low. Both of these species reside in the upper substrate layer so variability could be related to many factors, including changes in organic enrichment, physical forces such as storm events, and reproductive success in a given year as was described in previous reports (Maciolek et al. 2006, 2011). It is noteworthy that abundances of the oligochaete *Tubificoides intermedius* have steadily increased. While it dropped from its high abundance observed in 2015, it was evenly distributed across the Harbor stations in 2016 and remained higher than during Period I.

Patterns of abundance of *Ampelisca* spp. have been of particular interest throughout the past 24 years that Stations T01-T08 have been studied. Previous annual reports on the harbor surveys have related changes in the spatial extent of *Ampelisca* spp. beds and abundances of individual amphipods to changes in organic loading (the period from 1991 through about 1999) and storm events and subsequent recruitment (around 2005 through 2009; Maciolek et al. 2006, 2011). Following a period of low abundances (2005-2008), average abundances of *Ampelisca* at these stations reached moderately high levels from 2009 through 2011, declining in 2012-2014 to levels comparable to those seen in 2005-2008, and increasing slightly in 2015 (Figure 10). *Ampelisca* was more widespread in 2015 (seven stations) compared to 2014 (five stations) although in both years more than 90% of the population was found at Station T03 in the vicinity of the Main Ship Channel (Figure 11). Severe winter storms in 2004-2005 and 2012-2013 have been suggested as a major factor in disturbing *Ampelisca* mats. Maintenance dredging conducted in the nearby President Roads Anchorage and Main Ship Channel in 2004-2005 could also have resulted in disturbances (sedimentation or substrate contact from anchored vessels) to stations T03 and T05A. Abundances declined slightly in 2016 compared to 2015. As observed in the past two years, Station T03 supported the largest population of this species.

The numbers of species reported for 2016 ranged from 5.5 to 54 per station and averaged about 41 species per sample. These values were higher than numbers reported in most years in the 1990s and about average for the 2000s, when species richness exhibited inter-annual variation (Table 2, Figure 12). Mean species richness was slightly lower in 2016 than in 2015, decreasing at all stations except T02, T06, and T07. Stations T02, T03, and T08 were among the most species-rich stations from 2011 through 2015 (Pembroke et al. 2012, 2013, 2014, 2015, 2016); in 2016 species richness at T02 and T03 was at or above average for the Harbor. Station T04 has consistently supported the lowest species richness in this time frame. Species richness at T07 in Quincy Bay, which reached an unusual peak in 2013, again exhibited relatively high species richness in 2016 (Pembroke et al. 2013, 2014, 2015).

When averaged across the eight outer harbor stations, two measures of community structure, Pielou's evenness and Shannon-Weiner diversity, decreased in 2016 (Figures 13 and 14), and this pattern was evident at most stations (Table 2 and Pembroke et al. 2016). Across the eight stations in the outer harbor, values for these metrics remained within the high range of post-diversion values. Within each station, differences in these metrics between 2015 and 2016 were typically small and, in general, spatial patterns in these parameters were similar between the two years suggesting that the integrity of the benthic

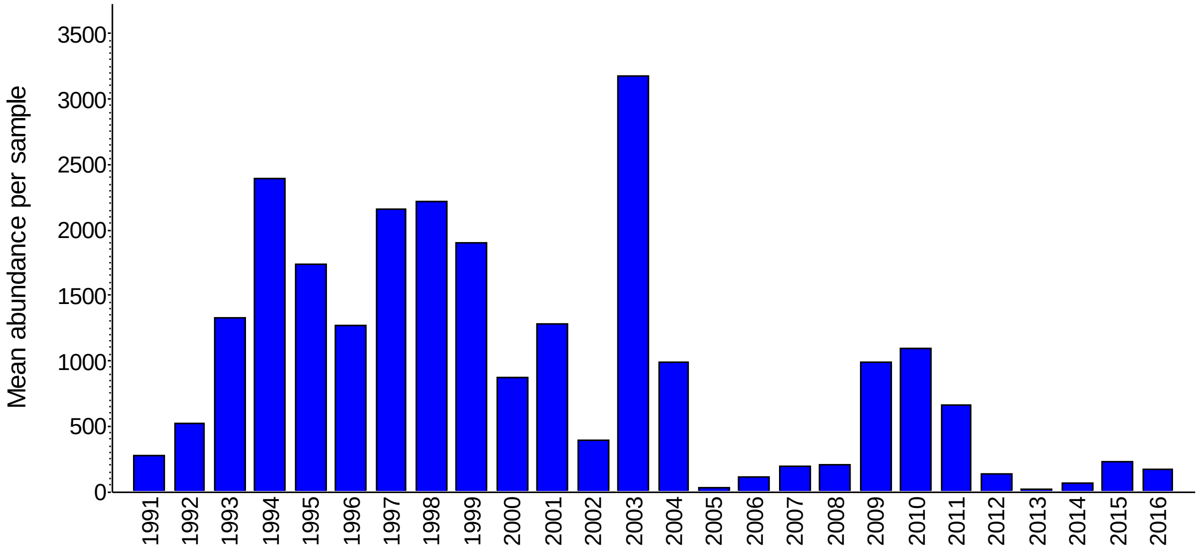

Figure 10. Mean annual abundance of *Ampelisca* spp. averaged over eight Boston Harbor stations, 1991-2016.

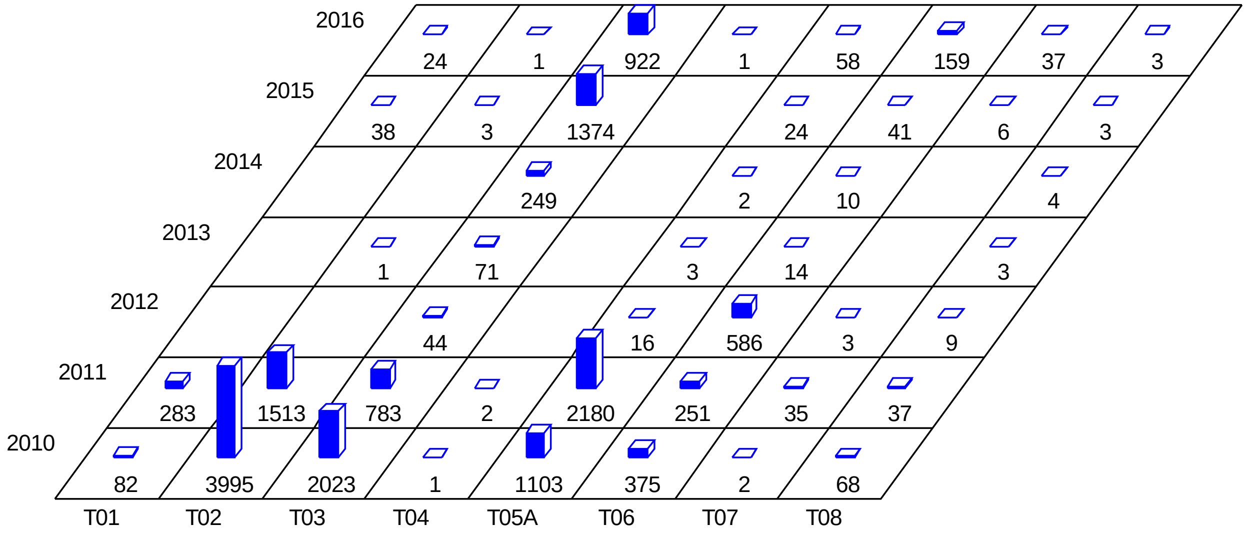

Figure 11. Spatial distribution of *Ampelisca* spp. at eight Boston Harbor stations, 2007-2016.

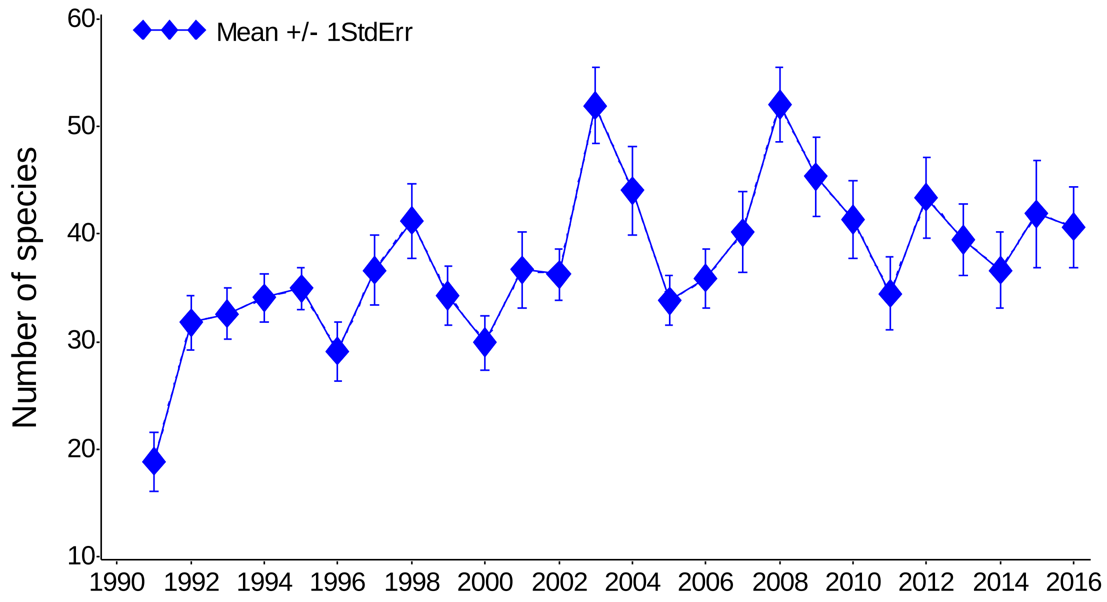

Figure 12. Mean species richness at eight Boston harbor stations, 1991-2016.

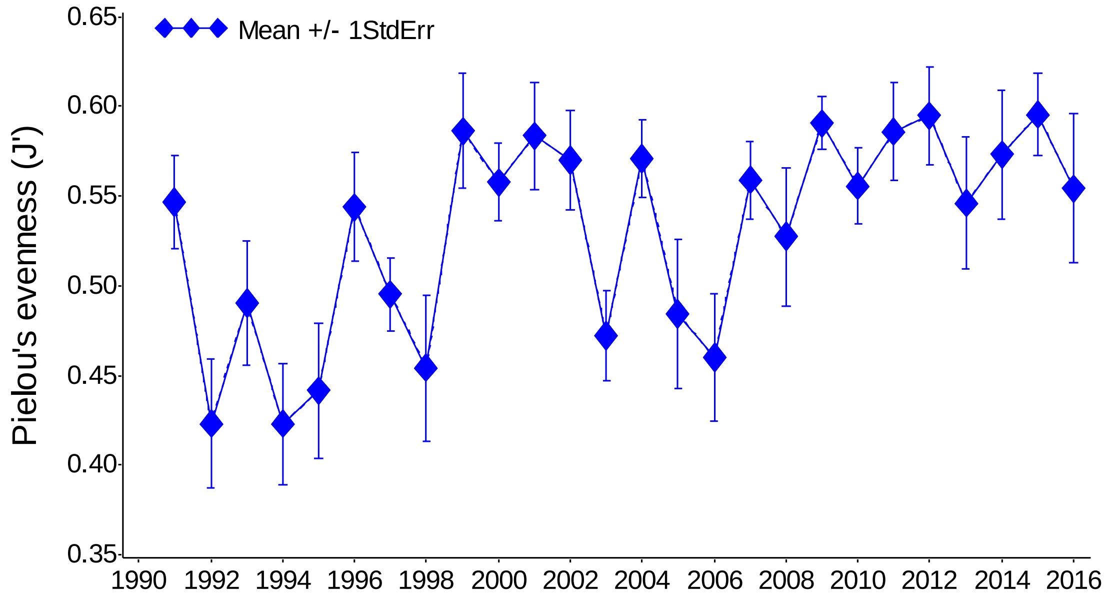

Figure 13. Mean community evenness at eight Boston Harbor stations, 1991-2016.

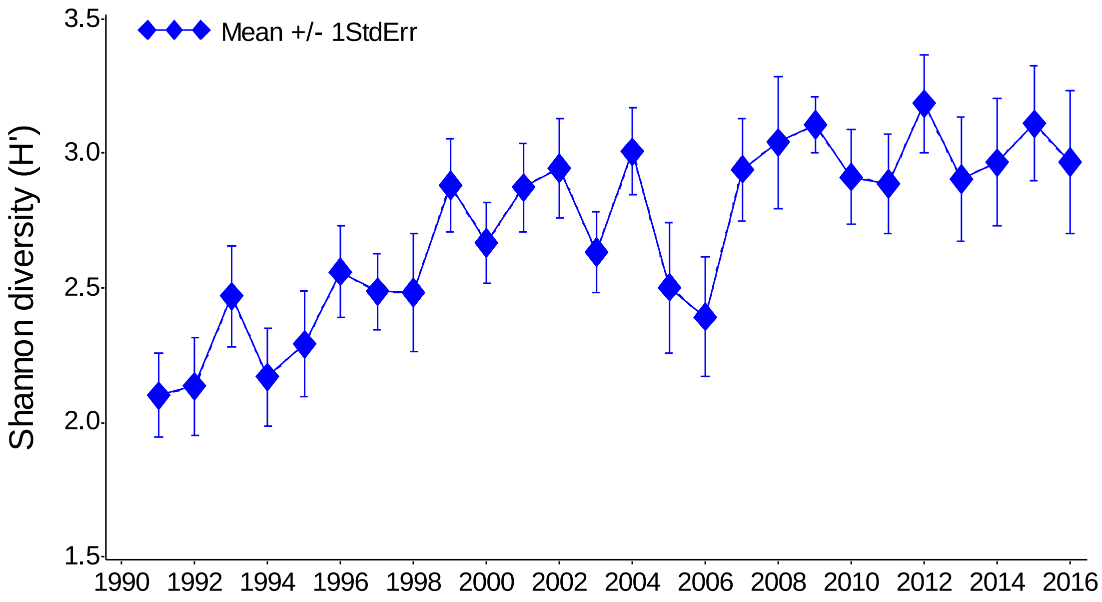

Figure 14. Mean Shannon-Weiner diversity at eight Boston harbor stations, 1991-2016.

infaunal community had not changed. Average diversity for the harbor stations, as measured by log-series alpha, increased in 2016 as it had 2015 (Pembroke et al. 2016). Although the value in 2016 was below the relatively high value seen in 2012 it was well above pre-diversion values (1991-2000; Figure 15). Highest log-series alpha diversity occurred at T08 as has often been observed. Consistent with recent patterns, log-series alpha diversity was lowest at T04 in 2016 (Table 2; Pembroke et al. 2014, 2015, 2016). The largest changes in log-series alpha compared to 2015 were decreases at T01 and T07.

3.2.2 Infaunal Assemblages

Multivariate analyses were used to assess spatial and temporal patterns in the faunal assemblages at the Boston Harbor sampling stations. Replicates within each station exhibited high similarities in community structure and, with the exception of T07, grouped together. Four main assemblages were identified in a cluster analysis of the 18 samples from 2016 (Figure 16). Patterns identified through cluster analysis were confirmed in the MDS ordination plot for the 2016 Harbor samples (Figure 16). All assemblages were dominated by polychaetes or oligochaetes. Spatial patterns in the faunal assemblages of Boston Harbor reflect a habitat gradient from the outer to inner Harbor stations. The Group I assemblage was found at Outer Harbor Station T08; the Group II assemblage was found at all outer Harbor to mid-Harbor stations (T01, T02, T03, T05A, T06, and T07); the Group III assemblage was found at Station C019 in the Inner Harbor. The most distinct assemblage occurred at Station T04 (Group IV) at the mouth of Savin Cove in Dorchester Bay as it typically has in past years. This gradient was also observed in the community parameters (Section 3.2.1) and likely reflects differences in tidal flushing in the Outer Harbor compared to the Inner Harbor along with differing proximity to sources of organic inputs, nutrients, and other possible contaminants.

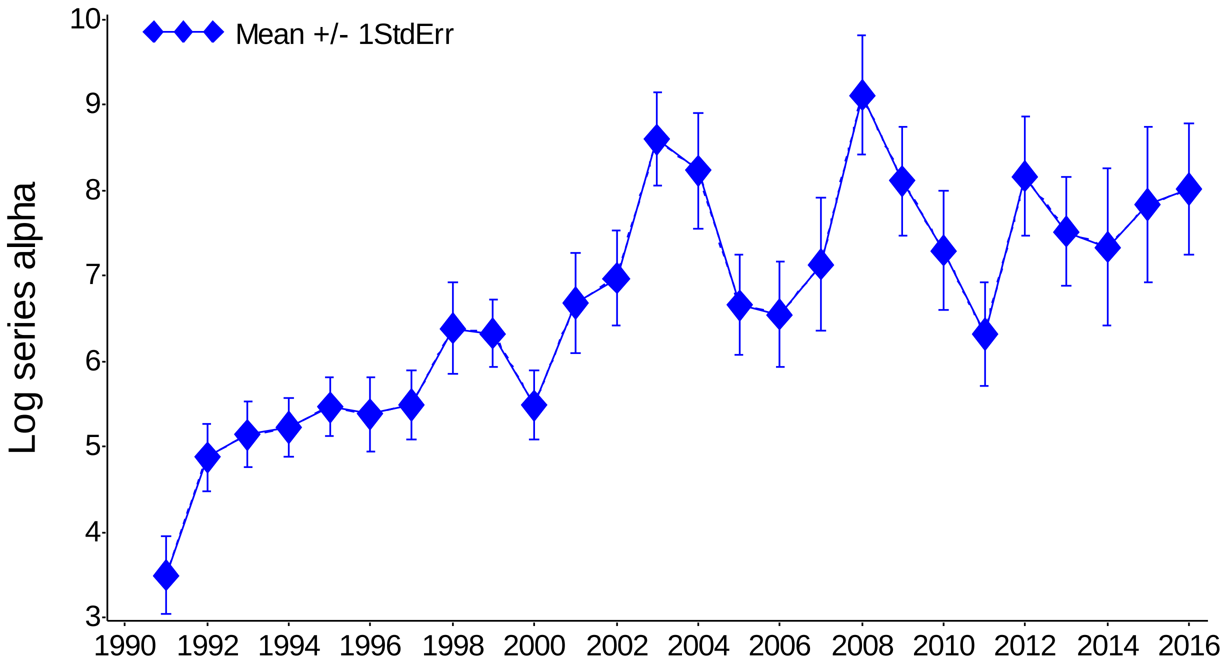

Figure 15. Mean log-series alpha diversity at eight Boston Harbor stations, 1991-2016.

Main Group I consisting only of replicates from Station T08, was characterized by moderately high species richness (averaging 38 species per collection) but low abundance. Three species (*Polygordius jouinae*, *Angulus agilis* and *Clymenella torquata*) together made up half of the total abundance (Table 5). Of these species, *P. jouinae* and *A. argulus* were among the dominants in 2015. The deeper-dwelling polychaete *C. torquata* is considered an indicator of a stable community.

Main Group II encompassed six stations (T01, T02, T03, T05A, T06 and T07) and abundances averaged 2243 individuals across 45.5 species. Five species (*Aricidea catherinae*, *Polydora cornuta*, *Limnodriloides medioporus*, *Ameplisca* spp., *Tubificoides intermedius*, and *Scoletoma hebes*) contributed 80% of the total abundance. Within Group II, Stations T01, T05A, and T07 (one replicate) were distinct enough to form subgroups. Station T01 (Subgroup IA) was dominated by *A. catherinae, P. cornuta*, *T. intermedius* and *L. medioporus* and had the highest species richness (54) of the 2016 collections. Station T05A (subgroup IIB) was dominated by *T. intermedius*, *P. cornuta* and *L. medioporus* had high species richness (46) but relatively low abundance. Subgroup IIC was made up of Stations T02, T03, T06 and one replicate from Station T07. Dominants included *A. catherinae*, *P. cornuta*, *L. medioporus*, *Ampelisca* spp., *S. hebes*, *Streblospio benedicti* and *T. intermedius*. Both abundance and species richness were high. The fourth subgroup was made up of a single replicate from Station T07 that was dominated by *P. cornuta* and *T. intermedius*; total abundance was low and species richness was moderate.

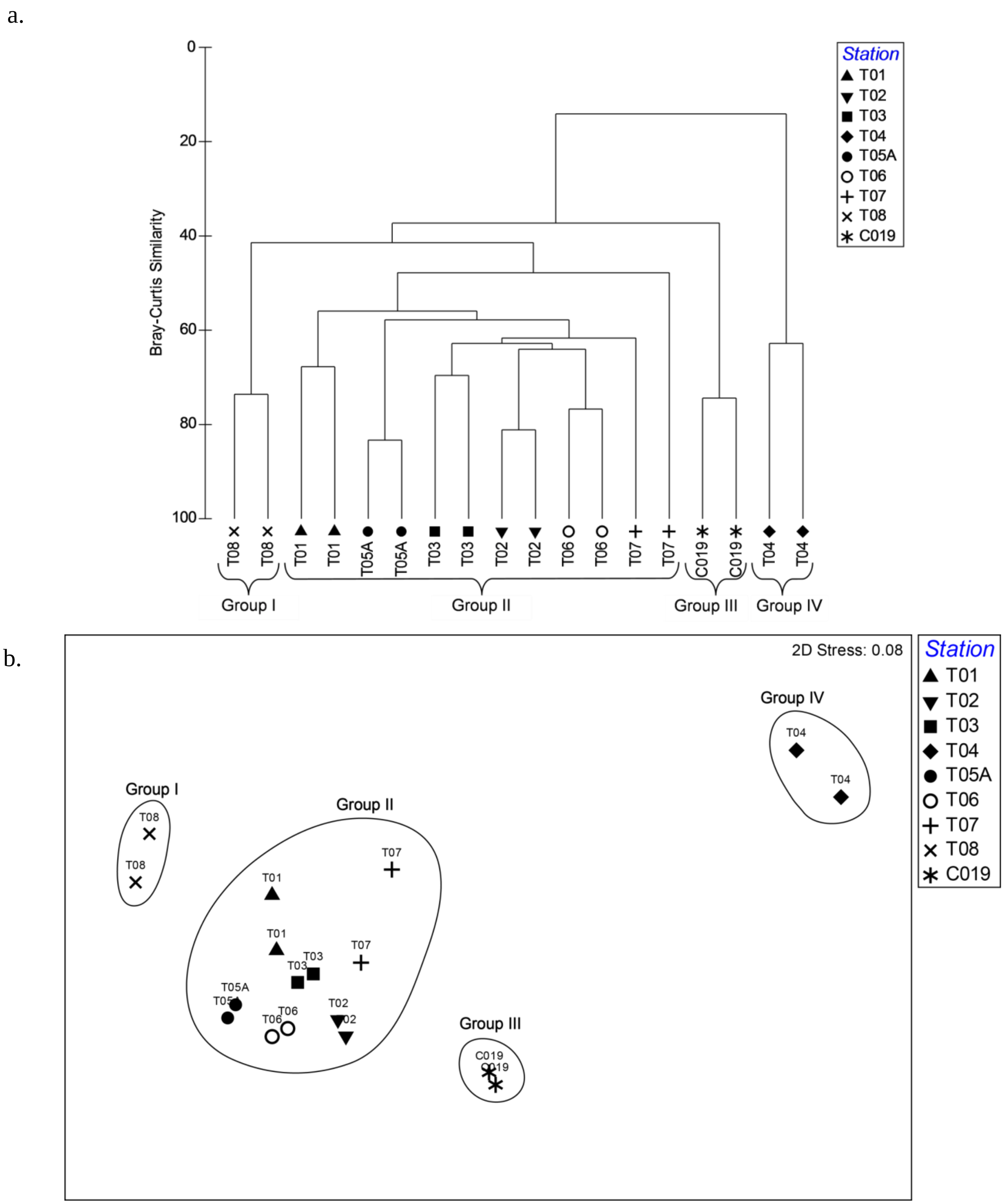

Figure 16. Results of (a) cluster analysis and (b) multidimensional scaling analysis of the 2016 infauna samples.

Table 5. Mean abundance of dominant taxa in 2016 Boston Harbor station groups defined by cluster analysis.

Major Taxon	Family	Species	I	II	IIA*	IIB*	IIC*	T07	III	IV
Bivalvia	Lyonsiidae	*Lyonsia arenosa*	8.5	9.7	34.0	3.0	5.7	2.0	-	-
	Mactridae	*Spisula solidissima*	21.0	1.2	-	3.0	0.7	3.0	3.0	-
	Nuculidae	*Nucula delphinodonta*	8.5	3.2	-	-	5.4	-	-	-
	Tellinidae	*Angulus agilis*	49.5	7.6	11.0	20.5	3.4	4.0	-	-
Polychaeta	Ampharetidae	*Ampharete lindstroemi*	0.5	0.4	1.0	-	0.4	-	-	-
		Ampharete oculata	-	0.3	0.5	0.5	0.3	-	0.5	-
	Cirratulidae	*Tharyx acutus*	12.5	21.2	8.5	22.5	24.4	21.0	1.0	2.0
	Cossuridae	*Cossura longocirrata*	-	0.2	-	-	0.3	-	62.5	-
	Lumbrineridae	*Scoletoma hebes*	0.5	127.3	88.5	22.0	180.7	42.0	2.5	-
	Maldanidae	*Clymenella torquata*	49.5	32.8	96.0	2.0	27.7	3.0	-	-
	Nephtyidae	*Aglaophamus circinata*	-	0.3	-	1.5	-	-	-	-
		Bipalponephtys neotena	-	21.7	1.0	-	30.6	44.0	63.0	-
		Nephtys ciliata	4.0	-	13.0	23.0	4.0	-	-	-
		Nephtys incisa	-	2.8	-	2.0	4.1	-	6.0	-
	Paraonidae	*Aricidea catherinae*	4.5	540.3	778.0	19.5	696.1	15.0	6.5	-
	Polygordiidae	*Polygordius jouinae*	92.0	13.5	0.5	79.5	0.3	-	-	-
	Spionidae	*Dipolydora quadrilobata*	-	-	24.0	-	0.4	-	-	-
		Dipolydora socialis	13.0	7.6	18.5	0.5	5.4	15.0	-	-
		Polydora cornuta	8.0	439.7	203.0	294.5	577.9	236.0	449.5	3.5
		Pygospio elegans	-	-	27.5	-	2.4	1.0	0.5	-
		Scolelepis bousfieldi	1.5	11.5	1.0	2.0	18.9	-	4.0	-
		Spiophanes bombyx	12.0	15.7	5.0	88.5	0.1	-	-	-
		Streblospio benedicti	-	93.1	12.5	4.5	141.1	95.0	150.5	1,298.0
	Syllidae	*Exogone hebes*	5.0	-	20.0	34.0	0.4	-	-	-
	Terebellidae	*Polycirrus phosphoreus*	-	3.3	0.5	-	5.6	-	2.5	-
Oligochaeta	Tubificidae	*Limnodriloides medioporus*	5.0	317.7	310.0	157.0	406.0	36.0	0.5	-
		Naidinae sp. 1	4.0	24.0	21.5	63.5	16.0	6.0	-	-
		Tubificoides intermedius	3.5	169.8	151.0	335.0	134.4	125.0	157.5	1.5
		Tubificoides sp. 2	-	-	-	-	-	-	-	91.0

(continued)

Table 5. (Continued)

Major Taxon	Family	Species	I	II	IIA*	IIB*	IIC*	T07	III	IV
Amphipoda	Ampeliscidae	*Ampelisca* spp.	**3.0**	**199.8**	23.5	58.0	317.4	13.0	-	**0.5**
	Aoridae	*Microdeutopus anomalus*	-	-	21.0	-	1.1	89.0	-	-
	Corophiidae	*Monocorophium sextonae*	-	-	-	-	-	27.0	-	-
	Phoxocephalidae	*Rhepoxynius hudsoni*	**17.5**	-	-	-	-	-	-	-
Isopoda	Idoteidae	*Edotia triloba*	-	-	-	26.0	2.6	-	-	-
Decapoda	Paguridae	*Pagurus longicarpus*	-	**1.2**	-	0.5	0.6	9.0	-	**1.0**

[a] distinct subgroup of Group II

Sediment conditions, particularly percent fines and TOC were likely factors in distinguishing the benthic communities among the Boston Harbor stations. Group I (T08) was predominantly sand and very low TOC. Sediments at stations in Group II ranged from about 45 to 87% sand and moderate to low TOC (0.4 to 2.3%). Sediments at stations C019 (Group III) and T04 (Group IV) were predominantly fines and TOC was higher than at other locations (Table 1).

3.2.3 Selected Stations

Station T01. Infaunal community conditions at Station T01, located near Deer Island Flats north of President Roads, have typically exemplified conditions at most stations in the Harbor throughout the survey period. In 2016, species richness was the highest of the harbor stations, evenness and Shannon-Weiner diversity were average, and log-series alpha was high at T01. All of these community parameters decreased compared to 2015 (Pembroke et al. 2016). Mean abundance in 2016 declined from its 2015 peak but was about average for the post-diversion period (Figure 17). Species richness and log-series alpha were on the high end of the range observed since the diversion (Figures 18 and 19) while Shannon-Weiner diversity and Pielou's evenness were about average for that period (Figures 20 and 21). Although mean log-series alpha was below the peak seen in 2015, it was one of the highest values observed since the diversion to the offshore outfall (Figure 19). In 2016, all of these community parameters except Pielou's eveness remained above the relatively low values observed in 2013 (Figures 17 through 21).

Station C019. Station C019 was initially included in the Harbor sampling program as part of the Sediment-Water Exchange (SWEX) study (Gallagher and Keay 1998). When first sampled in 1989, the benthic infauna consisted of only a few taxa and was overwhelmingly dominated by two polychaete species, *Streblospio benedicti* and *Chaetozone anasimus* (previously called *C. setosa*). Mean abundance declined from its 2013 peak in 2014 and 2015, but increased to average levels in 2016 (Figure 17). Species richness also peaked in 2013 and decreased in both 2014 and 2015 but reached average levels in 2016 (Figure 18). Log series alpha, Shannon-Weiner diversity, and Pielou's evenness all reached their peak values in 2014, declining in both 2015 and 2016 (Figures 19, 20, and 21). Despite two years of decreasing values, all diversity measures remained among the highest levels observed to date. The

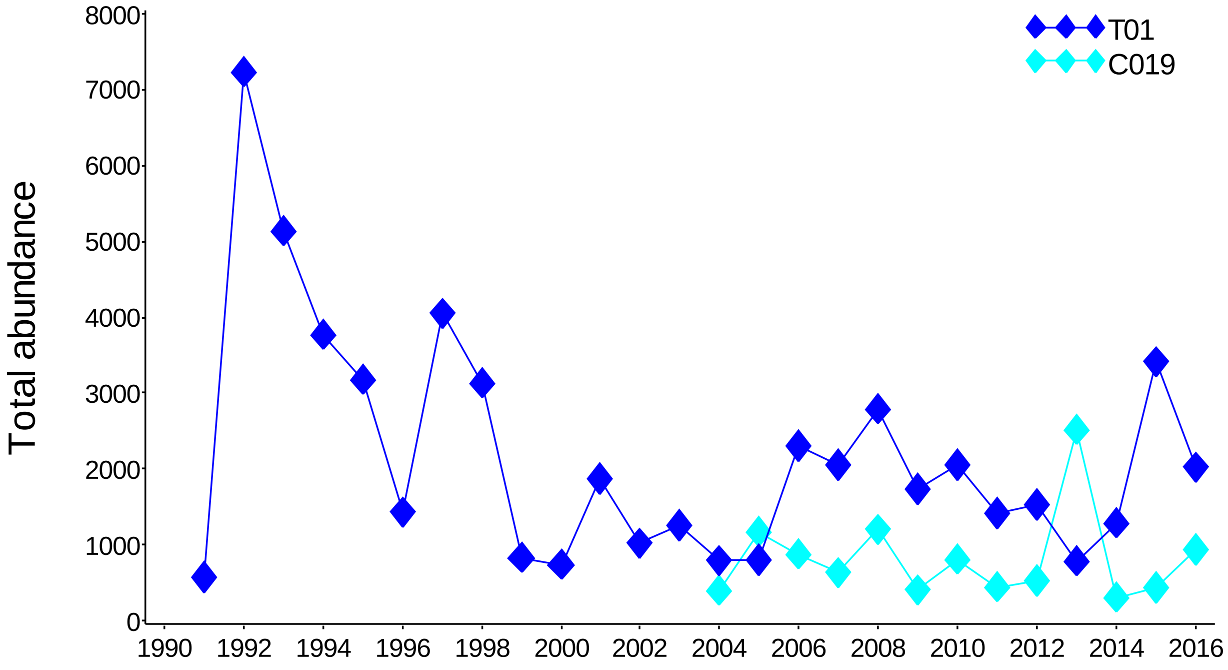

Figure 17. Mean total abundance at Boston Harbor Stations T01 and C019, 1991-2016.

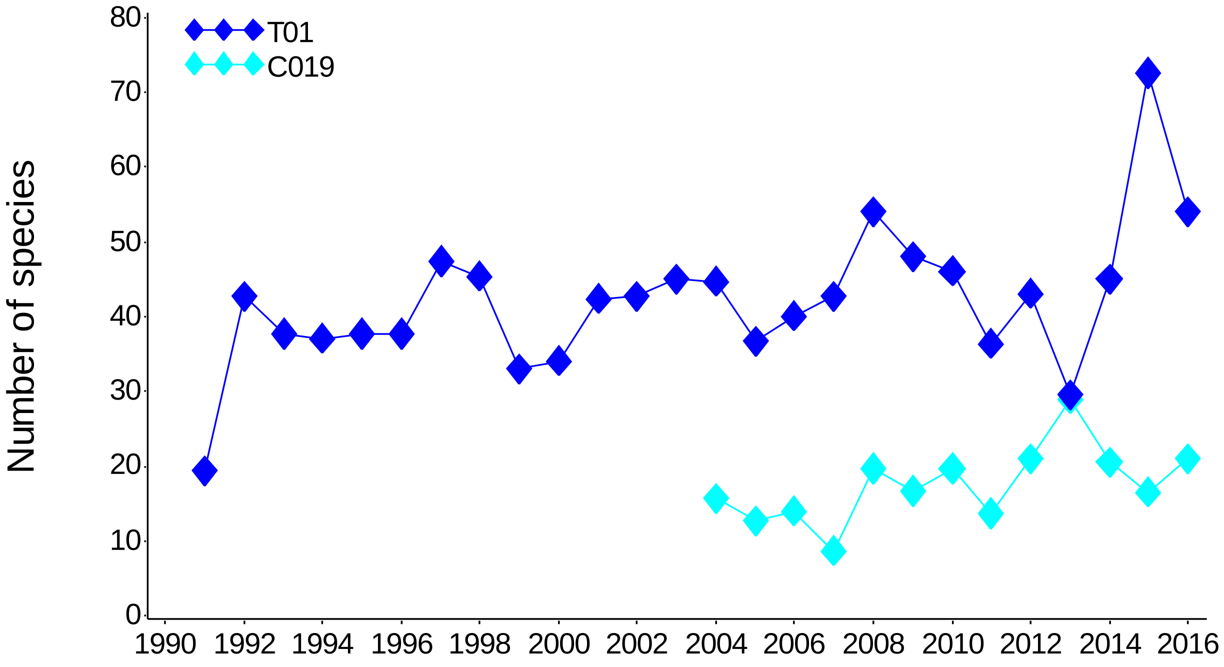

Figure 18. Mean species richness at Boston Harbor Stations T01 and C019, 1991-2016.

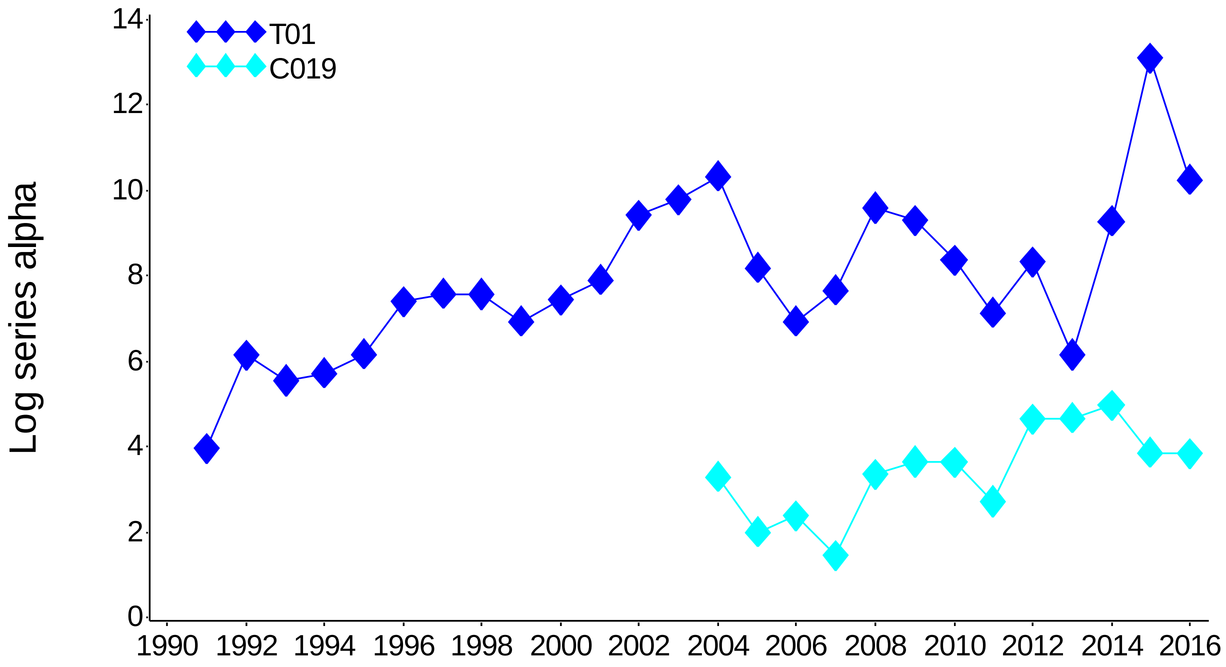

Figure 19. Mean log-series alpha diversity at Boston Harbor Stations T01 and C019, 1991-2016.

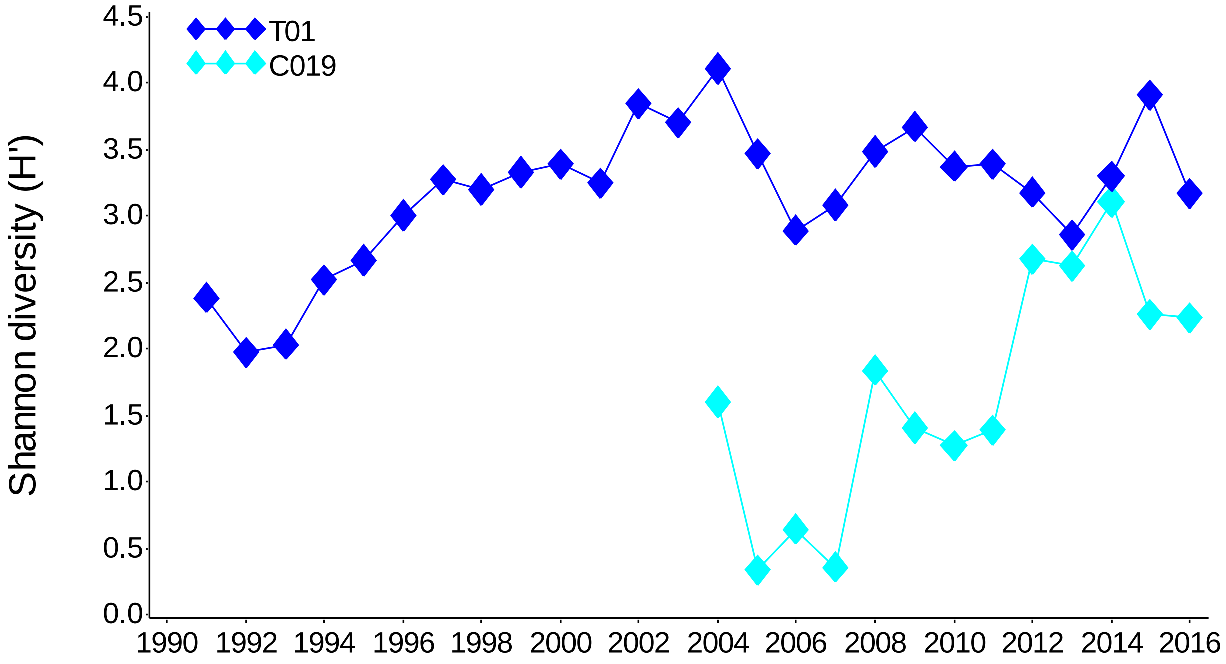

Figure 20. Mean Shannon-Weiner diversity at Boston Harbor Stations T01 and C019, 1991-2016.

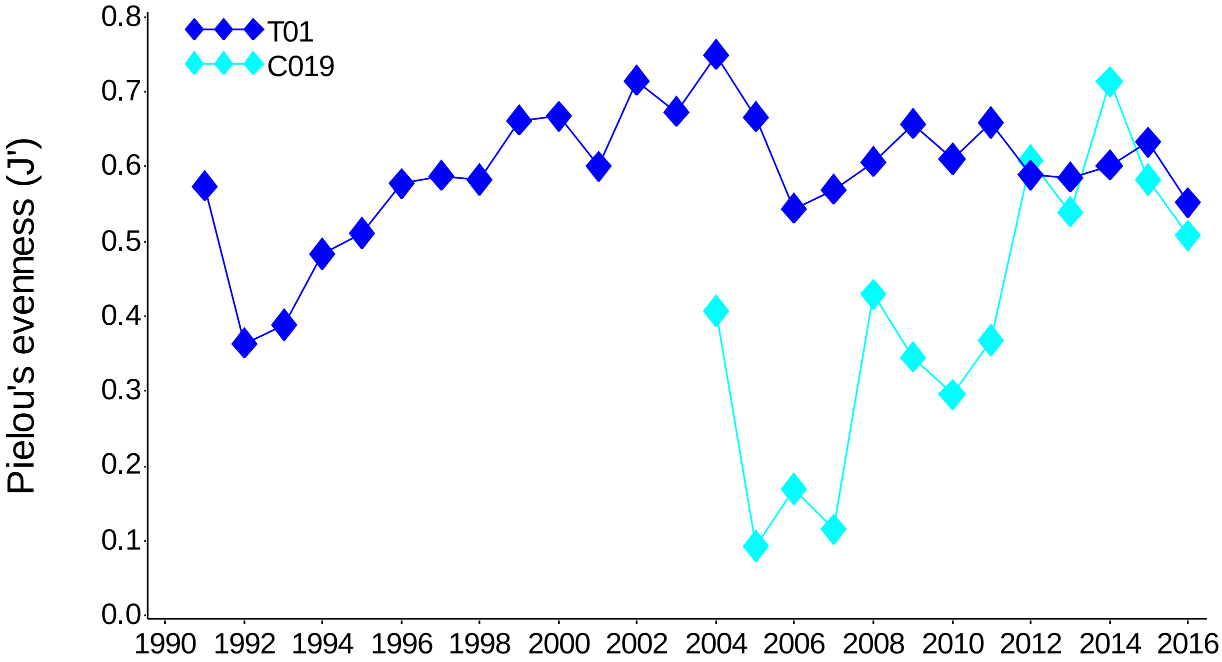

Figure 21. Mean evenness at Boston Harbor stations T01 and C019, 1991-2016.

polychaete *Bipalponephtys neotena* (formerly called *Nepthys cornuta*) had represented the majority of the infauna found at Station C019 from 2004-2011 (Figure 22) but the relative abundance of this species has been substantially lower since 2012 (Pembroke et al. 2013). The community structure has varied since then with *C. anasimus* dominating in 2013 (Pembroke et al. 2014), no numerical dominant in 2014 (Pembroke et al. 2015), and the oligochaete *Tubificoides intermedius* dominating in 2015. In 2016, *Polydora cornuta* dominated the infaunal community (Figure 22).

Temporal Trends

Benthic community parameters for the harbor have exhibited changes since 1991 that correspond well to the management changes defined by Taylor (2006) when a one-year offset is included to account for a lag in benthic community response (Table 6). While mean total abundance has not changed dramatically through these periods, increases in species richness, evenness, and diversity between Periods I and IV have been notable and the trend in all of these parameters suggests a response to the reduction in pollutant loading into the harbor. Mean Period IV values for total abundance, number of species, evenness, Shannon-Weiner diversity, and log-series alpha diversity for 2001-2016 were virtually the same as for 2001-2015 (Pembroke et al. 2016) so it is apparent that this trend has continued.

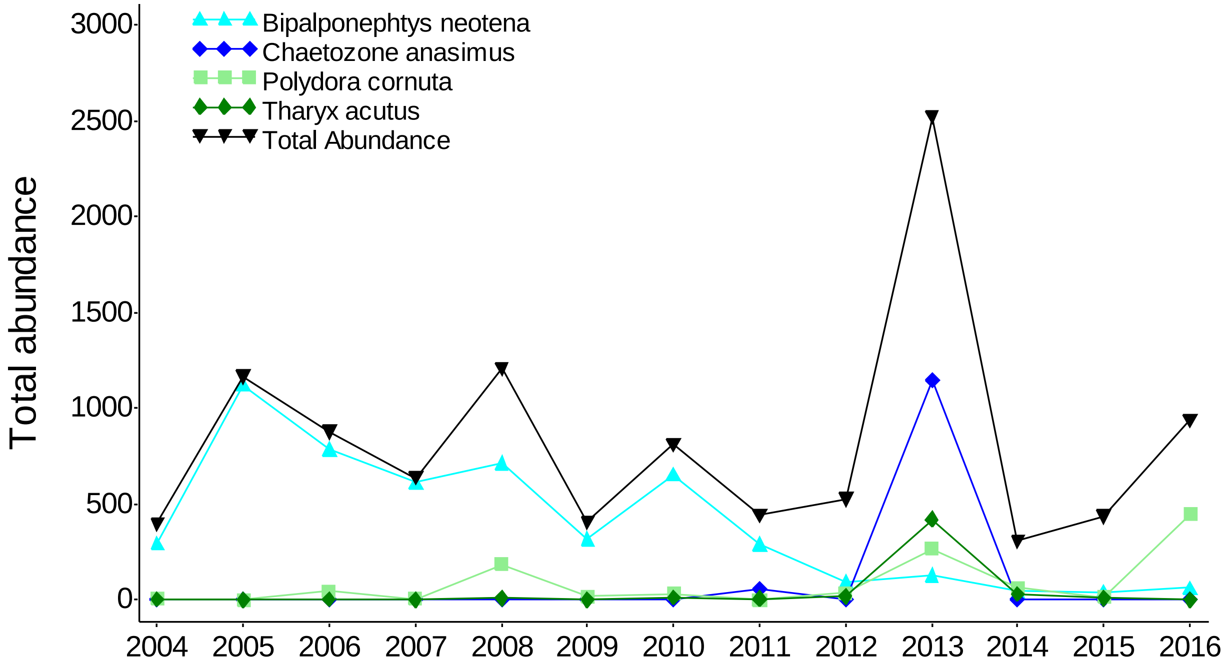

Figure 22. Mean abundance of *Bipalponephtys neotena* and other dominants and total community abundance at Station C019, 2004-2016.

Table 6. Benthic community parameters for stations T01-T08, summarized by time periods defined by Taylor (2006).

Parameter	Period I (prior to Dec. 1991)[a]		Period II (Dec. 1991-mid 1998)		Period III (mid-1998-Sept. 2000)		Period IV (after Sept. 2000)	
	Mean	Std Err	Mean	Std Err	Mean	Std Err	Mean	Std Err
Total Abundance	2,606	344	5,513	469	3,213	493	2,554	130
Log-series alpha	4.2	0.3	5.5	0.2	6.2	0.3	7.6	0.2
Shannon-Wiener Diversity (H')	2.12	0.1	2.4	0.1	2.8	0.1	2.88	<0.1
Pielou's Evenness (J')	0.48	0.02	0.47	0.01	0.58	0.02	0.55	0.01
Number of Species	25.5	2.1	34.7	1.1	33.6	1.7	41.2	0.9
Years included (with one year offset)	1991-1992		1993-1998		1999-2001		2002-2016	

3.3 Sediment Profile Imaging

Improvements in sewage treatment and relocation of outfalls within Boston Harbor in the 1990s with a diversion of all sewage in 2000 to an ocean outfall lead to recovery of pelagic and benthic habitats within the Harbor (Gallagher and Keay 1998, Oviatt et al. 2007, Diaz et al. 2008, Taylor 2010, Tucker et al.

2014). By the mid-2000s much of the recovery in soft bottom benthic habitat quality in terms of benthos and sediment fluxes had taken place (Diaz et al. 2008, Tucker et al. 2014). From the late 2000s to mid-2010s there was year-to-year variation in patterns of benthic habitat quality and benthic communities, but overlaid on this variation was a general long-term trend of improvement (Pembroke et al. 2016).

For 2016, soft bottom benthic habitat conditions in Boston Harbor appeared similar to 2015, as measured by the Organism Sediment Index (OSI) of Rhoads and Germano (1986). The 2015 and 2016 flat trend in OSI was a departure from the long-term trend of increasing OSI values, which started in 2000 and ended in 2009 (Break Point Linear Regression, $R^2 = 0.69$, $p = 0.003$, $N = 10$). In 2010 the OSI dropped and remained level through to 2014 (Break Point Linear Regression, $R^2 = 0.34$, $p = 0.220$, $N = 6$). Overall, the additional dip of OSI in 2015 and 2016 still represented improved benthic habitat quality over the early and late 1990s (Figure 23). OSI provides a means of scaling sediment profile image (SPI) parameters to arrive at a score that can be used to assess benthic habitat quality. The OSI is based on estimated benthic successional stage, thickness of the apparent color redox potential discontinuity layer (aRPD), and apparent presence of low dissolved oxygen (Rhoads and Germano 1986). The OSI ranges from -10, poorest quality habitats, to 11, highest quality habitats. For soft sediment benthic habitats within northeastern estuarine and coastal ecosystems, such as portions of Boston Harbor, values of 6 and greater were associated with higher quality habitats with well-developed macrofaunal communities. An OSI of <6 would indicate stressful benthic habitat conditions, although the OSI cannot identify the source

Figure 23. Plot of OSI anomaly (yearly - grand mean OSI) for all SPI stations in Boston Harbor over the 25 years of monitoring. Higher OSI years are positive and lower are negative values. Vertical lines separate periods of change in wastewater treatment based on Taylor (2010). IIA is post sludge disposal, IIB is full primary treatment, III is implementation of secondary treatment, and IV is offshore diversion. OSI less than 6 indicates stressed benthic habitat.

of stress. Stress as indicated by OSI is defined in the sense of Menge and Sutherland (1987) as a factor that prevents an organism from operating at its optimal level due to either physical forces (e.g. strong currents or sediment instability) or through inducing physiological responses in the organism (e.g., salinity or hypoxia). Diaz et al. (2003) found the OSI to be significantly correlated to benthic habitat quality (i.e., salinity, sediment type, low dissolved oxygen, and contamination) in Chesapeake Bay. In Narragansett Bay, Valente et al. (1992) found the OSI related to organic content of the sediment and OSI values >7 to be associated with equilibrium Stage III communities.

3.4 Regional Harbor Patterns

Stressed benthic habitat conditions continued to dominate the seven stations in Dorchester Bay for 2016 (Table 7, Figure 24). From 1992 to 2016 the grand mean OSI for Dorchester Bay was 4.9 (SD = 1.37 cm) with Periods IIA and III being lowest. By 2005, five years after diversion, benthic habitats improved with annual OSIs above 6 where it basically remained until 2012 when OSI again declined. Much of the pattern in OSI could be attributed to variation in aRPD layer depth around the grand mean of 1.5 cm (SD = 0.58 cm) with thinnest layers in Periods II and III and increases into Period IV. Advancement of estimated successional stage toward equilibrium Stage III from 2005 to 2009 produced the highest benthic habitat quality for Dorchester Bay. Estimated successional stage tended to decline after 2010. Poorest habitat quality was consistently found at Station T04 which always appeared to have Stage I pioneering communities except for 1996 when Stage II amphipod tubes were present (Figure 24). But improvements in habitat quality did occur as OSI for T04 was positively correlated with community structure variables J evenness ($r = 0.62$, $p = 0.002$) and H diversity ($r = 0.61$, $p = 0.002$) and negatively correlated with total abundance ($r = -0.78$, $p = <0.001$). After diversion, Stations R14, R40 and R41 exhibited the most improvement in Period IV relative to Periods II and III.

Benthic habitat conditions at the ten stations in Quincy Bay followed a similar pattern as Dorchester Bay, but had a higher grand mean OSI of 5.9 (SD = 1.18 cm) (Table 7, Figure 25). Periods II and III had the lowest OSI values. After diversion benthic habitats improved for several years before declining in 2015 and 2016. Much of the decline in OSI was associated with a declining trend in aRPD layer depth from 2010 to 2016. For these years the aRPD was below the grand mean of 1.9 cm (SD = 0.57 cm). Advancement of estimated successional stage toward equilibrium Stage III starting in Period IV lead to the highest benthic habitat quality for Qunicy Bay in 2008. This appeared to be related to increased bioturbation from high abundance of the burrowing amphipod *Leptocheirus pinguis* (Figure 25). OSI for Station T07 was positively correlated with abundance of *L. pinguis* ($r = 0.42$, $p = 0.038$). Poorest habitat quality was consistently found at Station R36 which always appeared to have Stage I pioneering communities except for 2000 and 2002 when Stage II amphipod tubes were present.

Stations within the Inner Harbor and Hingham Bay also tended to have lower benthic habitat quality with both regions having a grand mean OSI of 5.5 (SD = 1.41 and 1.34 cm, respectively) (Table 6, Figures 26 and 27). For the three Inner Harbor stations habitat quality remained low through Periods II and III, and well into IV. From 2011 on habitat quality was good, primarily related to advances in estimated

Table 7. OSI summarized by Boston Harbor region for all 25 years. Regions are arranged from lowest to highest OSI. OSI value below six indicates stressed benthic habitat.

Harbor Region	Minimum of All Years	Maximum of All Years	Grand Mean All Years	2015	2016	Change (2016-2015)	No. stations
Dorchester Bay	2.1	7.2	4.9	4.9	4.2	-0.7	7
Quincy Bay	3.3	8.4	5.9	5.7	5.6	-0.1	10
Inner Harbor	3.0	8.1	5.5	6.9	6.2	-0.7	3
Hingham Bay	2.8	7.9	5.5	6.2	6.5	0.2	7
Deer Island Flats	3.6	9.0	6.9	6.3	6.9	0.6	8
President Roads	2.9	9.3	6.6	6.0	7.3	1.3	3
Off Long Island	6.2	9.4	7.4	6.5	6.7	0.2	8
Nantasket Roads	5.8	9.8	7.8	8.1	8.1	0.0	6
Hull Bay	5.9	8.8	7.5	7.1	7.7	0.6	9

successional stage from Stage I to Stages II and III. For example, from 2011 to 2016 surface and subsurface biogenic features increased at CO19, which was first sampled in 2004, coincided with the appearance of both *Ampelsica* spp. and *L. pinguis.* Total amphipod abundance increased at CO19 from 2004 to 2013 ($r = 0.84$, $p = 0.003$), peaked in 2012 at about 1,900 m^2, and then declined. aRPD layer depth also tended to increase from 2011 to 2015. For these years the aRPD was above the grand mean of 1.7 cm (SD = 0.47 cm). In 2016 the aRPD declined to 1.1 cm. OSI was positively correlated with H diversity ($r = 0.72$, $p = 0.030$).

For the seven Hingham Bay stations the patterns for OSI were different then the Inner Harbor. Overall Hingham Bay habitat quality declined from Period IIA, which was moderately good to poor in Periods IIB and III, and remained lower until 2007 (Figure 27). After Period IIA, Hingham Bay did not consistently stay above the grand mean OSI of 5.5 (SD = 1.34 cm) until 2007. Much of the improvement in Hingham Bay was related to advancement in estimated successional stages from Stage I to Stage III with increased biogenic activity. Coarse sediment Station R19 was an exception and remained at Stage I for most of the monitoring period. With the start of Period IV, aRPD layer depths tended to be above the long-term mean of 1.7 cm (SD = 0.47 cm), which tended to drive OSI values higher.

Better habitat conditions characterized mid and outer harbor areas of President Roads and Deer Island Flats relative to the Inner Harbor and Hingham Bay (Table 7, Figures 28 and 29). Several years after diversion the three President Roads stations exhibited large improvements in benthic habitat quality that were sufficient to bring the grand mean OSI to 6.6 (SD = 2.07), above the <6 OSI threshold for stressed benthic habitat. Advancement of estimated successional stage toward equilibrium Stage III starting early in Period IV lead to the high benthic habitat quality until 2014 when OSI declined. The decline was

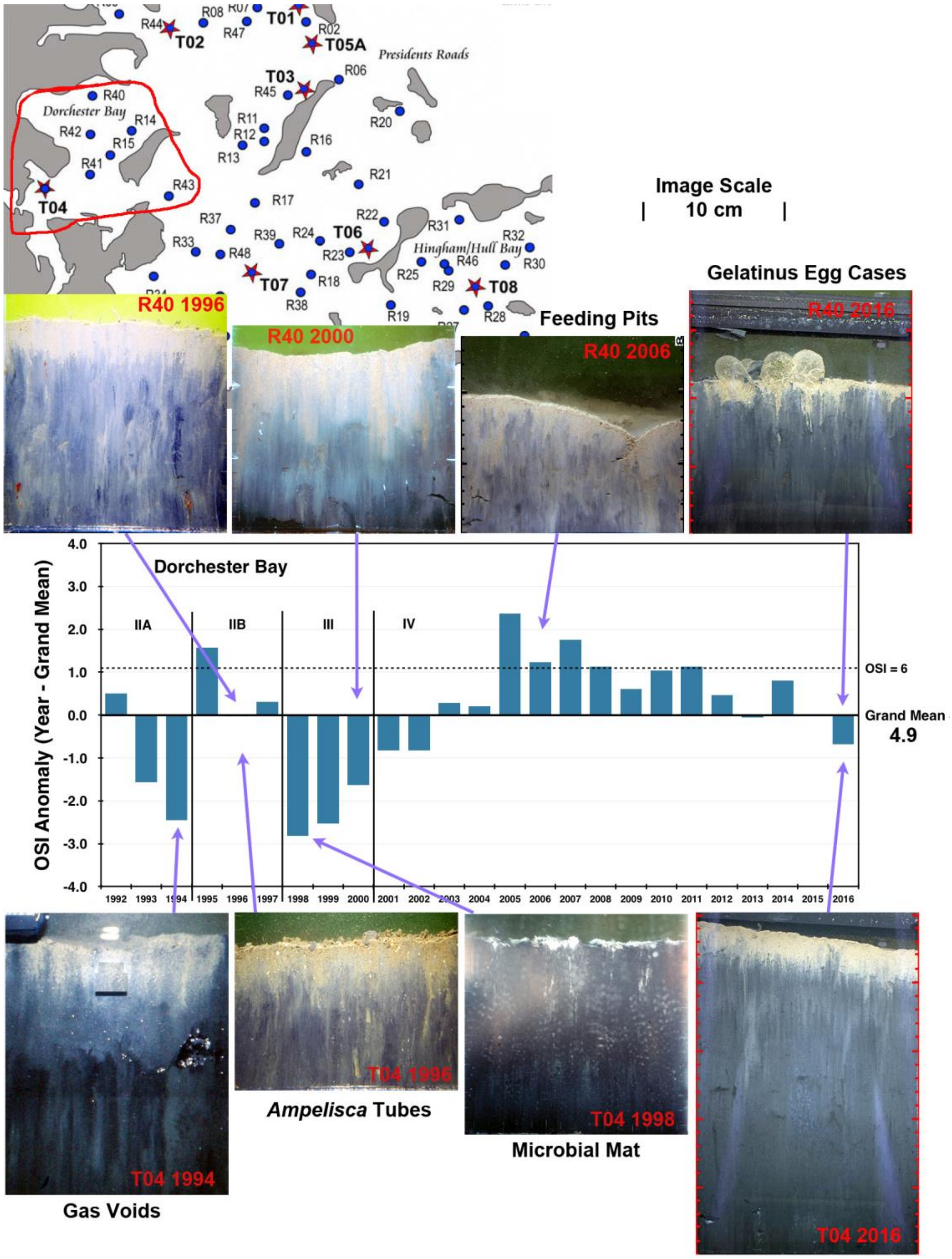

Figure 24. OSI anomaly (yearly - grand mean OSI) for Dorchester Bay stations. Station R40 is a typical and T04 the lowest OSI station in Dorchester Bay. Higher OSI years are positive and lower are negative values. Map insert shows stations within region. Vertical lines separate periods of change in wastewater treatment based on Taylor (2010). Period IIA is post sludge disposal, IIB is full primary treatment, III is implementation of secondary treatment, and IV is offshore diversion. OSI less than 6 indicates stressed benthic habitat.

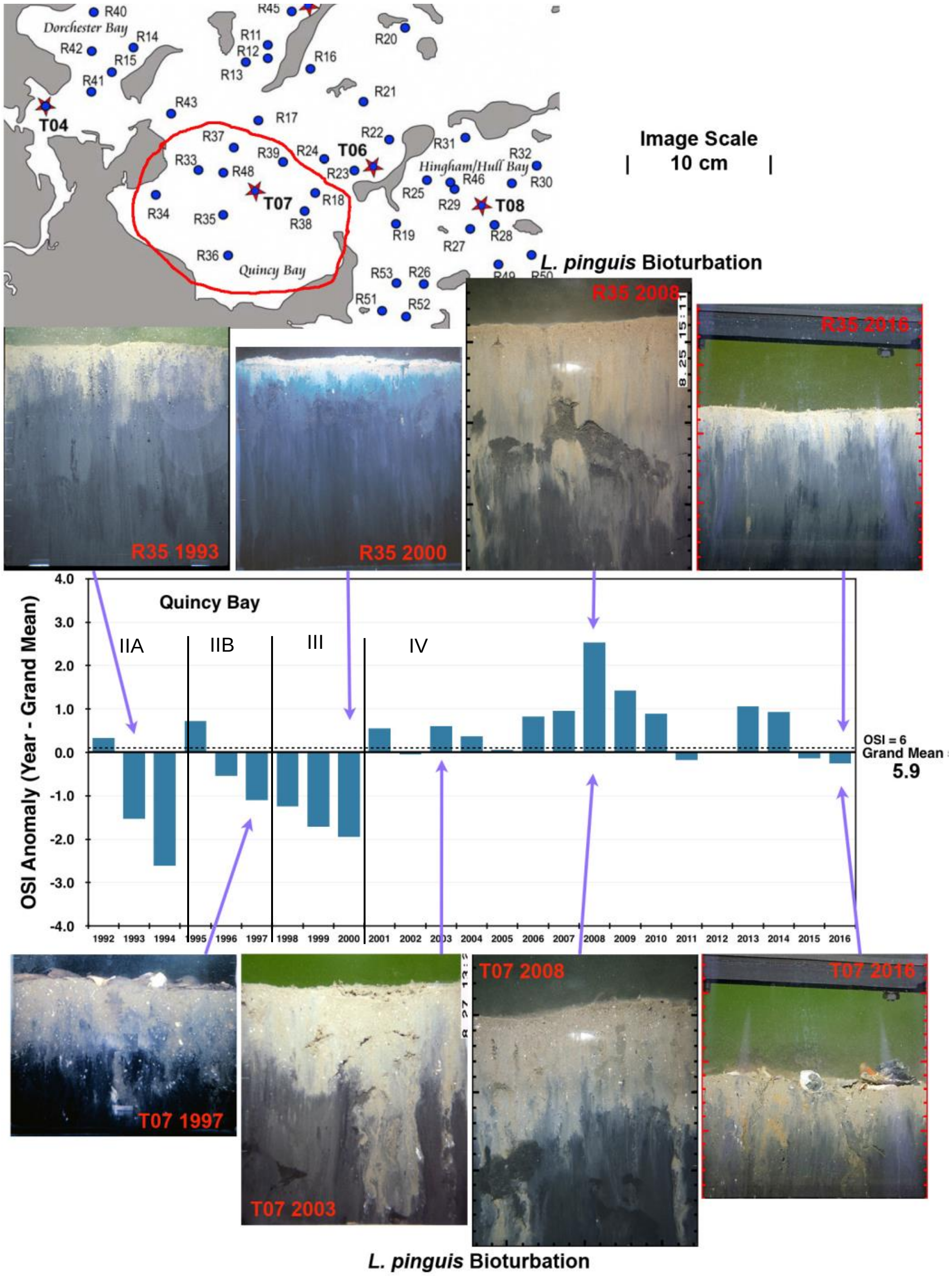

Figure 25. OSI anomaly (yearly - grand mean OSI) for Quincy Bay stations. R35 and T07are typical OSI stations in Quincy Bay. Higher OSI years are positive and lower are negative values. Map insert shows stations within region. Vertical lines separate periods of change in wastewater treatment based on Taylor (2010). Period IIA is post sludge disposal, IIB is full primary treatment, III is implementation of secondary treatment, and IV is offshore diversion. OSI less than 6 indicates stressed benthic habitat.

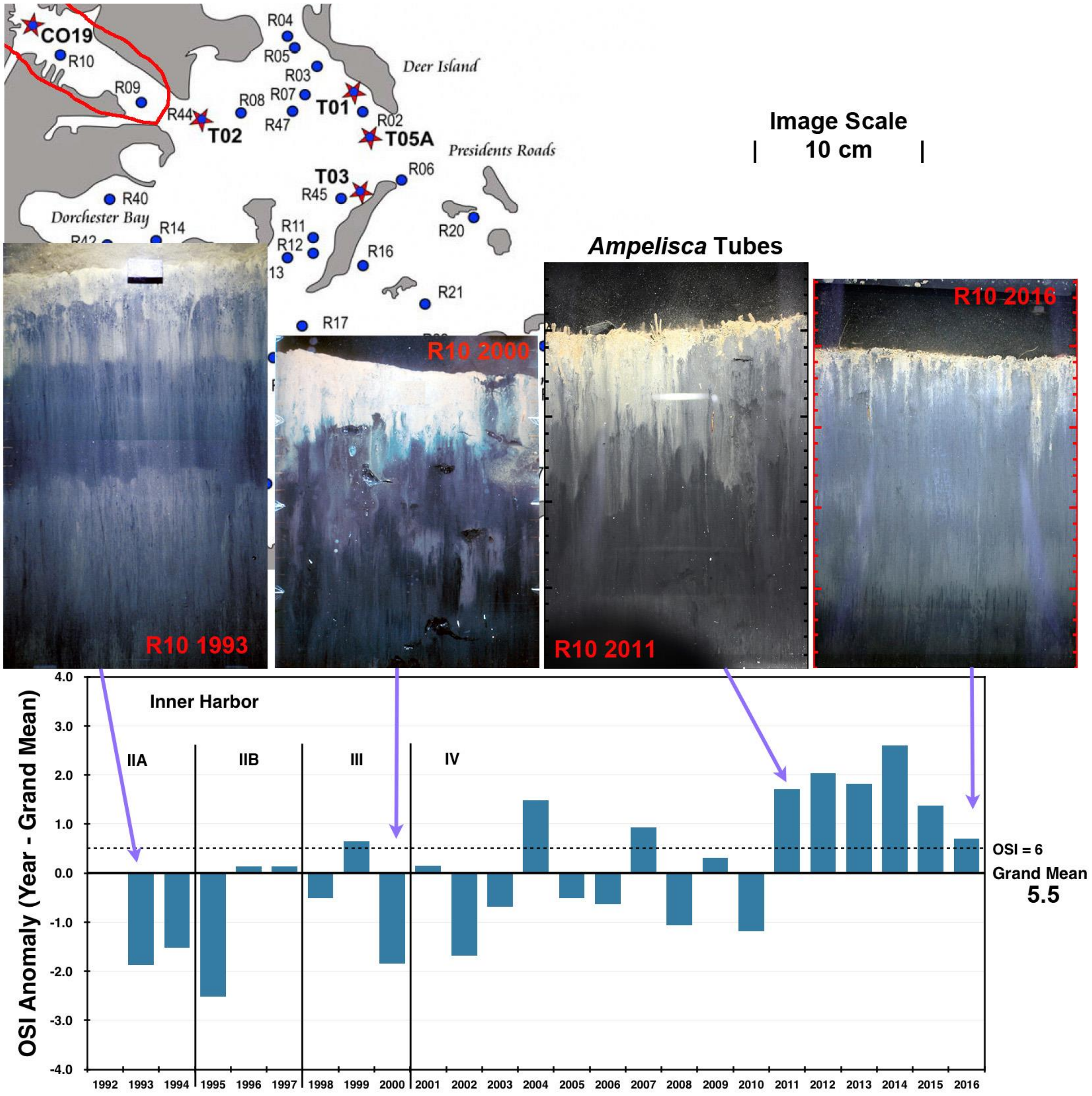

Figure 26. OSI anomaly (yearly - grand mean OSI) for Inner Harbor stations. R10 is typical OSI station for Inner Harbor. Higher OSI years are positive and lower are negative values. Map insert shows stations within region. Vertical lines separate periods of change in wastewater treatment based on Taylor (2010). Period IIA is post sludge disposal, IIB is full primary treatment, III is implementation of secondary treatment, and IV is offshore diversion. OSI less than 6 indicates stressed benthic habitat.

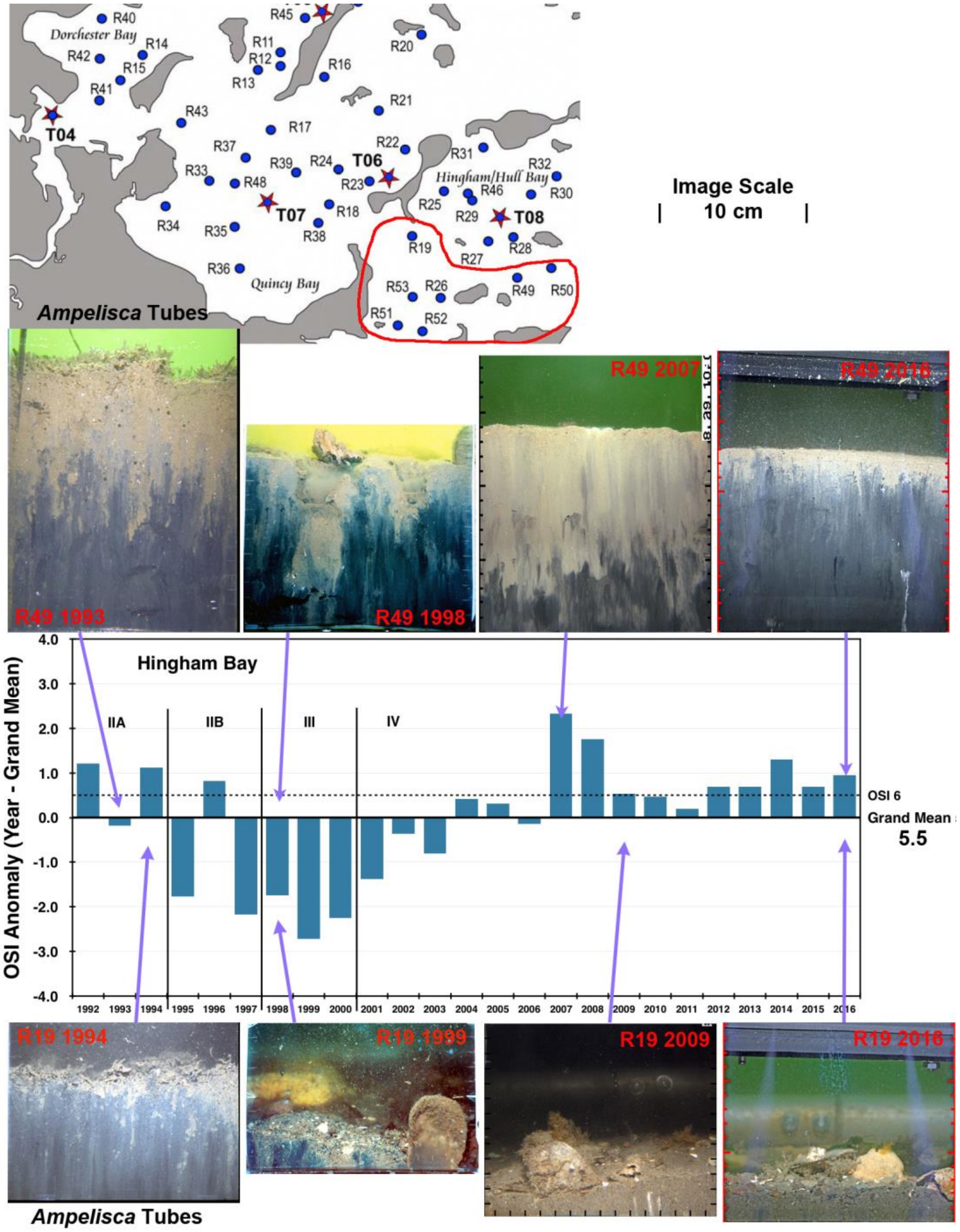

Figure 27. OSI anomaly (yearly - grand mean OSI) for Hingham Bay stations. R49 is a typical OSI station in Hingham Bay. Station R19 was coarse sediments with lower OSI. Higher OSI years are positive and lower are negative values. Map insert shows stations within region. Vertical lines separate periods of change in wastewater treatment based on Taylor (2010). Period IIA is post sludge disposal, IIB is implementation of primary treatment, III is full secondary treatment, and IV is offshore diversion. OSI less than 6 indicates stressed benthic habitat.

related to thinner aRPD layers at both Stations T02 and T05A, and to a decline in estimated successional stage for Station T05A. The increase in OSI appeared to be related to increased bioturbation from high abundance of the burrowing amphipod *L. pinguis* (Figure 28). In 2008 *L. pinguis* reached about 42,000 m^2 at T02 and only about 600 m^2 at T05A. OSI at Station T02 was positively correlated with abundance of *L. pinguis* (r = 0.43, p = 0.034) and total species (r = 0.52, p = 0.009), but not with the tube building amphipod *Ampelisca* spp. that was also abundant and formed tube mats in primarily in Period IIB and again in Period IV from 2010 to 2012. While tube mats were present during Period IIB, the aRPD layer depth associated with them was shallow ranging from 0.8 cm to 1.7 cm. The mats that appeared in Period IV were coincident with deeper aRPD layers from 2.0 cm to 4.2 cm. The grand mean aRPD for the entire monitoring period at President Roads was 2.2 cm (SD = 1.04 cm). All three of the President Roads stations improved greatly after diversion (Figure 28).

The eight stations on Deer Island Flats, the shallow area north of President Roads, followed a similar pattern to President Roads (Figure 29) with the long-term OSI grand mean of 6.9 (SD = 1.33). Periods IIA and III were the only time OSI was <6 for the eight stations. Period IIB was above 6 for all three years. After diversion the OSI gradually increased to a peak between 2007 and 2008. Much of the pattern in OSI could be attributed to a general deepening of the aRPD layer depth that started in Period III and continued till 2013 when aRPD declined to below the grand mean of 2.7 cm (SD = 0.87 cm). The thinnest aRPD layers occurred in Periods IIA. By the start of Period IIB in 1995, estimated successional stage had advanced toward equilibrium Stage III and stayed at that level through to 2016. This may have been related to increased bioturbation from increased abundance of *L. pinguis* at the start of Period IV. Station R08 was an exception with estimated successional stage staying at Stage I all years but with some Stage II amphipods present in 1996 and 1997. Station T01 followed a similar patter to R08 but did have a period of Stage III equilibrium communities present in 2008 and 2009. OSI for Station T01 was almost negatively correlated with *L. pinguis* abundance (r = -0.39, p = 0.059), positively correlated with Fisher alpha (r = 0.44, p = 0.032), and negatively correlated with total organic carbon (TOC, r = -0.47, p = 0.019).

The highest OSI regions were off Long Island, Nantasket Roads, and Hull Bay (Figures 30, 31, and 32). Over the 25 years of Boston Harbor SPI monitoring, stations in these three regions consistently had good benthic habitat quality. For the eight stations off Long Island the annual OSI mean never dipped below 6 with a grand mean of 7.4 (SD = .90) (Table 6) despite the individual means for Stations R06, R13, and R16 being 5.2 to 5.8. Stations R06 and R16 had coarser sediments that tend to score lower for OSI because of physical stress associated with naturally dynamic sandy sediments. Station R13 was finer sediment with most years having thin aRPD layers (Figure 30). If these three station are removed from, the grand mean OSI for the other five Long Island stations was 8.4. The overall high benthic habitat quality around Long Island was due to a combination of deep aRPD layers and predominance of estimated successional Stage II and III. The grand mean aRPD layer depth for all eight stations was 3.2 cm (SD = 0.89 cm), the deepest for all Harbor regions. Bioturbation and biogenic structures from high densities of tube building *Ampelsica* spp. and burrowing *L. pinguis* appeared to be responsible for the high habitat quality at Station T03. From 1994 to 2003 these amphipods averaged over 90,000 m^{-2} with a range of 32,000 m^{-2} to 240,000 m^{-2} (Pembroke et al. 2016), but the correlations of OSI with amphipod

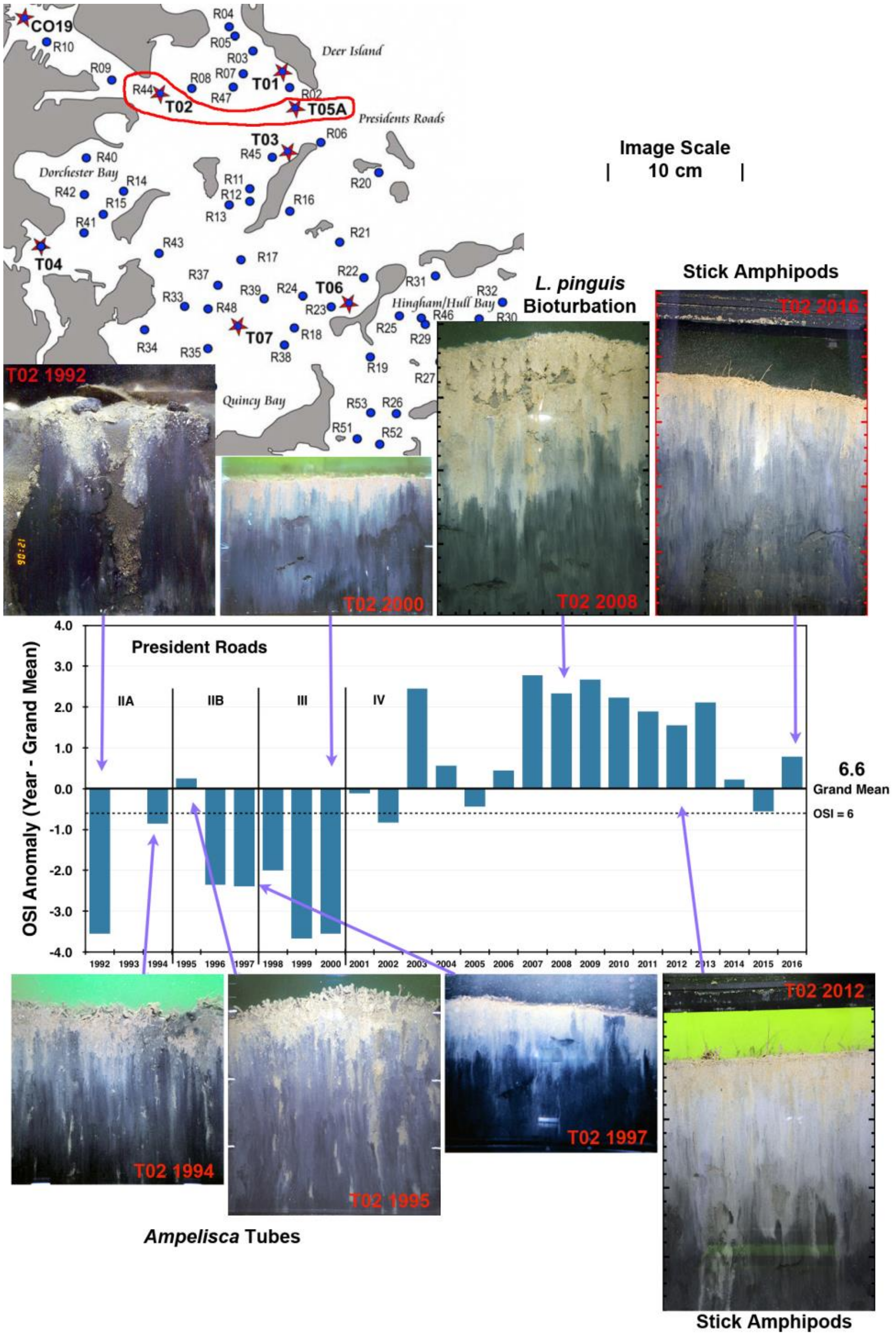

Figure 28. OSI anomaly (yearly - grand mean OSI) for President Roads stations. Station T02 improved greatly several years after diversion. Higher OSI years are positive and lower are negative values. Map insert shows stations within region. Vertical lines separate periods of change in wastewater treatment based on Taylor (2010). Period IIA is post sludge disposal, IIB is full primary treatment, III is implementation of secondary treatment, and IV is offshore diversion. OSI less than 6 indicates stressed benthic habitat.

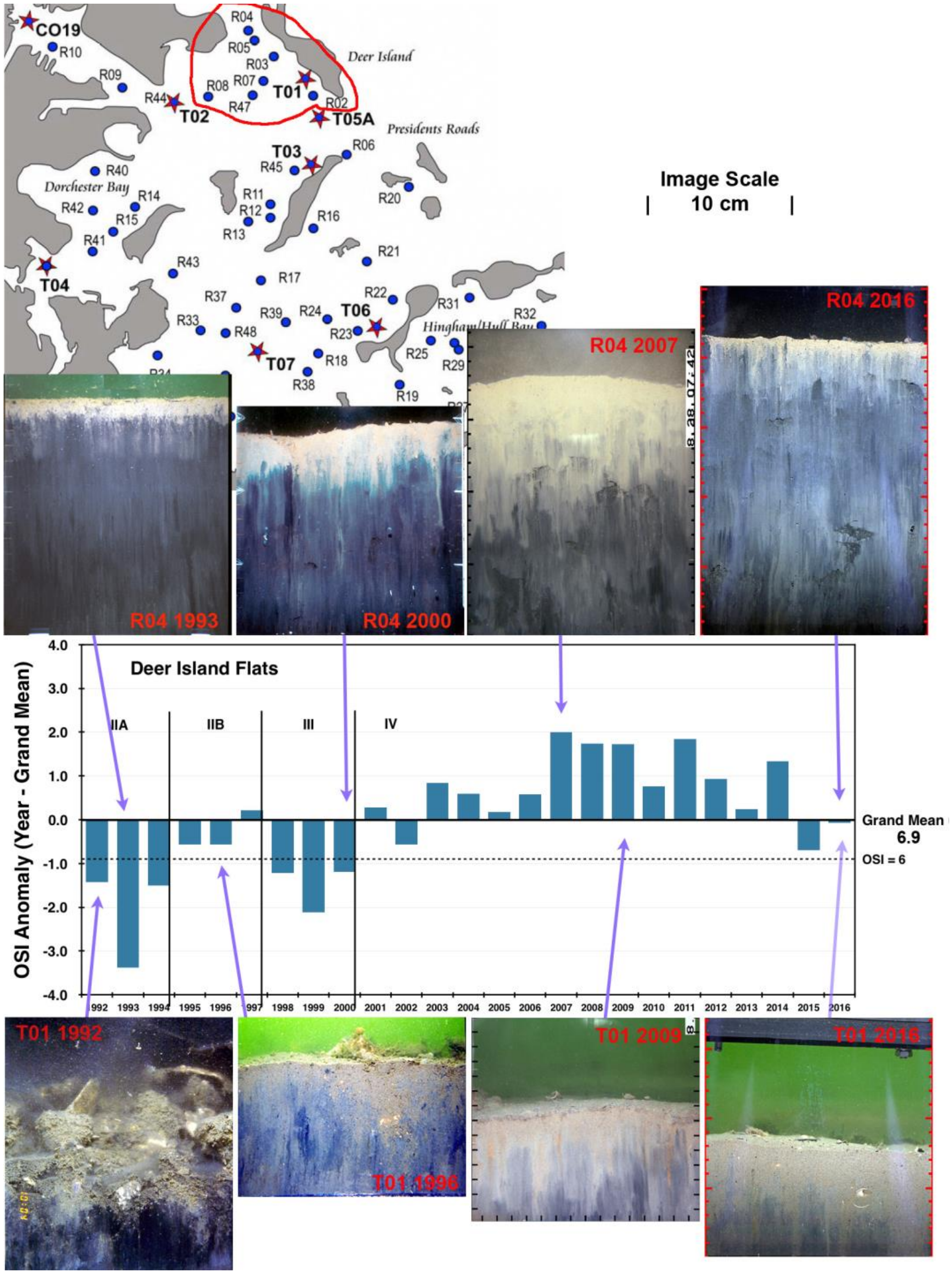

Figure 29. **OSI anomaly (yearly - grand mean OSI) for Deer Island Flats stations. Station R04 is typical finer sediment station and T01 coarser sediment station. Higher OSI years are positive and lower are negative values. Map insert shows stations within region. Vertical lines separate periods of change in wastewater treatment based on Taylor (2010). Period IIA is post sludge disposal, IIB is full primary treatment, III is implementation of secondary treatment, and IV is offshore diversion. OSI less than 6 indicates stressed benthic habitat.**

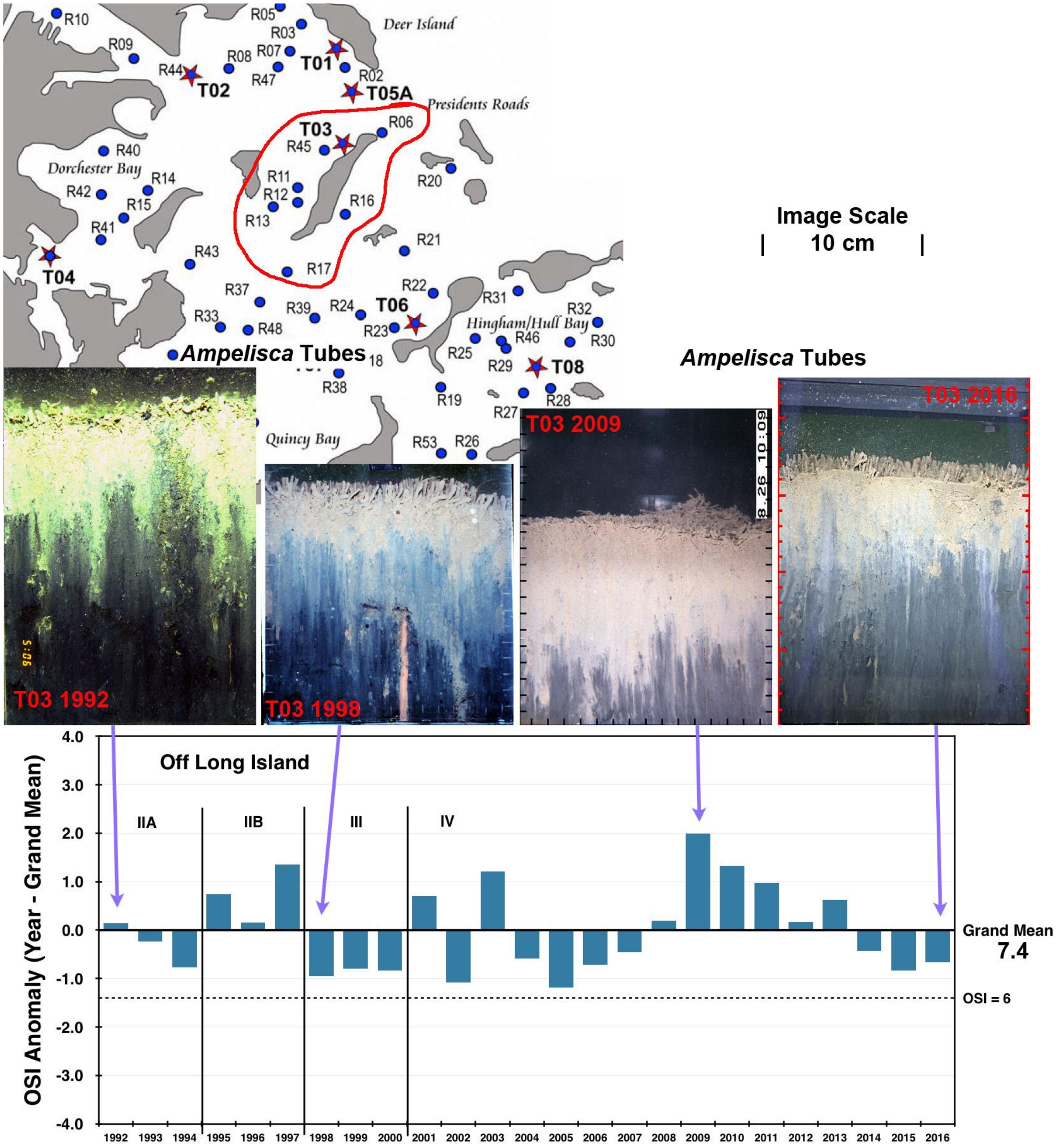

Figure 30. OSI anomaly (yearly - grand mean OSI) for stations off Long Island. Station T03 consistently had high habitat quality. Higher OSI years are positive and lower are negative values. Map insert shows stations within region. Vertical lines separate periods of change in wastewater treatment based on Taylor (2010). Period IIA is post sludge disposal, IIB is full primary treatment, III is implementation of secondary treatment, and IV is offshore diversion. OSI less than 6 indicates stressed benthic habitat.

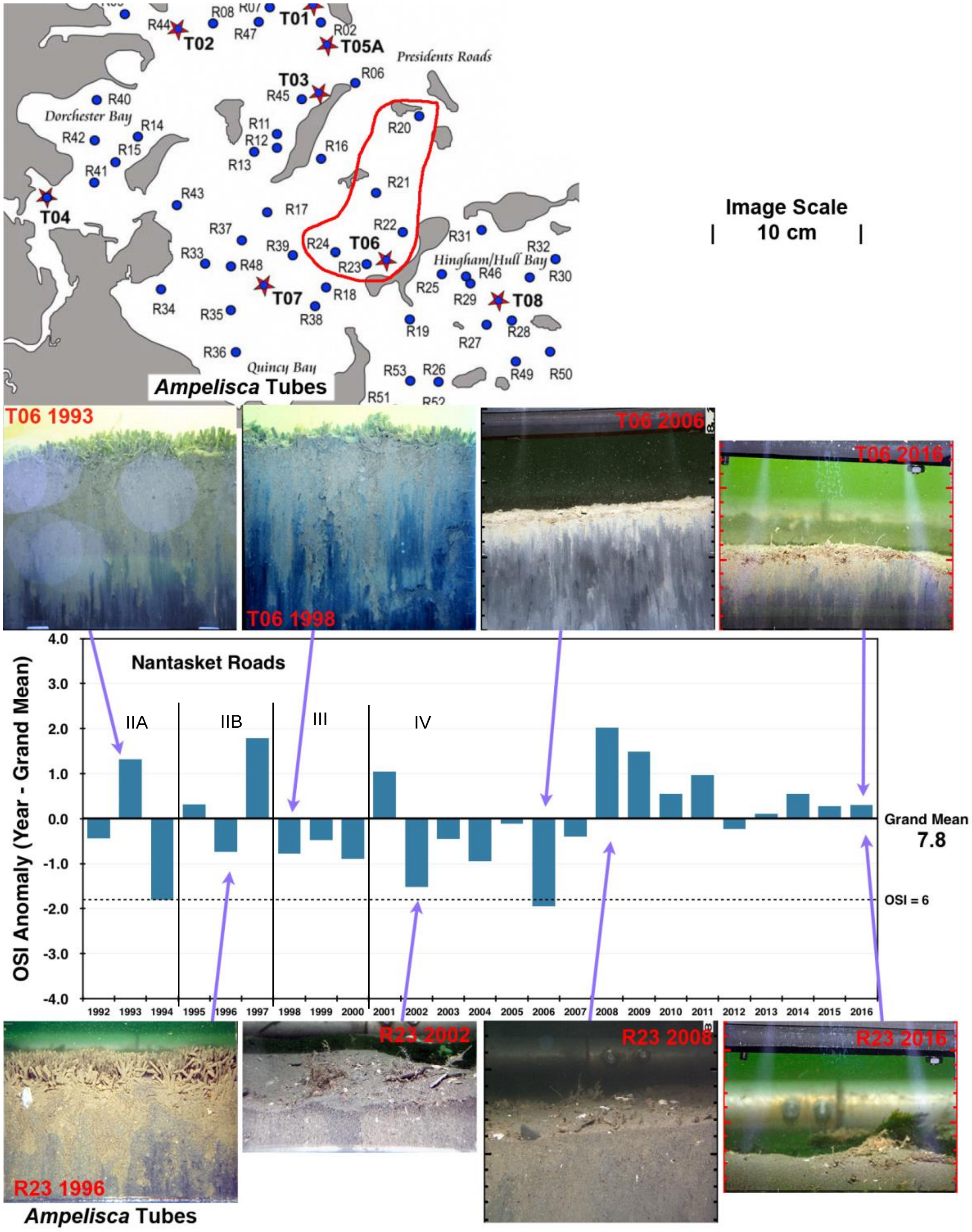

Figure 31. OSI anomaly (yearly - grand mean OSI) for Nantasket Roads stations. Higher OSI years are positive and lower are negative values. Map insert shows stations within region. Vertical lines separate periods of change in wastewater treatment based on Taylor (2010). Period IIA is post sludge disposal, IIB is implementation of primary treatment, III is full secondary treatment, and IV is offshore diversion. OSI less than 6 indicates stressed benthic habitat.

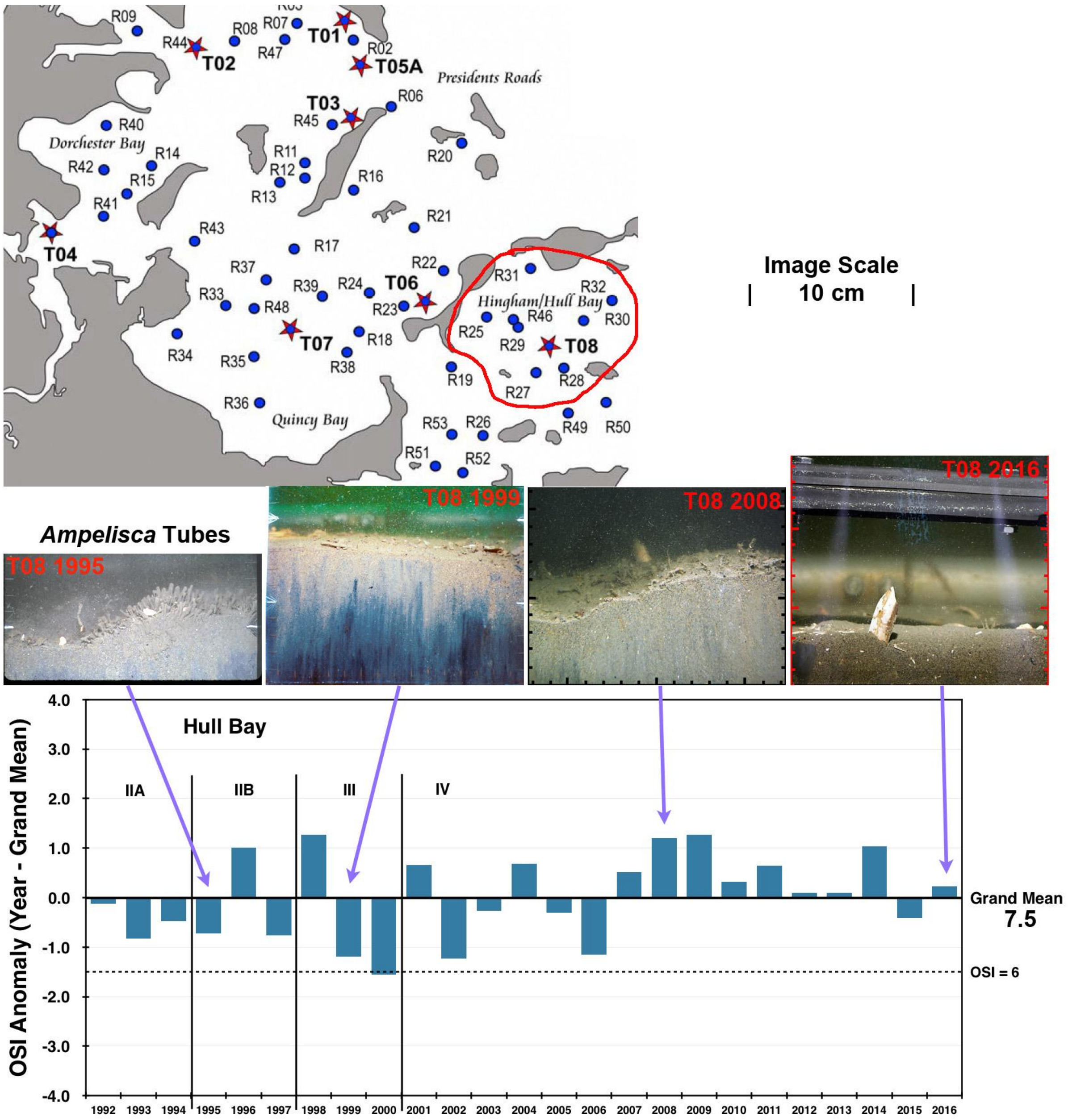

Figure 32. OSI anomaly (yearly - grand mean OSI) for Hull Bay stations. Higher OSI years are positive and lower are negative values. Map insert shows stations within region. Vertical lines separate periods of change in wastewater treatment based on Taylor (2010). Period IIA is post sludge disposal, IIB is implementation of primary treatment, III is full secondary treatment, and IV is offshore diversion. OSI less than 6 indicates stressed benthic habitat.

abundance were not significant. OSI at Station T03 was positively correlated with only TOC (r = 0.45, p = 0.026).

The six Nantasket Roads stations consistently had the highest benthic habitat quality of all Boston Harbor regions. The OSI grand mean was 7.8 (SD = 1.06), and ranged from 5.8 in 2006 to 9.8 in 2008 (Table 7). The lowest OSI in 2006 appeared related to shallowing of the aRPD at Stations R20, R21, R24, and T06.

The aRPD at these stations deepened during the highest OSI years of 1993, 1997, 2001, 2008 and 2009. For individual Nantasket Roads stations the average OIS ranged from 6.7 at R23 to 8.8 at R21. This range in OSI was in part due to differences in modal grain-size. Coarser sediments at Station R23, primarily fine-medium-sands, tended to have deeper aRPD layers, when prism penetration was sufficient to measure aRPD (OSI could be calculated only 15 of 24 years due to low prism penetration), and lower estimated successional stage. At Station R21 sediments were fine-sand-silt with both deep aRPD layers and higher estimated successional stage. Similar to Long Island stations, the overall high benthic habitat quality in Nantasket Roads was due to a combination of deep aRPD layers and predominance of estimated successional Stage II and III. Bioturbation and biogenic structures from high densities of tube building *Ampelsica* spp. and burrowing *L. pinguis* drove these variables at Station T06. From 1993 to 2004 these amphipods averaged over 62,000 m^{-2} with a range of 6,500 m^{-2} to 114,000 m^{-2} (Pembroke et al. 2016). The OSI for Station T06 was positively correlated with *L. pinguis* abundance (r = 0.62, p = 0.001) but notwith *Ampelsica* spp. OSI at Station T06 was also positively correlated with community structure variables J evenness (r = 0.47, p = 0.021) and H diversity (r = 0.57, p = 0.003) and negatively correlated with percent fine sediments (silt+clay, r = -0.44, p = 0.031). The negative correlation of OSI with percent fines appeared to be related to an independent long-term decline in fine sediments at T06 that started during Period IIB around 1996 (Linear Regression, R^2 = 0.49, p = 0.024, N = 21). The decline in percent silt+clay sediment fraction may have been related to the closure of the nearby Nut Island outfall, located within a km of Station T06, which discharged significant quantities of solids until 1998 (Taylor 2010).

The nine Hull Bay stations consistently had high benthic habitat quality. The OSI grand mean was 7.5 (SD = 0.85), and ranged from 5.9 in 2000 to 8.8 in 2009 (Table 6). The <6 mean OSI in 2000 was due to Stations R25 and R32 having aRPD layer depth that were <1.0 cm and lower estimated successional stages. For individual Hull Bay stations the average OSI ranged from 6.4 at R32 to 8.7 at R31. Similar to Long Island and Nantasket Roads stations, the overall high benthic habitat quality in Hull Bay was due to a combination of deep aRPD layers and predominance of estimated successional Stage II and III. Bioturbation and biogenic structures from high densities of tube building *Ampelsica* spp. drove these variables at Station T08. From Period IIA through to diversion and into Period IV to 2003 these amphipods averaged over 26,000 m^{-2} with a range of 120 m^{-2} in 1999 to 60,000 m^{-2} in 1993 (Pembroke et al. 2016). While the benthic habitat quality in Hull Bay tended to always be high, there was a pattern of increasing OSI through time with only one year (2015) below grand mean after 2006 (Figure 32).

Amphipod Patterns

To varying degrees, all Boston Harbor regions showed improvements in benthic habitat quality through time that were related to improvements in sewage treatment, relocation of outfalls, and diversion of all sewage in 2000 to an ocean outfall. Much of these improvements can be seen in the dynamics of the tube building amphipods *Ampelisca* spp. and the burrowing amphipod *L. pinguis* populations. Over the 25 years of SPI monitoring, biogenic activity associated with the presence of *Ampelisca* spp. had the most influence on benthic habitat quality followed by *L. pinguis* (Diaz et al. 2008, Tucker et al. 2014).

At some time between 1990 and 1992, when the SPI monitoring started, there was an increase in the occurrence of *Ampelisca* spp. tube mats (Figure 33). Prior to the dominance of *Ampelisca* spp. it appeared that blue mussels and polychaete tube mats were widely distributed (SAIC 1990, 1992). Amphipod tube mats peaked from 1994 to 1997 likely in response to the end of sludge discharges in 1991 and implementation of full primary treatment at Deer Island in 1995. It is possible that prior to the end o sludge discharge and other improvements in treatment levels, either organic or pollutant loading was too high for *Ampelisca* spp. to thrive. *Ampelisca* spp. do 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).

As the organic and pollutant loading declined greatly with implementation of full secondary treatment and diversion of sewage offshore, primary production within the Harbor also continued to decline as did mat densities of *Ampelisca* spp. This started in 1998 and by 2005 no tube mats were observed. The loss of tube mats and the crash of *L. pinguis* populations in 2005 may also have been associated with a strong storm in late 2004 that disrupted tube mats. *Ampelisca* spp. tube mats reappeared in 2006 and increased to levels seen in the late 1990s in 2011 and 2012. Populations of *L. pinguis* also started to increase in 2006, and by 2008 and 2009 bioturbation by *L. pinguis* was very prominent (Figure 34). For example, at Station T02 the aRPD went from 1.5 cm with little evidence of bioturbation in 2005 to 5.8 cm with high levels of bioturbations and oxic feeding voids in 2008. Eh measurements indicated that in 2005 actual RPD was about 2 cm and sediments below 8 cm were highly anaerobic and reduced. By 2007 with increasing amphipod densities the RPD layer depth increased to 10 cm and anaerobic conditions were pushed further down to 14 cm. In 2008 with the RPD was still deeper at more than 18 cm, with suboxic sediments still present to the end of the core at 18 cm (Tucker et al. 2009).

In 2013 no tube mats were observed for the second time in the 25-year monitoring record. In 2014 tube mats reappeared at four stations, occurred at two stations in 2015, and were present at 18 stations in 2016 signaling a return to widespread tube mats possibly related to elevated total phytoplankton abundance observed at the mouth of the harbor (Libby et al. 2017). The size of the tubes in 2016, and by implication the size of the amphipods, did vary by Harbor region with largest and longest tubes found in the outer Harbor (Figure 35). But high levels of bioturbation from *L. pinguis* have not been observed since 2009. Overall, both these amphipods declined through time in grab samples from the Traditional stations (Pembroke et al. 2016).

Summary

From 1992 to the present there is strong evidence that benthic habitats within Boston Harbor 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 (Figure 34) (Taylor 2010, Tucker et al. 2014). There were also corresponding decreases in primary production due to

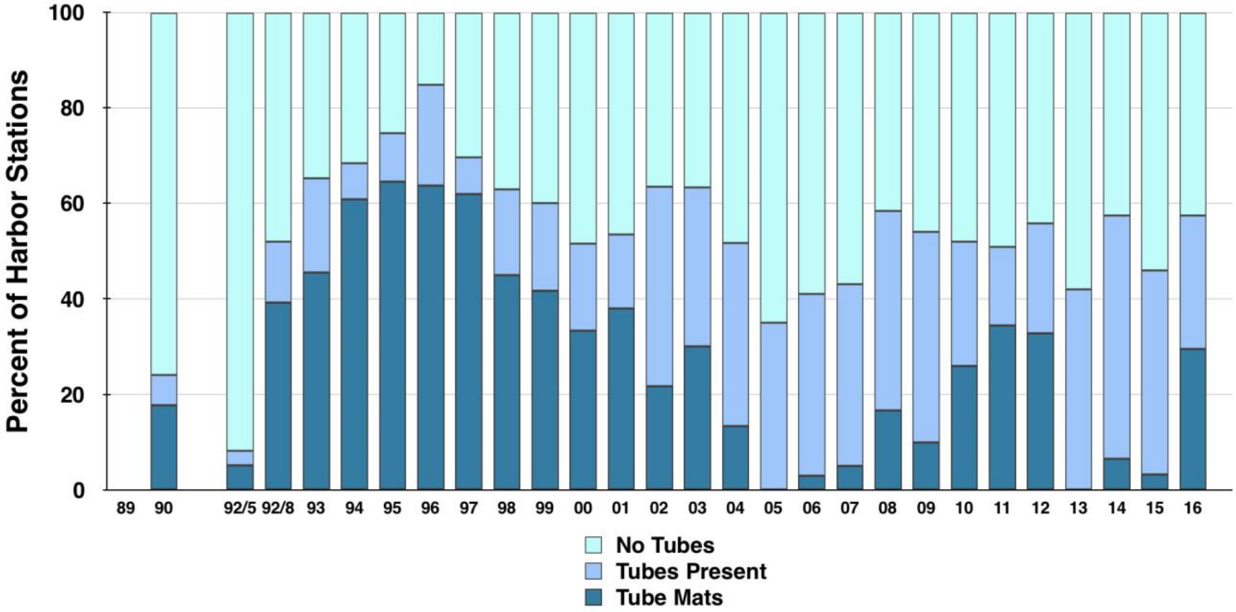

Figure 33. Histogram of *Ampelisca* spp. tubes present at Harbor stations. Mats densities of tubes are the bottom part of the bar in dark blue. There are no data from 1989 or 1991, but in 1989 there were mat densities of polychaete tubes present at some of the benthic grab stations. There were two sample periods in 1992, spring and summer (92/8). Baseline years are up to 2000. Post-baseline years are from 2001.

reduced nutrient loadings (Oviatt et al. 2007). Overall, these changes led to improvements in benthic habitats within Boston Harbor by favoring processes that enhance bioturbation or the mixing of sediment by organisms.

Much of the improvement in benthic habitat quality from 1992 to the present can be attributed to upgrades in wastewater treatment and discharge diversion to offshore outfall (Diaz et al. 2008, Taylor 2010). Further evidence of these improvements was the eelgrass (*Zostera marina*) bed that has persisted at Station R08 since 2008 (Figure 36). In 2015 and 2016 there also appeared to be large amounts of macro algae within the grass bed. Beds of eelgrass have also been reported in and around Nahant and Lynn Harbor, inside the northernmost breakwater in Winthrop, western and southwestern sides of Calf Island, off Long Island, and Whitehead Flats in Hull (P. Colarusso personal communication to K. Keay).

In a statewide analysis of eelgrass trends between 1996 and 2007, Costello and Kenworthy (2011) found eelgrass area declined within Boston Harbor from about 81 ha to 27 ha between 1996 and 2001 and then increased to 47 ha by 2007. The increase in Harbor eelgrass coincided with the startup of the offshore outfall. Costello and Kenworthy (2011) reported a similar decadal scale recovery of eelgrass in a small embayment on Long Island Sound following the removal of a municipal wastewater discharge. They concluded that with improved management of water quality, environmental conditions exist in Massachusetts where seagrasses can either thrive or expand.

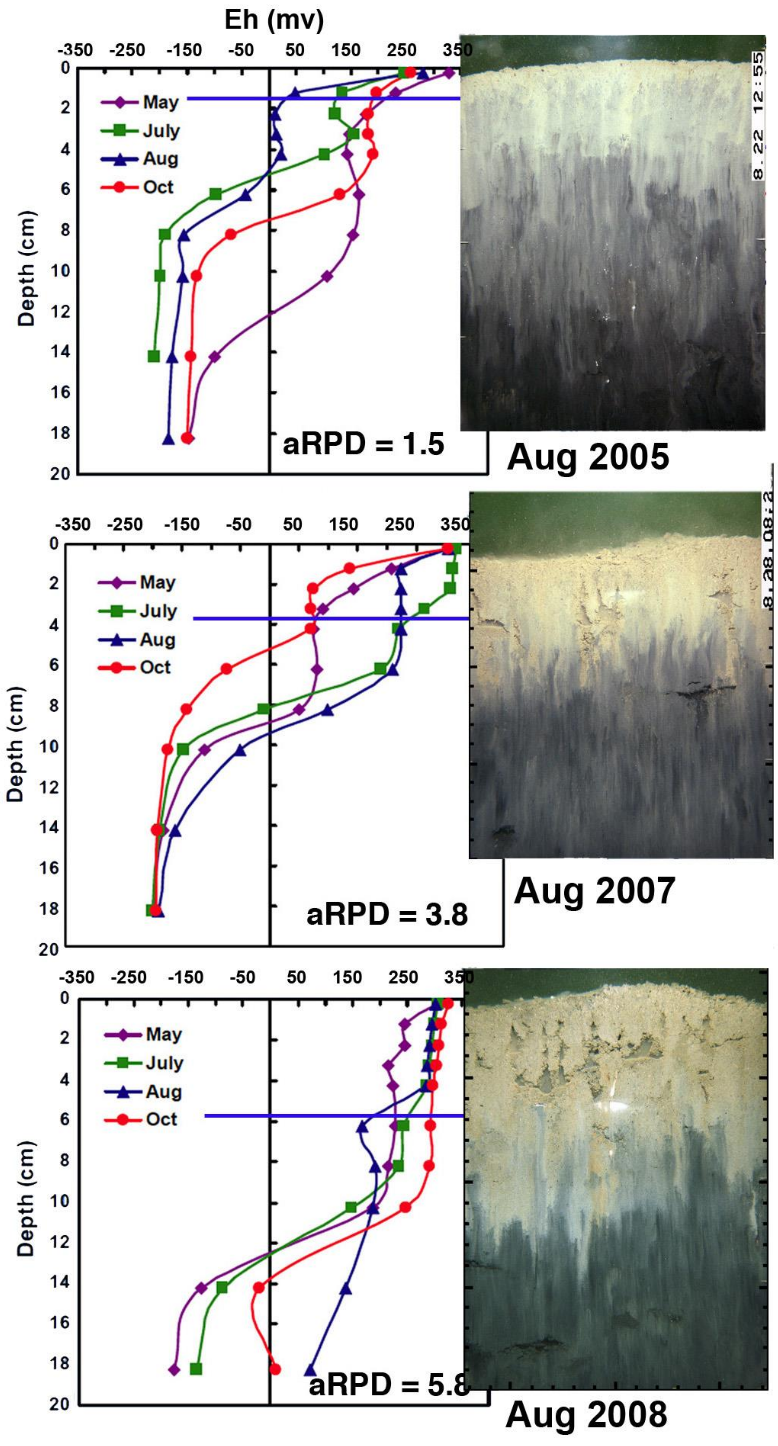

Figure 34. Comparison of August 2005, 2007, and 2008 SPI from Station T02 with redox profiles showing the transition from more anaerobic to more aerobic sediment biogeochemistry with increased bioturbation and deeper redox depth (RPD is at Eh of 0 mv) over time. Horizontal purple line is aRPD depth from SPI. Source of redox profiles is Tucker et al. (2009).

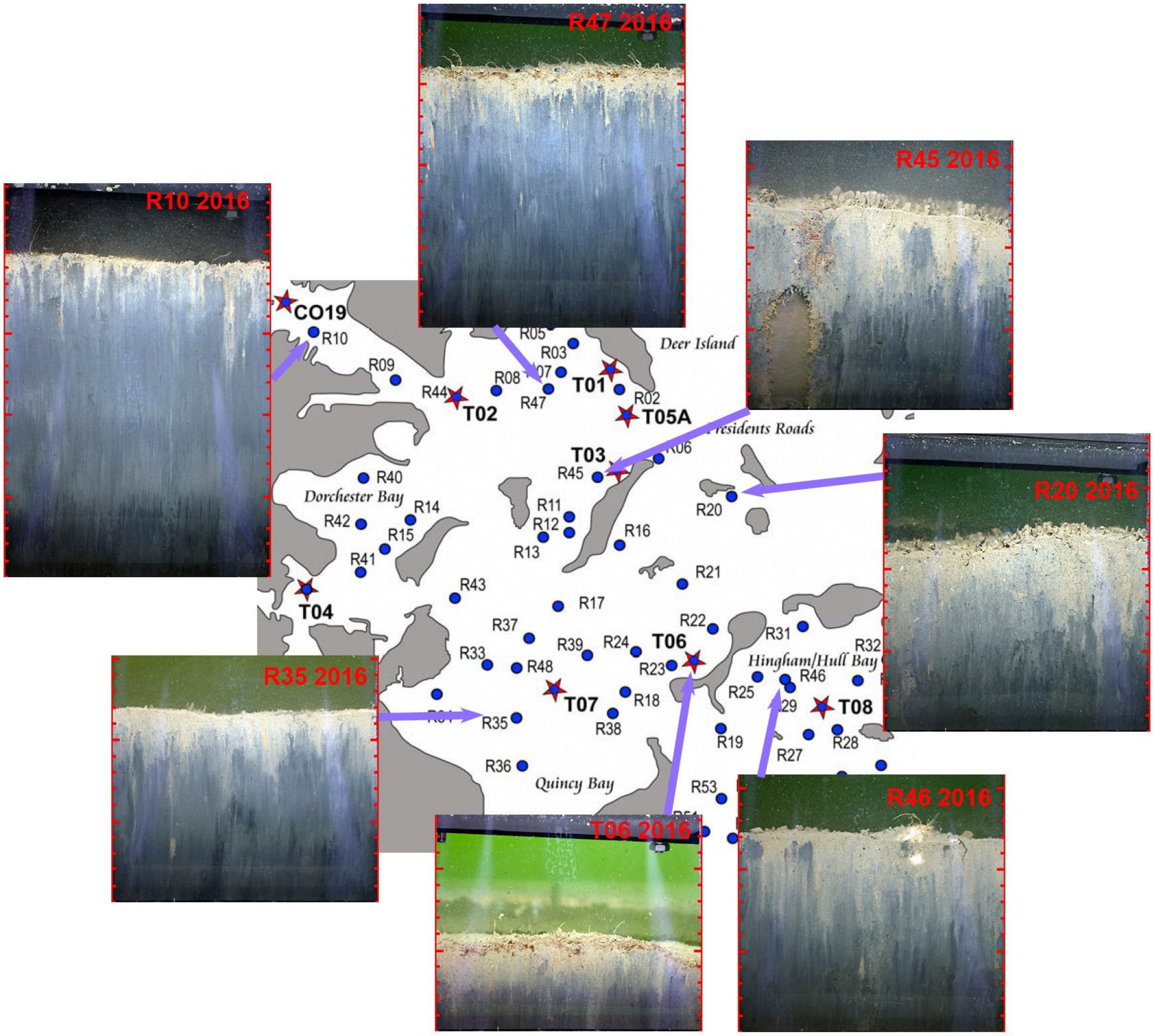

Figure 35. Examples of *Ampelisca* spp. tube size and mats for 2016. Longer tubes occurred at outer Harbor stations. Shorter tubes almost buried at the sediment-water-interface occurred at interior Harbor stations. Scale on side of image is in cm.

4. CONCLUSION

Overall, the improvements in wastewater treatment and moving the outfall offshore have led to improvements in water quality and benthic habitat quality within Boston Harbor by reducing organic and nutrient loading and favoring processes that enhance bioturbation or the mixing of sediment by organisms. From 1990 to the present, the predominant origin of sediment organic matter in Boston Harbor has shifted from sewage to marine derived. Recovery of benthic communities has enhanced bioturbation rates by infaunal and epibenthic species and has led to more aerobic and 'healthier' sediment conditions by enhancing remineralization of legacy organics and nutrients stored in the sediments from years of sewage disposal. Physical and biological properties of the soft substrate in Boston Harbor in

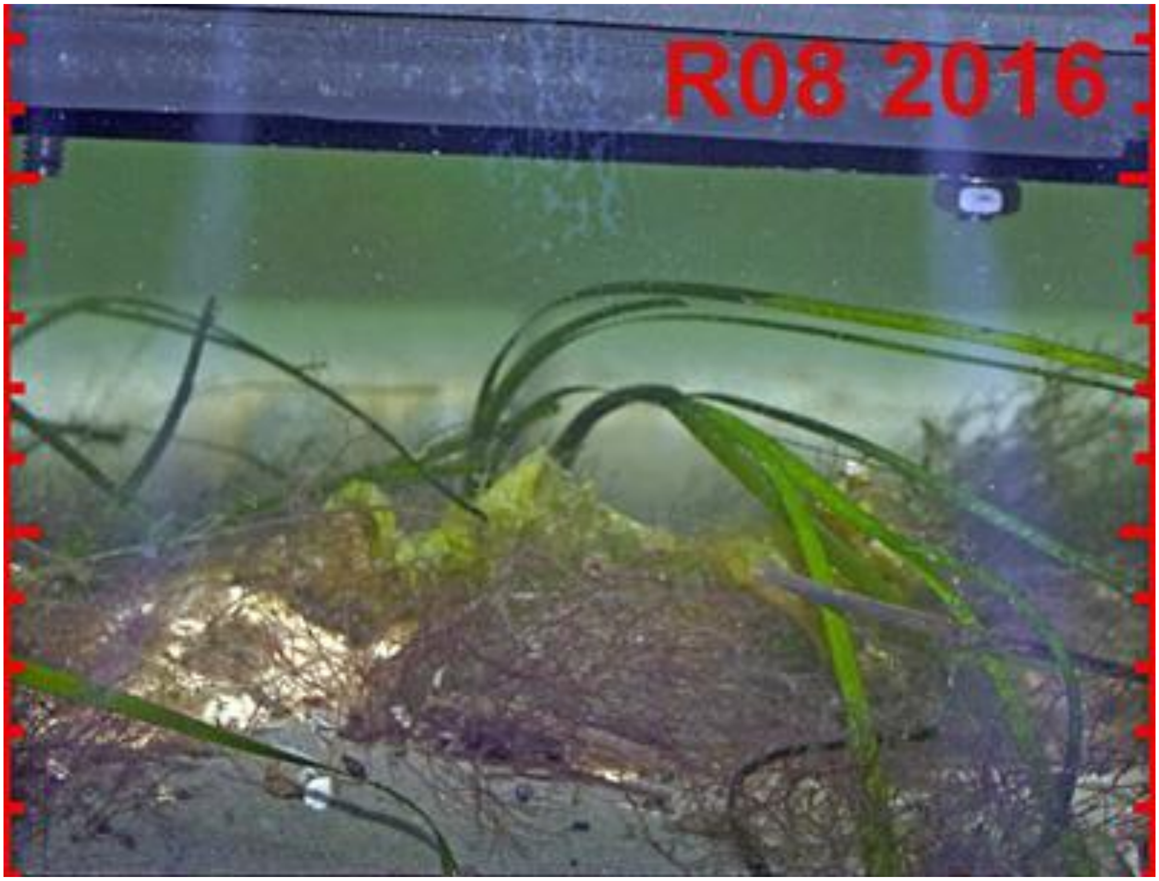

Figure 36. Eelgrass bed at station R08 on Deer Island Flats. The bed first appeared in SPI in 2008 and has persisted. Prior to 2008, R08 was always fine-sand with macroalgae. Scale on sediment profile image is in cm.

2016 exhibited minor changes from recent years but were consistent with longer-term trends (Pembroke et al. 2016). Concentrations of both TOC and *Clostridium perfringens*, indicators of organic enrichment and deposition from municipal wastewater discharge, have remained low at most stations compared to the levels occurring prior to the offshore diversion.

Community structure measures also continue to point to improving benthic conditions. Since municipal wastewater and sludge discharges have been eliminated from the harbor, total abundance has trended downward, particularly for opportunistic species such as *Capitella capitata*. Species richness, while variable, has trended upward as did evenness (J’), Shannon diversity (H’), and log series alpha diversity with all measures appearing to reach static levels in recent years. Although abundances of individual taxa, such as the dominants *Ampelisca* spp., *Aricidea catherinae*, and *Polydora cornuta* have varied over time, the infaunal community structure and evidence from sediment profile imaging suggest that these changes relate more to normal physical disturbances than organic stress in the years since wastewater impacts to the Harbor have been reduced. The trends observed in previous years, including reduction of indicators of organic enrichment and increases in species diversity that persisted in the 2016 survey are consistent with the recovery of benthic habitats from decades of inadequately treated sewage discharges.

5. REFERENCES

Clarke, KR (1993). Non-parametric multivariate analyses of changes in community structure. Aust. J. Ecol., 18: 117-143.

Clarke, KR and RH Green (1988). Statistical design and analysis for a 'biological effects' study. Mar. Ecol. Prog. Ser., 46: 213-226.

Constantino J, W Leo, MF Delaney, P Epelman, S Rhode. 2014. Quality Assurance Project Plan (QAPP) for Sediment Chemistry Analyses for Harbor and Outfall Monitoring, Revision 4 (February 2014). Boston: Massachusetts Water Resources Authority. Report 2014-02. 53 p.

Costello, CT and WJ Kenworthy. 2011. Twelve-year mapping and change analysis of eelgrass (*Zostera marina*) areal abundance in Massachusetts (USA) identifies statewide declines. Estuaries and Coasts 34:232-242.

Diaz, RJ, GR Cutter, Jr. and DM Dauer. 2003. A comparison of two methods for estimating the status of benthic habitat quality in the Virginia Chesapeake Bay. Journal of Experimental Marine Biology and Ecology 285-286:371-381.

Diaz, RJ, DC Rhoads, JA Blake, RK Kropp, and KE Keay. 2008. Long-term trends in benthic habitats related to reduction in wastewater discharges to Boston Harbor. Estuaries and Coasts 31:1184–1197.

Gallagher, ED and KE Keay. 1998. Organisms-Sediment-Contaminant Interactions in Boston Harbor. Pp. 89-132 In: *Contaminated Sediments in Boston Harbor.* K.D. Stolzenbach and EE. Adams (eds.) Marine Center for Coastal Processes, MIT Sea Grant College Program. Cambridge, MA 02139.

Kubiak, DA, NS Smoske, K Coughlin, L Rando, D Wu, and E Whittaker. 2016. Combined Sewer Overflow Control Plan Annual Progress Report 2015. 2015 csoar-r4. 58 p.

Libby PS, DG Borkman, WR Geyer, JT Turner, AS Costa, D Codiga, Draft. 2017. 2016 Water column monitoring results (Draft). Boston: Massachusetts Water Resources Authority. 56 p.

McCall, PL 1977. Community patterns and adaptive strategies of the infaunal benthos of Long Island Sound. Journal of Marine Research 35:221–266.

Maciolek, NJ, DT Dahlen, and RJ Diaz. 2011. 2010 Boston Harbor Benthic Monitoring Report. Boston: Massachusetts Water Resources Authority. Report 2011-18. 20 pages + appendix.

Maciolek, NJ, RJ Diaz, DT Dahlen, and IP Williams. 2006. 2005 Boston Harbor Benthic Monitoring Report. Boston: Massachusetts Water Resources Authority. Report ENQUAD 2006-24. 87 pages + appendices.

Maciolek, NJ, RJ Diaz, DT Dahlen, and SA Doner. 2008. 2007 Boston Harbor Benthic Monitoring Report. Boston: Massachusetts Water Resources Authority. Report ENQUAD 2008-22. 77 pages + appendices.

McCall, PL. 1977. Community patterns and adaptive strategies of the infaunal benthos of Long Island Sound. Journal of Marine Research 35:221–266.

Menge, BA and JP Sutherland. 1987. Community regulation: variation in disturbance, competition and predation in relation to environmental stress and recruitment. American Naturalist 130:730–757.

MWRA. 2010. Ambient monitoring plan for the Massachusetts Water Resources Authority effluent outfall revision 2. July 2010. Boston: Massachusetts Water Resources Authority. Report 2010-04. 107 p.

Nestler, EC, AE Pembroke, and RC Hasevlat. 2014. Quality Assurance Project Plan for Benthic Monitoring 2014–2017. Boston: Massachusetts Water Resources Authority. Report 2014-03, 92 pp. plus Appendices.

Oviatt, CA, KJW Hyde, and AA Keller. 2007. Production patterns in Massachusetts Bay with outfall relocation. Estuaries and Coasts 30:35–46.

Pembroke, AE, RJ Diaz, and EC Nestler. 2012. Harbor Benthic Monitoring Report: 2011 Results. Boston: Massachusetts Water Resources Authority. Report 2012-14. 28 pp.

Pembroke, AE, RJ Diaz, and EC Nestler. 2013. Harbor Benthic Monitoring Report: 2012 Results. Boston: Massachusetts Water Resources Authority. Report 2013-13. 41 pp.

Pembroke, AE, RJ Diaz, and EC Nestler. 2014. Harbor Benthic Monitoring Report: 2013 Results. Boston: Massachusetts Water Resources Authority. Report 2014-12. 43 pp.

Pembroke AE, RJ Diaz, EC Nestler. 2015. Boston Harbor Benthic Monitoring Report: 2014 Results. Boston: Massachusetts Water Resources Authority. Report 2015-10. 37 p.

Pembroke, AE, RJ Diaz, and EC Nestler. 2016. Boston Harbor Benthic Monitoring Report: 2015 Results. Boston: Massachusetts Water Resources Authority. Report 2016-14. 38 pages.

Rhoads, DC and JD Germano. 1986. Interpreting long-term changes in benthic community structure: a new protocol. Hydrobiologia 142:291-308.

SAIC. 1990. REMOTS® sediment-profile photography surveys of Boston Harbor, Dorchester, Quincy, Hingham, and Hull Bays: June 1989 and May 1990. SAIC Report No. SAIC-90/7578&236. Science Applications International Corporation, Woods Hole, MA 45 pp.

SAIC. 1992. REMOTS® sediment-profile photography survey of Boston Harbor, Dorchester, Quincy, Hingham, and Hull Bays: May 1992. SAIC Report No. 266. Science Applications International Corporation, Newport, RI. 20 pp.

Taylor, DI 2006. Update of patterns of wastewater, river, and non-point source loadings to Boston Harbor (1990-2005). Boston: Massachusetts Water Resources Authority. Report 2006-22. 77pp.

Taylor, DI. 2010. The Boston Harbor Project, and large decreases in loadings of eutrophication-related materials to Boston Harbor. Marine Pollution Bulletin 60:609–619.

Tucker, J, AE Giblin, CS Hopkinson, SW Kelsey and BL Howes. 2014. Response of benthic metabolism and nutrient cycling to reductions in wastewater loading to Boston Harbor, USA. Estuarine, Coastal and Shelf Science 151: 54-68.

Tucker J, S Kelsey, and A Giblin. 2009. 2008 Annual Benthic Nutrient Flux Monitoring Summary Report. Boston: Massachusetts Water Resources Authority. Report ENQUAD 2009-08. 32 p.

Valente, RM, DC Rhoads, JD Germano and VJ Cabelli. 1992. Mapping of benthic enrichment patterns in Narragansett Bay, Rhode Island. Estuaries 15:1-17.

Wallace, GT, C Krahfrost, L Pitts, M Studer, and C Bollinger. 1991. Assessment of the chemical composition of the Fox Point CSO effluent and associated subtidal and intertidal environments: Analysis of CSO effluent and surficial sediments for trace metals prior to CSO modification.

Final report to the Massachusetts Department of Environmental Protection, Office of Research and Standards.

Wolfe, DA, ER Long, and GB Thursby. 1996. Sediment toxicity in the Hudson-Raritan Estuary: Distribution and correlations with chemical contamination. Estuaries 19:901–912.

Massachusetts Water Resources Authority
Charlestown Navy Yard
100 First Avenue
Boston, MA 02129
(617) 242-6000
www.mwra.com