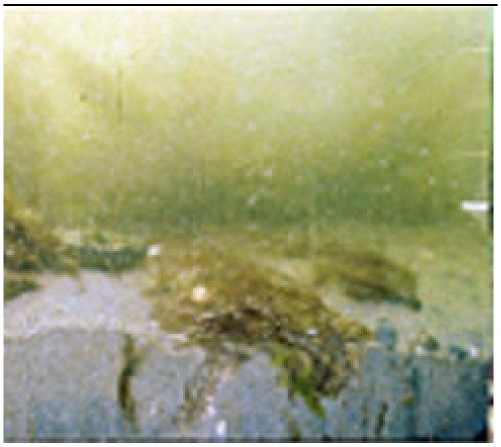
2021 Boston Harbor Benthic Monitoring Report



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2021 Boston Harbor Benthic Monitoring Report

Submitted to

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

Prepared by

Deborah A. Rutecki[1]
Robert J. Diaz[2]
Maureen Madray[1]

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

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

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EXECUTIVE SUMMARY

The Massachusetts Water Resources Authority's (MWRA) Deer Island Treatment Plant treats sewage from more than 40 communities in Greater Boston. Discharge of sludge into Boston Harbor from the treatment process stopped in 1991. However, effluent was discharged into Boston Harbor until September 2000. Direct discharge of sludge and wastewater with limited treatment into the harbor had affected both water quality and ecological conditions. Since September 2000, the effluent has been discharged offshore to Massachusetts Bay via a 9.5 mile outfall tunnel with additional secondary treatment. MWRA has conducted ongoing benthic monitoring in Boston Harbor since 1991 to evaluate changes to the ecosystem and the benthic (seafloor) community resulting from reductions in contaminated discharges over time. The conditions in the sediments and the associated benthic infaunal community reflect cumulative water quality exposures. This report summarizes the results of the 2021 benthic surveys, which include sediment conditions, benthic infauna, and sediment profile imagery.

Sediment conditions were characterized based on analyses of sediment grain size composition, total organic carbon (TOC), and colony counts of the anaerobic bacterium *Clostridium perfringens,* an indicator of the presence of sewage. Grain size composition ranged from predominantly sand at outer harbor stations to almost entirely silt and clay in Savin Hill Cove and the Inner Harbor. The highest TOC concentrations in 2021 were observed in Savin Hill Cove and the Inner Harbor. *C. perfringens* counts during 2021 were generally low. These observations are consistent with longer-term trends (Rutecki et al. 2021). Concentrations of both TOC and *C. perfringens* have remained low compared to the levels in the early 1990s.

The monitoring program evaluates benthic infauna by measuring species abundance and other benthic community measures. These measures continue to indicate improving benthic conditions in 2021. Since the cessation of MWRA discharges to the harbor, total species abundance has trended downward, particularly for opportunistic species such as *Capitella capitate*. Total species abundance has been fairly stable for the last decade. Species richness and other biodiversity measures have trended upward.

Although abundances of individual taxa 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.

Sediment profile imaging showed overall habitat conditions improved in 2021 relative to 2020, as measured by the Organism Sediment Index. The trends observed in previous years, including a reduction of indicators of organic enrichment and increases in species diversity, continued in the 2021 survey. These results are consistent with the recovery of benthic habitats from decades of inadequately treated sewage discharges.

Overall, benthic monitoring results in 2021 were consistent with results in the years since the discharge was moved offshore and indicate recovery of the harbor benthic community continues.

1. INTRODUCTION

Boston Harbor was once considered among the most degraded urban estuaries in the country. Direct discharge of sludge and wastewater with limited treatment into the harbor had affected both water quality and ecological conditions. Through litigation, the EPA prevailed upon the Commonwealth of Massachusetts to take actions to improve these conditions and the Massachusetts Water Resources Authority (MWRA) was created in response. In 1985, MWRA initiated a multi-faceted plan to meet these mandates, including elimination of sludge disposal into the harbor, an upgrade to secondary treatment, and relocation of wastewater discharge through an offshore diffuser located 9.5 mi off Deer Island in Massachusetts Bay. By 2001, MWRA had met all of these goals. 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).

The upgrades 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 the mixing of sediment by organisms. At one time, the sediment organic matter in Boston Harbor was derived primarily from sewage but since changes in wastewater treatment and disposal were initiated, marine-derived organic material has become more 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.

Conditions in the sediments and the associated benthic infaunal community reflect cumulative water quality exposures. MWRA has conducted ongoing benthic monitoring in Boston Harbor since 1991 to evaluate changes to the ecosystem and the benthic community resulting from reductions in contaminated discharges over time. This report summarizes the results of the 2021 benthic surveys, which 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. This included soft-bottom sampling for sediments and infauna at 9 stations and sediment profile imaging (SPI) at 61 stations. This program 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 Rutecki et al. (2021) for previous monitoring years. Detailed descriptions of the methods are contained in the Quality Assurance Project Plan (QAPP) for Benthic Monitoring (Rutecki et al. 2020a). 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 2021 (Figure 2-1). Soft-bottom stations were sampled for grain size composition; total organic carbon (TOC); the sewage tracer *Clostridium perfringens*, an anaerobic bacterium found in the intestinal tract of mammals; and benthic infauna. One sediment sample and triplicate infauna samples were collected at each station on August 3, 2021.

SPI samples were collected in triplicate at 61 stations from August 1-2, 2021 (Figure 2-1).

2.2 LABORATORY METHODS

Laboratory methods for benthic infauna and sediment profile imaging (SPI) image analyses were consistent with the QAPP (Rutecki et al. 2020a). Two of the infauna samples from each site sampled for infauna 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).

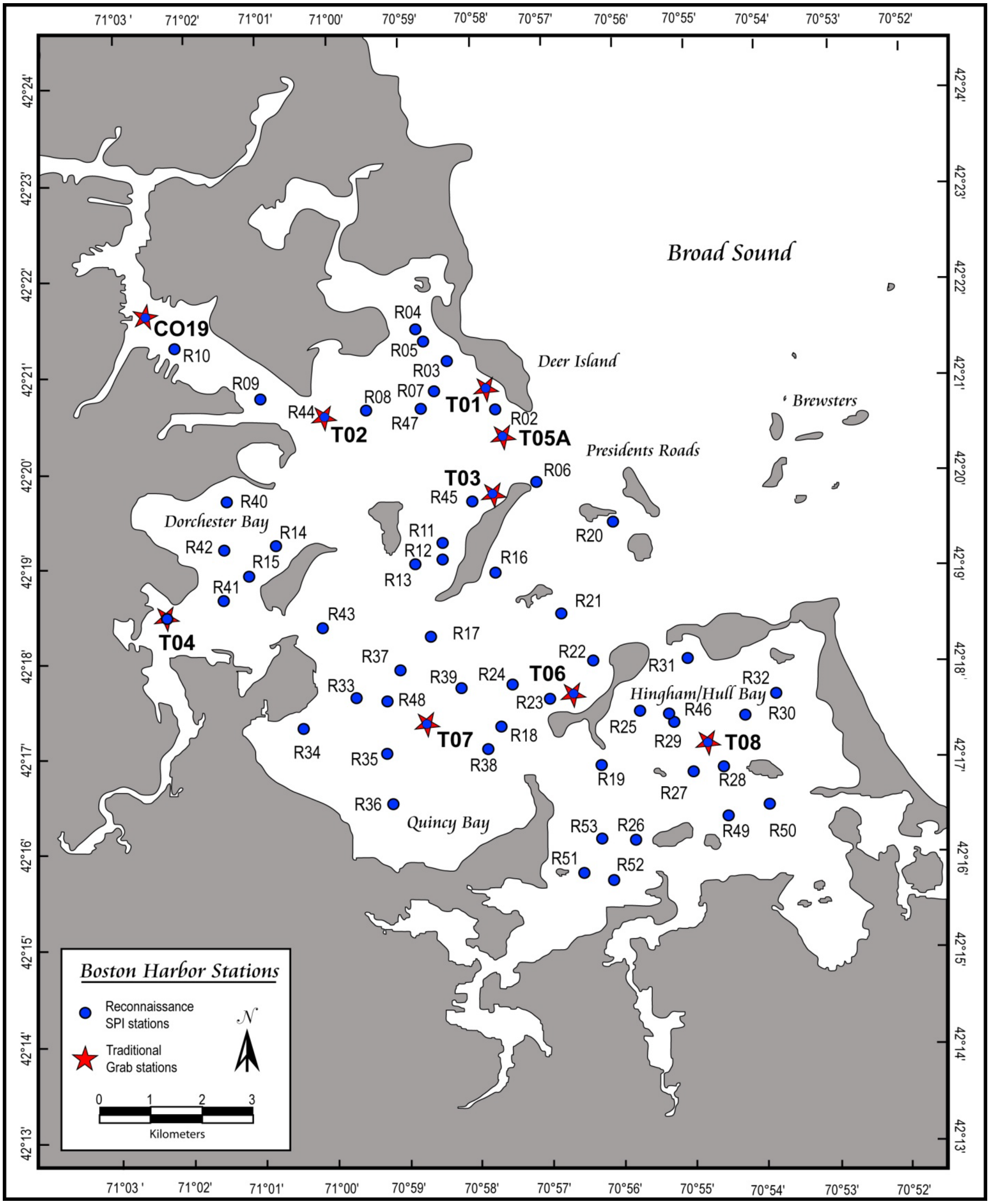

Figure 2-1. Locations of soft-bottom sampling and sediment profile imaging stations for 2021.

2.3 DATA HANDLING, REDUCTION, AND ANALYSIS

All benthic data were extracted directly from the MWRA 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 (Rutecki et al. 2020a) or in Maciolek et al. (2008). Data are presented graphically as means (averages per station) unless otherwise noted. The Shannon-Weiner diversity index (H') was calculated using log base 2. Multivariate analyses were performed using PRIMER v7 (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 in order to delineate 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). The periods denote significant events that had a likelihood of affecting the harbor benthic community, including, cessation of 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). Since sediment communities can take time to respond to changes, for example reductions in the deposition of organic matter, these periods were offset by one year. These evaluations generally focused on Stations T01 to T08 (traditional stations, Periods I-IV) and excluded data from Station C019 which are only available since 2004 (Period IV).

Details on parameters and analysis of SPI images can be found in Diaz et al. (2008). Median grain-size was estimated graphically using cumulative percentage weights of Phi intervals from sediment analysis. Modal Phi was the interval with the highest percentage weight. For this report, quantitative SPI parameters (e.g., apparent redox potential discontinuity [aRPD] layer depth) were averaged from the three replicate images. For categorical parameters (e.g., presence of biogenic structures), the median value of the three replicate images was assigned to a station. As the selection of station locations in the Harbor was non-random, fixed-effect nominal logistic models, which treat each station measurement as a separate observation, were used to analyze patterns in categorical data (Agresti 1990). For continuous variables, general linear models (GLM) were used to test for differences within and between quantitative parameters. Trends in quantitative variables were tested using various GLMs (simple linear regression, segmented linear regression, analysis of variance). Significance of odds was tested using logistic regression. All statistical tests were conducted with the statistical package R version 3.6.2 (2019-12-12, R Foundation for Statistical Computing).

3. RESULTS AND DISCUSSION

3.1 SEDIMENT CONDITIONS

Sediment conditions in Boston Harbor were characterized in 2021 by measuring three parameters at each of the nine sampling stations: (1) grain size (gravel, sand, silt, and clay), (2) total organic carbon, and (3) *Clostridium perfringens* (Table 3-1).

Grain Size. Surface sediments at the nine stations sampled during 2021 included a wide range of sediment types (Table 3-1, Figure 3-1). Grain size profiles ranged from predominantly sand (T08) to almost entirely silt and clay (C019 and T04). Most stations had mixed sediments. The outer harbor stations generally had more than 50% sand with varying fractions of silt-clay. Grain size at Station T03, in the lee of Long Island, has had higher percentages of fines (silt plus clay) than sand from 2017 through 2021. Although this trend started before the 2018 dredging of the President Roads Anchorage, the dredging could have enhanced this trend post-2018. The grain size composition at each station in 2021 generally remained within the ranges reported in prior years. 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 large drops in percent fines (Figure 3-2).

Total Organic Carbon. Concentrations of total organic carbon (TOC) in 2021 were generally similar to the values reported in 2020 and recent years at most stations. TOC concentrations remained within the ranges reported in previous years (Figure 3-3). Higher TOC values were generally associated with higher percent fine sediments (Figures 3-2 and 3-3). During 2021, Stations T03, T04, and C019 had among the highest concentrations of TOC and had the highest proportions of fines (Table 3-1). T04 and C019 have typically had the highest TOC. TOC levels at T03 have been below 3% since 2005 and below 2.5% since 2011; levels in 2021 are consistent with this trend. The lowest TOC concentrations for 2021 were reported at Stations T08 and T05A which have predominantly sand sediments.

***Clostridium perfringens*.** *Clostridium perfringens* provide a sensitive tracer of sewage effluent. *C. perfringens* data were normalized to percent fines because the distribution of *C. perfringens* has been found to vary with the proportion of fine-grained material in the sediments (Parmenter and Bothner 1993), and normalization provides a more conservative means of evaluating the data for trends. Abundances of *C. perfringens* (normalized to percent fines) during 2021 (Table 3-1) were generally low and comparable across all monitoring stations, especially when compared to historic data (Figure 3-4). Abundances at T04, a depositional site in Savin Hill Cove, historically exhibited relatively high variability among years. Since 2014, *C. perfringens* counts at T04 have remained relatively low and steady through 2021 (Figure 3-4). Normalized *C. perfringens* counts at Station T08 have consistently been low since 2010 with the exceptions in 2016 and 2020. The 2016 occurrence was largely an artifact of the atypically low percent fines at T08 that year. Except at Inner Harbor station C019, *C. perfringens* counts at Harbor stations have generally remained below historical averages since the late 1990's (Figure 3-4). Station C019 is a depositional area located in the upper Inner Harbor near several CSOs. *C. perfringens* counts at C019 declined in 2017 and have remained low through 2020 compared to historic data. The decline may reflect the completion of the Reserved Channel Sewer Separation project in 2015 that minimized CSO discharges to meet Class SB(cso) water quality standards. The 2021 concentration was higher than the 2020 concentration and the highest observed since 2016 (Figure 3-4). Rainfall in Boston during July 2021 was unusually high at 10.07 inches (normal 3.27 inches) and may have decreased overall water quality at Station C019 and contributed to the higher *C. perfringens* concentration observed.

Table 3-1. Monitoring results for sediment condition parameters in 2021.

Parameter		C019	T01	T02	T03	T04	T05A	T06	T07	T08
Grain Size	**Gravel (%)**	**0.0**	**9.6**	**1.0**	**0.3**	**0.0**	**0.0**	**1.0**	**0.0**	**0.0**
	Sand (%)	**5.3**	**63.3**	**48.5**	**40.4**	**9.8**	**73.1**	**76.7**	**41.1**	**94.0**
	Silt (%)	**46.5**	**14.8**	**30.6**	**33.0**	**67.3**	**16.8**	**14.3**	**35.2**	**3.0**
	Clay (%)	**48.2**	**12.3**	**19.9**	**26.3**	**22.8**	**10.1**	**8.0**	**23.7**	**3.0**
	Percent Fines (Silt + Clay)	**94.7**	**27.1**	**50.6**	**59.3**	**90.2**	**26.9**	**22.2**	**58.9**	**6.0**
Total Organic Carbon	**TOC (%)**	**2.3**	**0.9**	**1.1**	**1.8**	**3.7**	**0.6**	**0.7**	**1.9**	**0.2**
Clostridium perfringens	**Not Normalized**	**10500**	**666**	**130**	**2850**	**3320**	**269**	**453**	**776**	**104**
	Normalized (cfu/g dry/%fines)	**110.9**	**24.6**	**2.6**	**48.1**	**36.8**	**10.0**	**20.4**	**13.2**	**17.3**

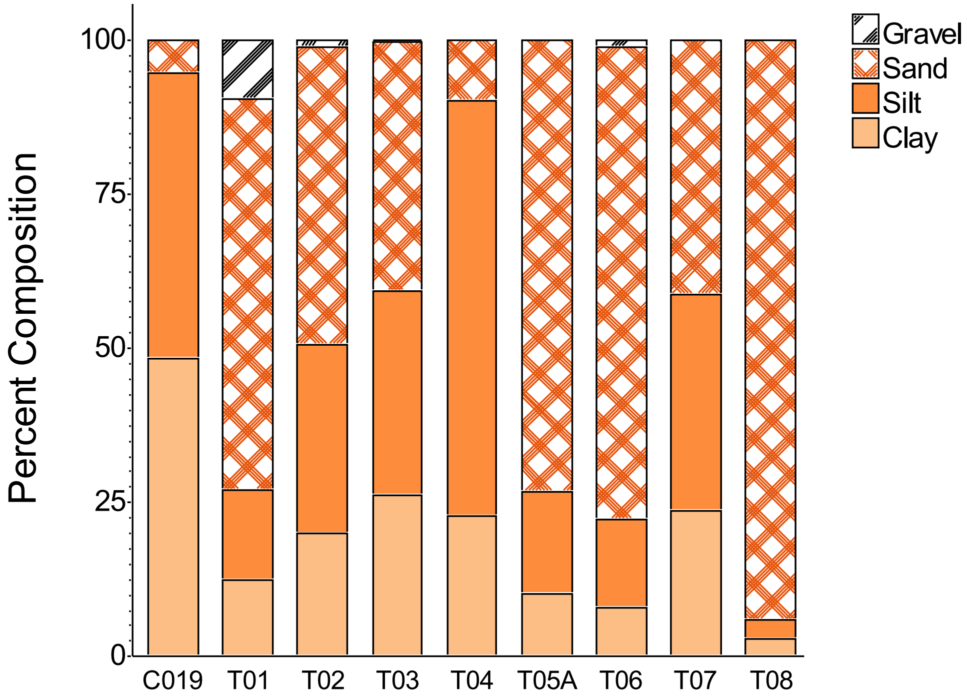

Figure 3-1. Monitoring results for 2021 sediment grain size in Boston Harbor.

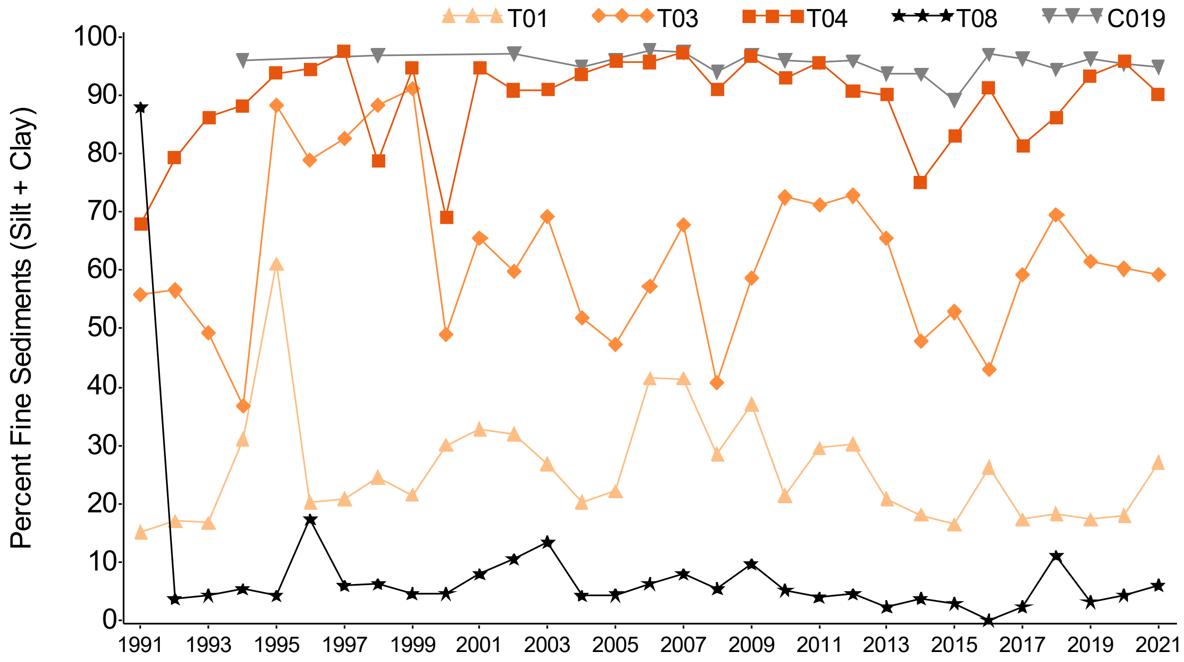

Figure 3-2. **Mean percent fine sediments at five stations in Boston Harbor, 1991 to 2021. Five stations selected to illustrate the trends in percent fine sediments at stations in the outer harbor (T08), mid harbor (T01 and T02), and inner harbor (T04 and C019).**

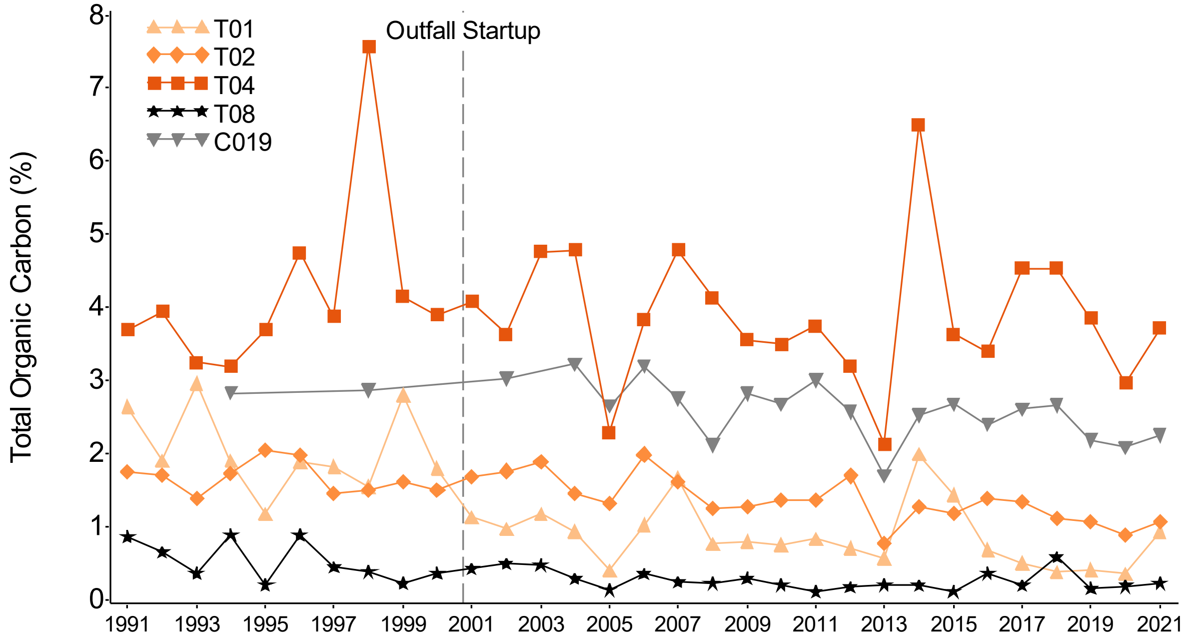

Figure 3-3. **Mean concentrations of TOC at five stations in Boston Harbor, 1991 to 2021. Five stations selected to illustrate the trends in TOC at stations in the outer harbor (T08), mid harbor (T01 and T02), and inner harbor (T04 and C019).**

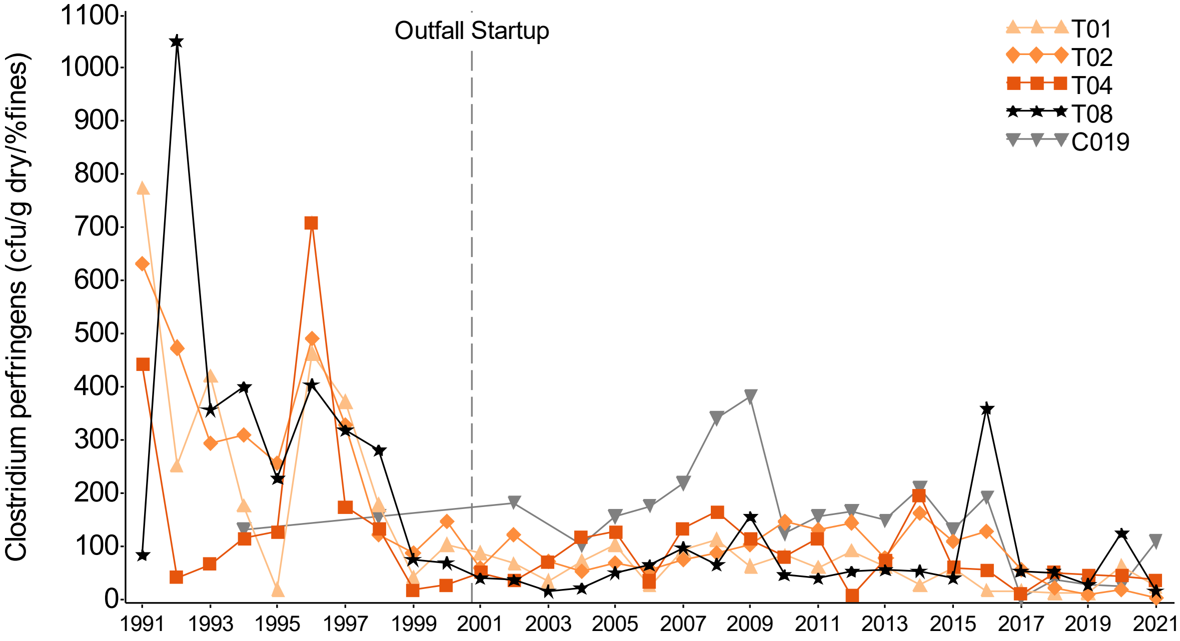

Figure 3-4. Mean normalized concentrations of *Clostridium perfringens* at five stations in Boston Harbor, 1991 to 2021. Five stations selected to illustrate the trends in *Clostridium perfringens* at stations in the outer harbor (T08), mid harbor (T01 and T02), and inner harbor (T04 and C019).

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. We are currently in Period IV which started with the implementation of the offshore outfall. The data is offset from the Taylor (2006) periods by one year to allow time for the benthic communities to respond to the reduced loadings of eutrophication-related materials to Boston Harbor. Results during 2021 for grain size, TOC, and *C. perfringens* in Boston Harbor sediments, are consistent with monitoring results from previous post-outfall implementation years (Maciolek et al. 2008, 2011; Rutecki et al. 2021). 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 3-5 and 3-6). In Figures 3-5 and 3-6, Period IV has been divided into multi-year segments in comparison to the most recent year, to show potential changes of TOC and *C. perfringens* concentrations over time in this period. 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 (Taylor 2006, Taylor et al. 2019, Maciolek et al. 2008).

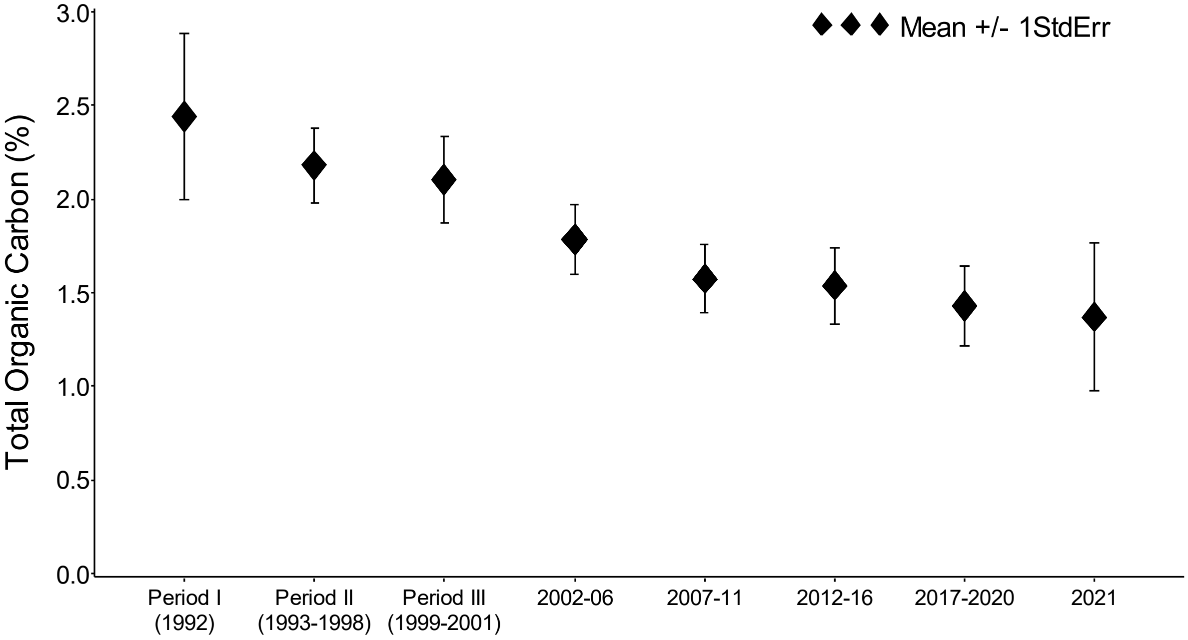

Figure 3-5. Comparison of TOC across time periods (offset by one year) at Boston Harbor stations (T01-T08) from 1992 to 2021 (1991 excluded).

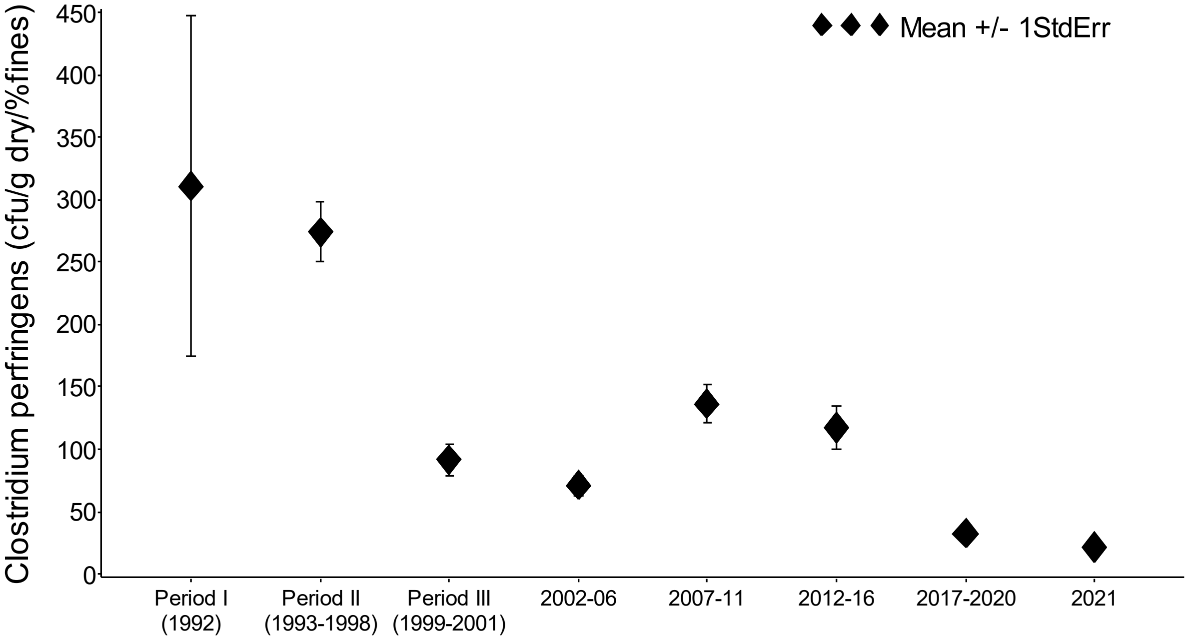

Figure 3-6. Comparison of *Clostridium perfringens* across time periods (offset by one year) at Boston Harbor stations (T01-T08) from 1992 to 2021 (1991 excluded).

3.2 BENTHIC INFAUNA

3.2.1 Community Parameters

A total of 31,438 infaunal organisms were counted from the 18 samples processed in 2021. Organisms were classified into 149 discrete taxa, 132 of which were species-level identifications. Ninety-seven percent of the individuals were identified to species; all remaining individuals 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 3-2). Data are presented in figures as means (averages per station) unless otherwise noted.

Table 3-2. Mean 2021 infaunal community parameters by station.

Station	Total Abundance	Number of Species	Pielou's Evenness (J')	Shannon-Wiener Diversity (H')	Log-series alpha
C019	223.5	9.5	0.64	2.07	2.08
T01	2353.5	51.5	0.62	3.52	9.41
T02	2311.5	45.0	0.60	3.27	7.93
T03	2527.0	48.5	0.52	2.90	8.53
T04	904.5	11.5	0.38	1.33	1.86
T05A	3057.5	55.5	0.61	3.56	9.72
T06	2857.5	33.5	0.55	2.80	5.34
T07	202.5	17.0	0.73	2.93	4.55
T08	1281.5	59.0	0.68	3.97	13.40

Mean total abundance at the eight traditional Harbor stations reported for 2021 was higher than in 2020 and comparable to values reported since 2011. Increases in mean abundance occurred at all traditional stations except Station T06 and ranged from 4% at Station T02 to 68% at Station T05A. Total mean abundance at Station T06 decreased by 9% compared to the 2020 value (Rutecki et al. 2021). Abundances in 2021 were within the range observed during the post-offshore diversion period but relatively low compared to pre-diversion values (Figure 3-7). The seven most abundant species in 2021 each contributed 4.0% or more of the animals counted, and together they provided 67% 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 2021 (Table 3-3) although the rank order changed. Five species of polychaetes were among the most abundant taxa in 2021. The five most abundant taxa in 2021 have frequently been among the most abundant in the harbor during previous years (Table 3-4). Certain spatial patterns of abundance also appeared to be consistent with previous years; T07 and C019 continued to support low infaunal abundances (Table 3-2). Station T05A had the highest abundance in 2021, and Station T02, T03, and T06 continued to support some of the highest abundances among the harbor stations.

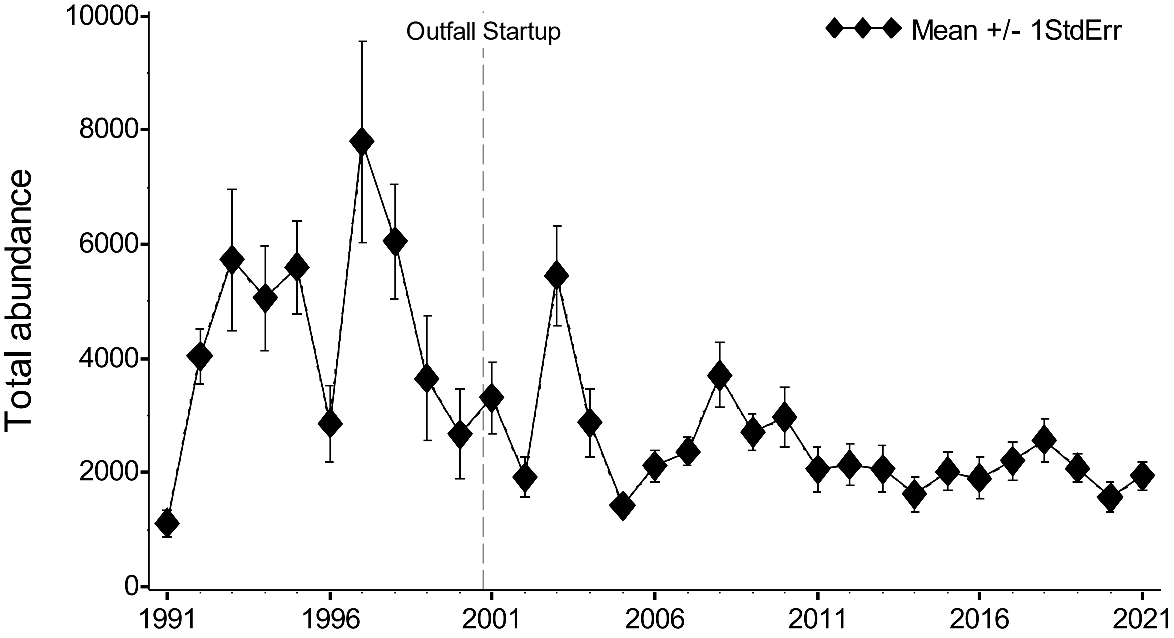

Figure 3-7. Mean abundance of benthic infauna at eight Boston Harbor stations (T01-T08), 1991-2021.

Table 3-3. Dominant taxa at eight grab stations (T01-T08) in Boston Harbor in August 2021.

Taxon	Total 2021 Abundance (compared with 2020)[a]
Aricidea catherinae	4,775 (similar)
Tubificoides intermedius	4,206 (increase)
Polydora cornuta	3,572 (increase)
Limnodriloides medioporus	2,712 (increase)
Ampelisca spp.	2,599 (increase)
Naidinae sp. 1	1,777 (increase)
Scoletoma hebes	1,167 (similar)

[a] increase or decrease indicates $\geq$25% change from previous year

Temporally, benthic infaunal abundance in the harbor has been controlled by a limited number of species (Table 3-4). 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 3-8. *A. catherinae* and *L. medioporus* have exhibited little interannual variation in abundance whereas both *P. cornuta* and *Ampelisca* spp. have exhibited fluctuations of one to two orders of magnitude, and abundances of both species are currently low. *P.*

cornuta and *Ampelisca* spp. 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).

Table 3-4. Mean abundance per sample of dominant taxa during four discharge periods at eight Boston Harbor stations (T01-T08), 1992-2021.

Phylum	Higher taxon	Family	Species[a]	Period I	Period II	Period III	Period IV	2021
Annelida	Polychaeta	Capitellidae	*Capitella capitata complex*	65.2	88.8	3.4	6.3	9.3
		Cirratulidae	*Tharyx acutus*	50.6	111.8	52.4	58.7	63.3
		Lumbrineridae	*Scoletoma hebes*	3.4	10.5	4.2	77.3	72.9
		Nephtyidae	*Micronephthys neotena*	-	11.4	10.3	160.2	27.0
		Paraonidae	*Aricidea (acmira) catherinae*	325.0	237.4	204.3	251.9	298.4
		Spionidae	*Dipolydora quadrilobata*	0.6	1.3	0.7	7.7	60.8
			Polydora cornuta	525.8	1053.0	269.6	263.6	223.3
			Streblospio benedicti	236.0	298.6	27.7	89.5	43.6
	Oligochaeta	Tubificidae	*Limnodriloides medioporus*	484.7	297.9	315.2	228.5	169.5
			Naidinae sp. 1	-	0.0	0.0	21.4	111.1
			Tubificoides intermedius	42.6	101.4	231.2	236.8	262.9
			Tubificoides sp. 2	-	-	12.1	14.0	64.8
Arthropoda	Amphipoda	Ampeliscidae	*Ampelisca* spp.	354.3	1698.3	1205.9	476.3	162.4
		Corophiidae	*Corophiidae* spp.	16.1	336.2	23.0	1.4	0.3
			Crassicorophium bonellii	7.9	217.3	37.3	6.4	1.3
			Leptocheirus pinguis	29.0	117.4	66.0	67.1	4.6
		Photidae	*Photis pollex*	11.4	77.0	86.8	25.8	1.3
		Phoxocephalidae	*Phoxocephalus holbolli*	28.0	116.9	125.9	5.8	5.6

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

[b] Previously identified as *Nepthys cornuta* and *Bipalponephtys neotena.*

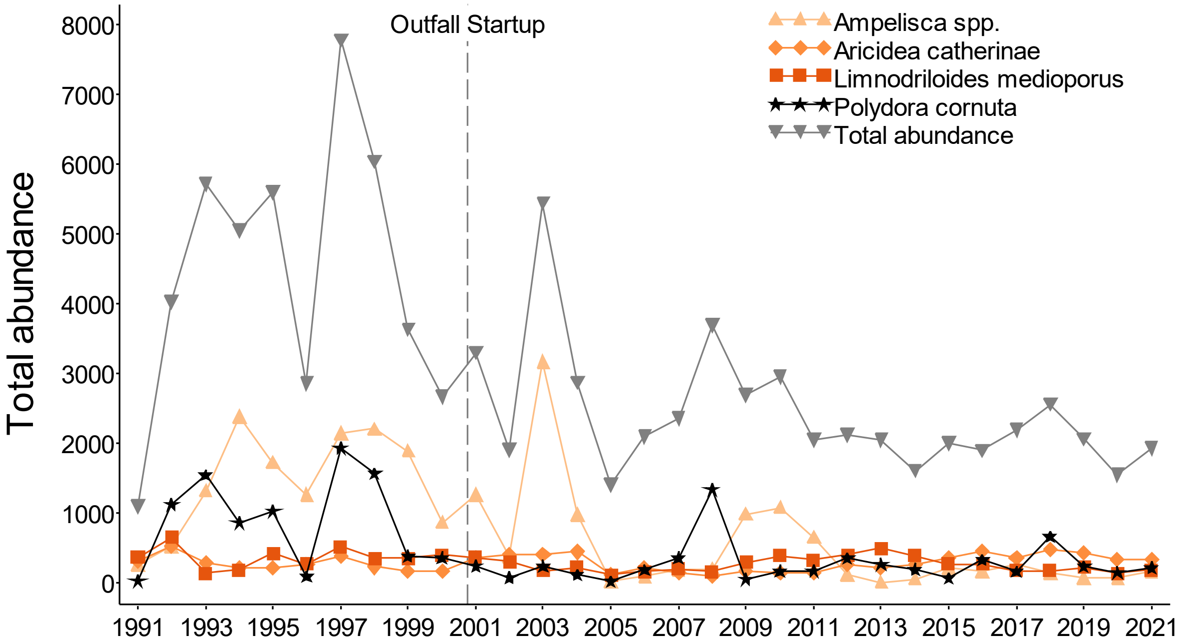

Figure 3-8. Total abundance of four dominant taxa at eight Boston Harbor stations (T01-T08), 1991-2021.

Patterns of abundance of *Ampelisca* spp. have been of particular interest throughout the history of the program due to the numerical dominance of this taxon in Harbor assemblages and the tolerance of *Ampelisca abdita* to highly enriched sediments. 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 to 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, declined in 2012-2014 to levels comparable to those seen in 2005-2008, increased slightly in 2015 and 2017, and then declined (Figure 3-9). *Ampelisca* abundance in 2021 was higher than 2020 and similar to 2018 (Figure 3-9). *Ampelisca* have been most abundant at Stations T03 and T06. For example, *Ampelisca* was more widespread in 2015 (seven stations) compared to 2014 (four 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 3-10). 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 and in 2018 could also have resulted in disturbances (sedimentation or substrate contact from anchored vessels) to stations T03 and T05A. *Ampelisca* abundances at Station T06 increased from 2019 through 2021.

Species identifications of *Ampelisca* spp., which began in 1995, indicate that the changes in abundance discussed above are also related to changes in the species of *Ampelisca* spp. present in the Harbor. From 1995 through 2012, *Ampelisca abdita* was the predominant species of *Ampelisca* accounting for 80 to

100% of the individuals collected. Beginning in 2013, the percentage of *A. abdita* declined to nearly zero and remained low through 2019 ranging from 0 to 20%. In 2021, *A. abdita* accounted for approximately 33% of the *Ampelisca* spp. collected. *Ampelisca vadorum* now accounts for the majority of the *Ampelisca* collected, although abundances of *A. vadorum* do not appear to have changed from 1995 through 2021 (Figure 3-11). These two species of *Ampelisca* have different habitat preferences, *A. abdita* inhabits fine sediments (i.e., find sand and mud) and *A. vadorum* occurs on coarse sand. *A. abdita* occurs at lower salinities than *A. vadorum* (Mills 1967). Changes over time in the populations of *Ampelisca* relative to changes in salinity were further discussed in Rutecki et al. (2020b).

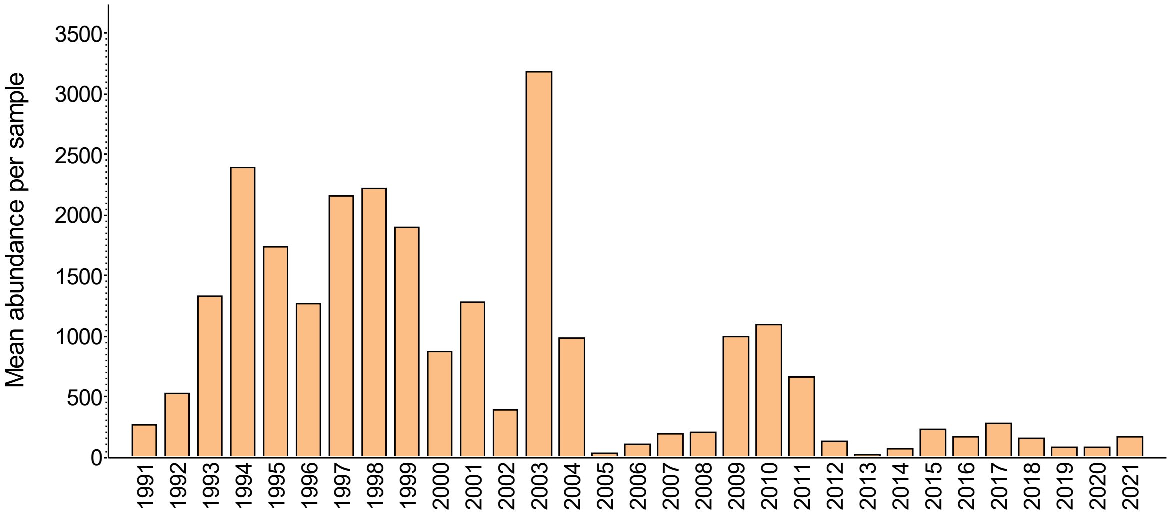

Figure 3-9. Mean annual abundance of *Ampelisca* spp. averaged over eight Boston Harbor stations (T01-T08), 1991-2021.

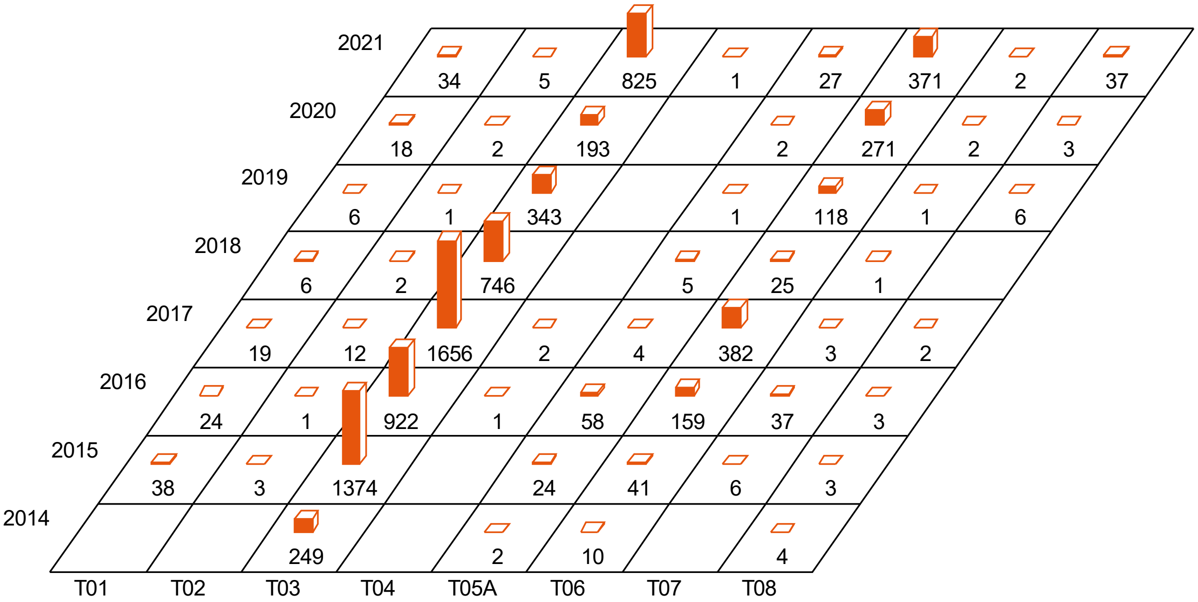

Figure 3-10. Spatial distribution of *Ampelisca* spp. at eight Boston Harbor stations (T01-T08), 2014-2021.

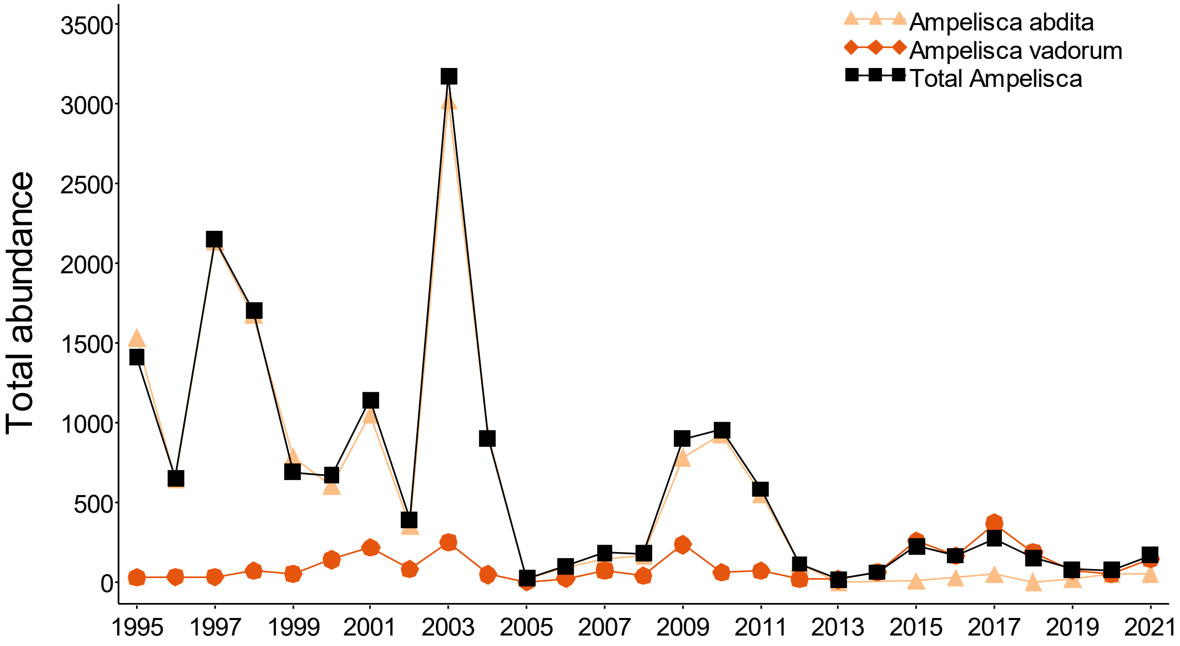

Figure 3-11. Mean total abundance of the two dominant *Ampelisca* taxa at eight Boston Harbor stations (T01-T08), 1995-2021.

The numbers of species reported for 2021 ranged from 11.5 to 59.0 per station and averaged 40.2 species per station. These values were higher than numbers reported in most years in the 1990s and about average for the 2000s, when species richness exhibited relatively high inter-annual variation (Table 3-2, Figure 3-12). Mean species richness was slightly lower in 2021 than in 2019 and 2020 but remained within the range of historical variation (Figure 3-12). Stations T02, T03, and T08 were among the most species-rich stations from 2011 through 2020 (Rutecki et al. 2021); in 2021 species richness at each these three stations was above the average for the Harbor. Station T04 has consistently supported the lowest species richness in this time frame. Stations T01 and T05A also exhibited species richness above the average for the Harbor in 2021.

When averaged across the eight outer harbor stations Pielou's evenness and Shannon-Weiner diversity, two measures of community structure, were similar to the values in 2020 and remain at high levels. Average Pielou's evenness declined from 0.60 in 2015 to 0.52 in 2019 but increased in 2021 to 0.59. Average Shannon-Weiner diversity declined from 3.11 in 2015 to 2.81 in 2019, increased in 2020 to 3.05, and then decreased slightly in 2021 (3.04; Figures 3-13 and 3-14, Table 3-2). Within each station, differences in these metrics between 2020 and 2021 were typically small and, in general, spatial patterns in these parameters were similar between the two years suggesting that the integrity of the benthic infaunal community had not changed. Average diversity for the harbor stations, as measured by log-series alpha, decreased in 2021 (7.6) compared to 2020 (8.1, Rutecki et al. 2021), but remained well above pre-diversion values (1991-2000; Figure 3-15). The highest log-series alpha diversity in 2021 occurred at Station T08, which is typical as Stations T08 or T01 have historically had the highest log-series alpha diversity in the Harbor. Consistent with recent patterns, log-series alpha diversity was lowest at T04 in 2021 (Table 3-2; Pembroke et al. 2017, Rutecki et al. 2021). The largest change in log-series alpha compared to 2020 was the decrease at T06.

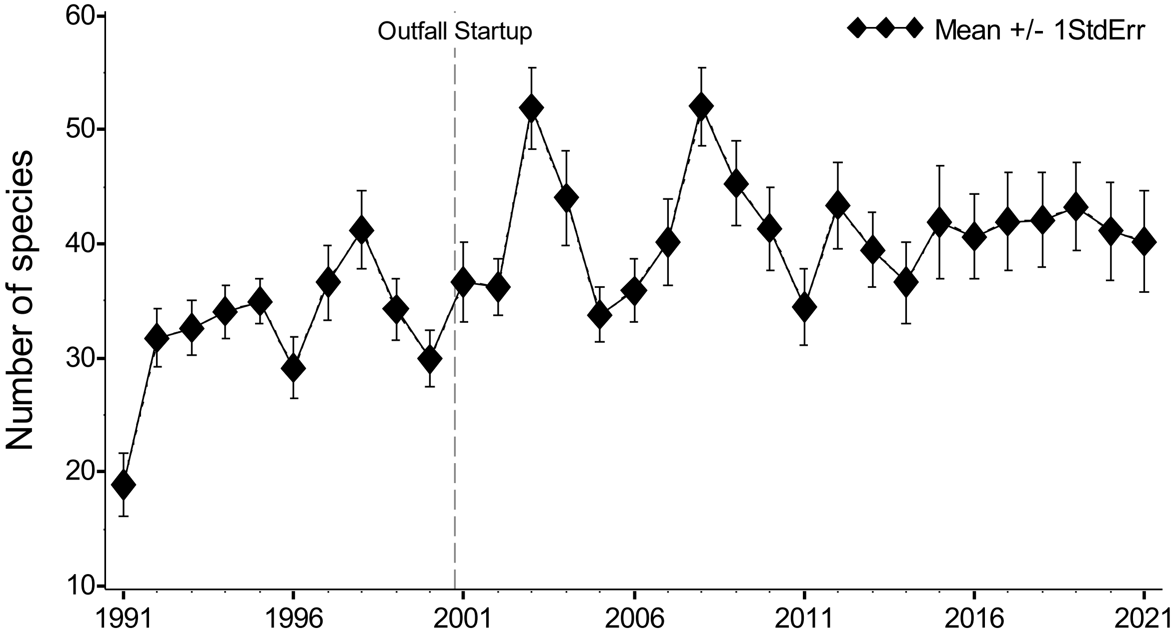

Figure 3-12. Mean species richness at eight Boston harbor stations (T01-T08), 1991-2021.

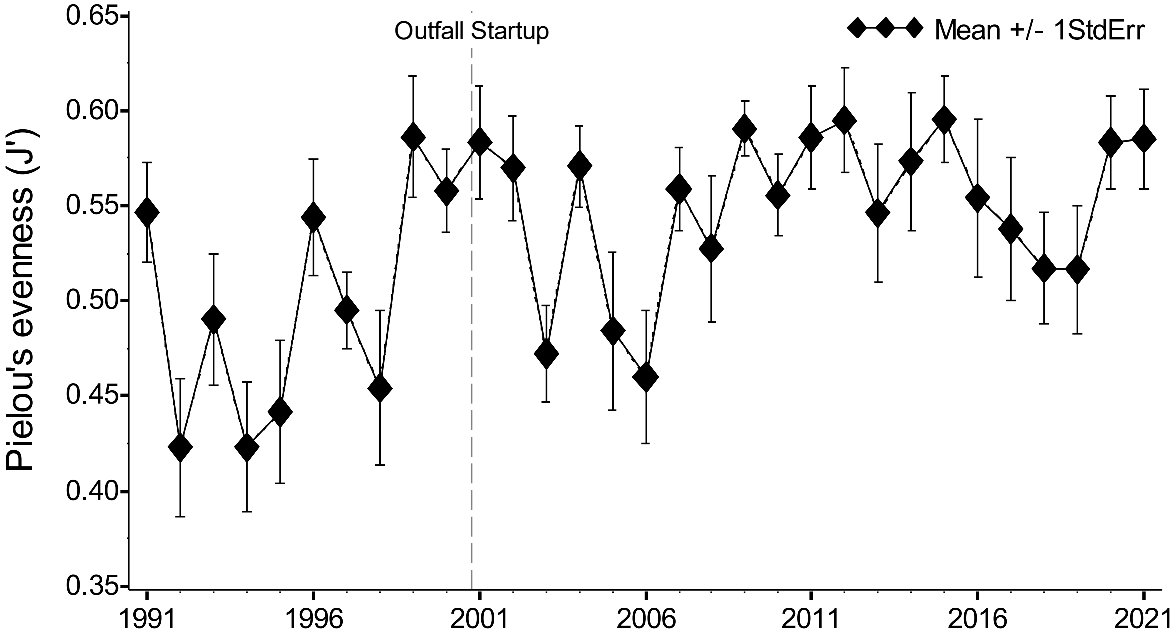

Figure 3-13. Mean community evenness at eight Boston Harbor stations (T01-T08), 1991-2021.

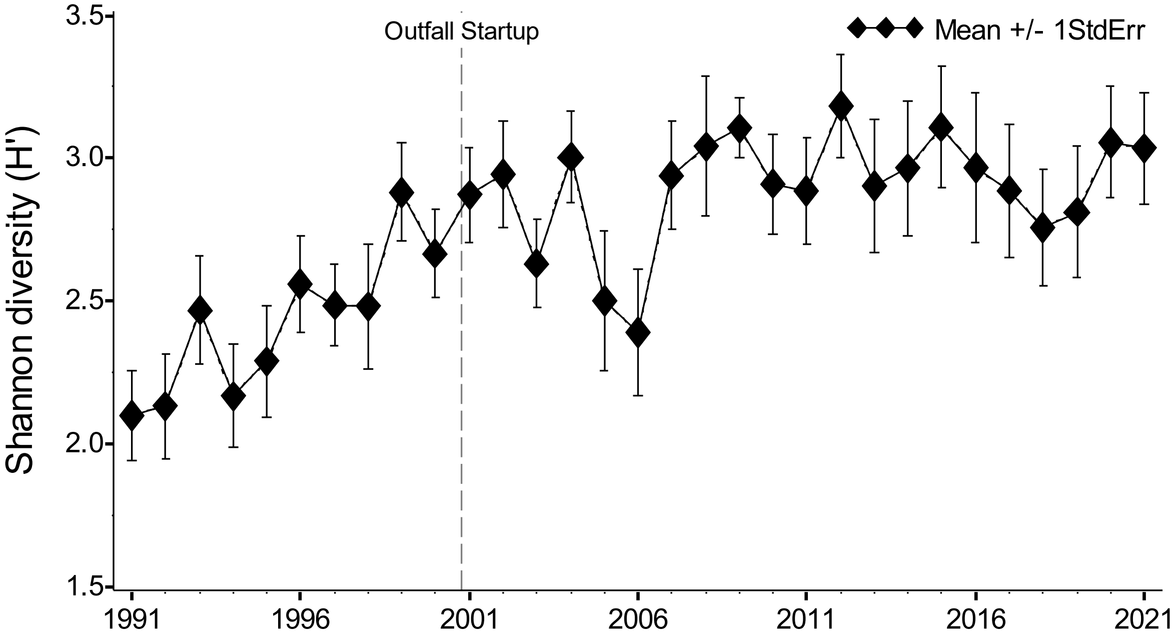

Figure 3-14. Mean Shannon-Weiner diversity at eight Boston harbor stations (T01-T08), 1991-2021.

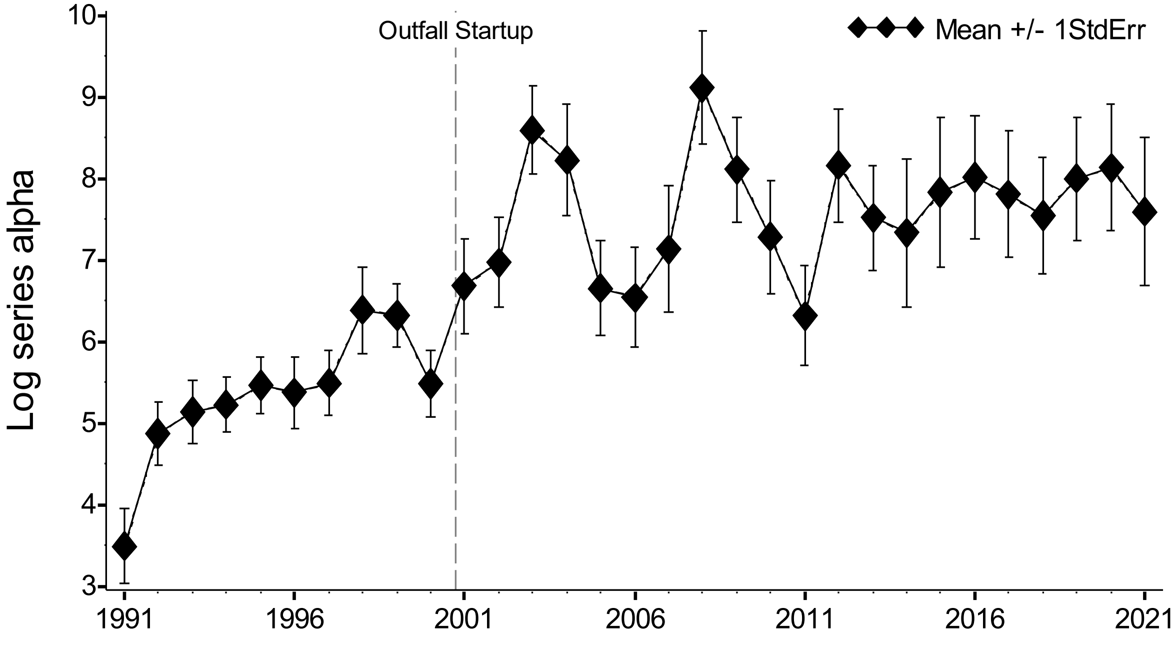

Figure 3-15. Mean log-series alpha diversity at eight Boston Harbor stations (T01-T08), 1991-2021.

3.2.2 Infaunal Assemblages

Multivariate analyses were used to assess spatial patterns in the faunal assemblages at the Boston Harbor sampling stations. Replicates within each station exhibited high similarities in community structure and grouped together. Five main assemblages were identified in a cluster analysis of the 18 samples from 2021 (Figure 3-16). Patterns identified through cluster analysis were confirmed in the MDS ordination plot for the 2021 Harbor samples (Figure 3-16). All assemblages were dominated by polychaetes or oligochaetes (Table 3-5). Spatial patterns in the faunal assemblages of Boston Harbor reflect a gradient from species poor stations C019, T04, and T07, to more diverse stations which tend to be in the outer Harbor.

The Group IA assemblage was found at outer Harbor Stations T08 (Hingham/Hull Bay) and T05A (Deer Island); the Group IB assemblage was found at outer Harbor to mid-Harbor stations (T01, T02, T03 off Deer Island and the Main Ship Channel, and T06 in outer Quincy Bay); the Group IIA assemblage was found at Station T07 (Quincy Bay); the Group IIB assemblage was found at Station C019 in the Inner Harbor; and the Group IIC assemblage was found at Station T04, at the mouth of Savin Hill Cove, in Dorchester Bay. The assemblage at Station T04 is typically the most different from all of the others. 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.

Main Group I encompassed most of the outer Harbor stations (T01, T02, T03, T05A, T06, and T08) characterized by relatively high abundance (averaging 2,398 individuals) and species richness (averaging 49 species per collection). Four species of polychaetes and oligochaetes (*Aricidea (Acmira) catherinae*, *Tubificoides intermedius*, *Polydora cornuta*, and *Limnodriloides medioporus*) along with *Ampelisca*. sp. had relatively high abundances (Table 3-5). Within Group I, Stations T05A and T08 were distinct enough to form Group IA dominated by *P. cornuta*, *T. intermedius*, *Naidinae* sp. 1, *Tharyx acutus*, and *Spiophanes bombyx*, and were characterized by high species richness (averaging 57 species per collection). Group IB was comprised of Stations T01, T02, T03, and T06 characterized by high abundance and species richness (averaging 45 species per collection). Dominants included *A. catherinae*, *T. intermedius*, *L. medioporus*, *Ampelisca* sp., and *P. cornuta.*

The main Group II consisted of Stations C019, T04, and T07 and were dominated by *Tubificoides* sp. 2, *Streblospio benedicti*, and *Micronephthys neotena* (Table 3-5). Each station in main Group II was distinct enough to form its own subgroup. Station T07 formed Group IIA and was dominated by *M. neotena*, *T. intermedius*, and *P. cornuta*. This subgroup was characterized by low abundance and species richness (averaging 17 species per collection). Station C019 formed Group IIB dominated by *Cossura* sp. 1 and *M. neotena*; total abundance and species richness were low. Station T04 formed Group IIC dominated by *Tubificoides* sp. 2 and *S. benedicti*, total abundance was moderate and species richness was low. Sediment conditions, particularly percent fines and TOC were likely factors in distinguishing the benthic communities among the Boston Harbor stations. Group IA (T05A and T08) was predominantly sand and very low TOC. Sediments at stations in Group IB ranged from approximately 40 to 77% sand and moderate to low TOC (0.7 to 1.8%). Sediments at Station T07 (Group IIA) were approximately 59% fines with a moderate TOC (1.9%). Sediments at C019 (Group IIB) were predominantly fines (95%) with a moderate TOC (2.3) and sediments at Station T04 (Group IIC) were predominantly fines and TOC was higher than at other locations (Table 3-1).

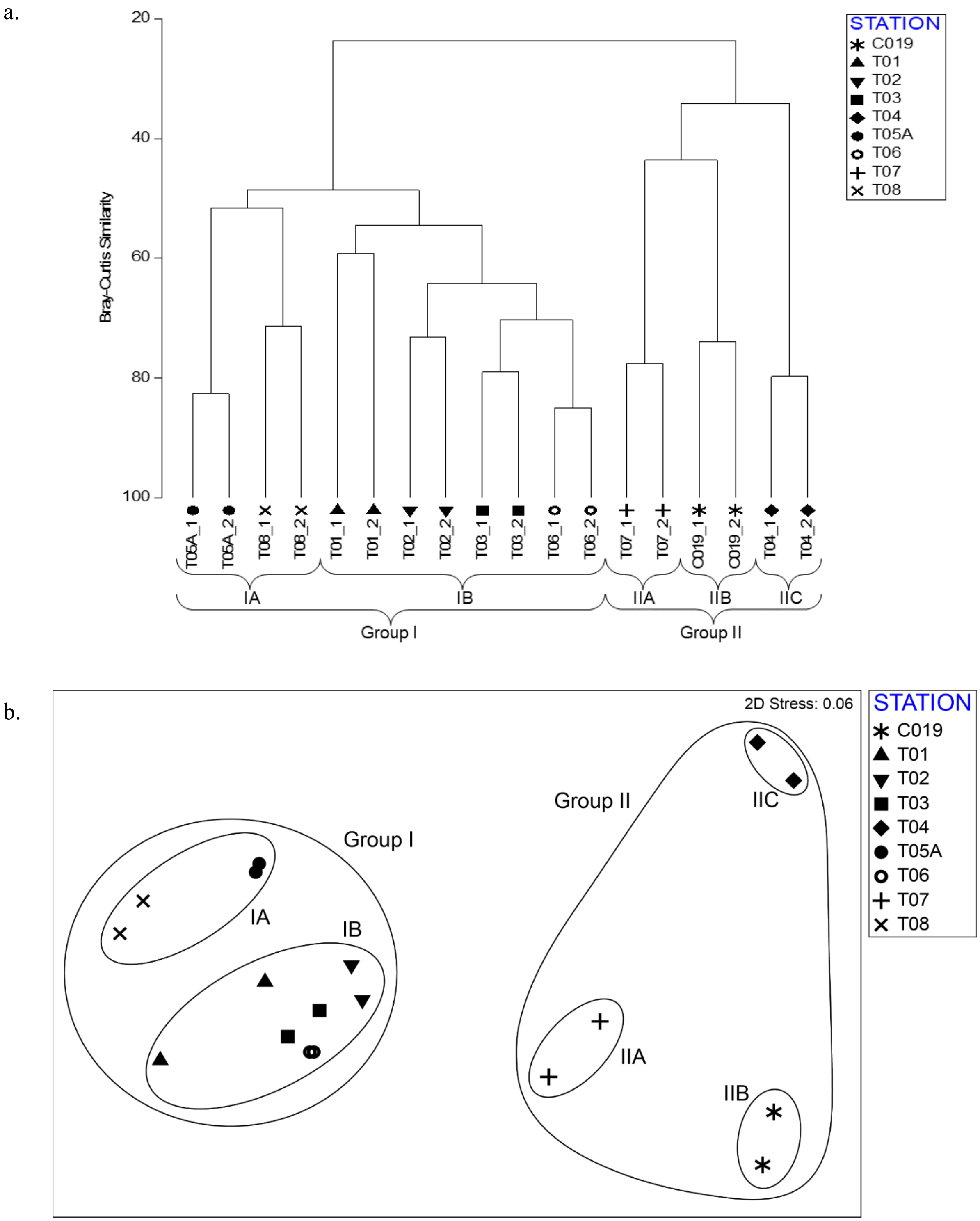

Figure 3-16. Results of (a) cluster analysis and (b) multidimensional scaling analysis of the 2021 infauna samples.

Table 3-5. Mean abundance of dominant taxa in 2021 Boston Harbor station groups defined by cluster analysis. Bold numbers denote the dominant taxa in the two main assemblages.

Major Taxon	Family	Species	I	IA[a]	IB[a]	II	IIA[b]	IIB[b]	IIC[b]
Turbellaria		*Platyhelminthes* sp. 17	**-**	-	0.4	**-**	-	-	1.0
Bivalvia	Pandoridae	*Pandora gouldiana*	**-**	0.2	0.6	**-**	2.5	-	-
	Tellinidae	*Ameritella agilis*	**-**	67.2	9.1	**-**	3.5	-	2.5
Polychaeta	Capitellidae	*Mediomastus californiensis*		34.8	39.0	**-**	-	0.5	-
	Cirratulidae	*Tharyx acutus*	**82.5**	213.8	16.9	**3.8**	9.5	0.5	1.5
	Cossuridae	*Cossura* sp. 1	**19.1**	-	28.6	**27.8**	-	83.0	0.5
	Lumbrineridae	*Scoletoma hebes*	**95.7**	16.0	135.5	**3.2**	9.5	-	-
	Microphthalmidae	*Microphthalmus pettiboneae*	**-**	3.5	8.2	**-**	-	-	7.0
	Nephtyidae	*Micronephthys neotena*	**22.4**	-	33.6	**54.0**	57.0	80.5	24.5
		Nephtys incisa	**-**	1.2	1.5	**-**	-	5.5	0.5
	Orbiniidae	*Leitoscoloplos robustus*	**6.9**	7.0	6.9	**4.2**	6.0	-	6.5
	Paraonidae	*Aricidea (Acmira) catherinae*	**395.1**	21.2	582.0	**5.7**	17.0	-	-
	Pholoidae	*Pholoe* spp.	**-**	1.2	8.1	**-**	1.5	2.0	-
	Polygordiidae	*Polygordius jouinae*	**-**	97.0	0.1	**-**	-	-	-
	Spionidae	*Dipolydora quadrilobata*	**81.0**	0.2	121.4	**-**	-	-	-
		Polydora cornuta	**293.2**	356.5	261.6	**16.5**	25.0	23.0	1.5
		Spiophanes bombyx	**68.1**	201.2	1.5	**-**	-	-	-
		Streblospio benedicti	**1.7**	0.8	2.1	**113.8**	1.5	2.5	337.5
	Terebellidae	*Polycirrus phosphoreus*	**-**	1.0	0.1	**-**	-	1.0	-
Oligochaeta	Tubificidae	*Limnodriloides medioporus*	**244.8**	7.8	333.4	**2.3**	7.0	-	-
		Naidinae sp. 1	**147.8**	281.2	81.1	**0.5**	1.5	-	-
		Tubificoides intermedius	**342.1**	333.5	346.4	**22.3**	50.5	16.5	-
		Tubificoides sp. 2	**-**	-	-	**172.8**	-	-	518.5
Amphipoda	Ampeliscidae	*Ampelisca* spp.	**216.2**	31.8	308.5	**0.7**	1.5	-	0.5
	Corophiidae	*Crassicorophium crassicorne*	**-**	75.8	-	**-**	-	-	-
		Leptocheirus pinguis	**-**	9.0	4.6	**-**	-	5.0	-

[a] distinct subgroup of Group I

[b] distinct subgroup of Group II

3.2.3 Selected Stations

Station T01. Infaunal community structure at Station T01, located near Deer Island Flats north of President Roads, has typically exemplified conditions at most stations in the Harbor throughout the survey period. In 2021, species richness, Shannon-Weiner diversity, evenness, and log-series alpha were high at T01. Species richness, diversity, and log-series alpha all declined compared to 2020 but remained within the ranges of values recorded in recent years (Rutecki et al. 2021). Mean abundance and evenness increased in 2021 compared to 2020 and were similar to other values observed in the post-diversion period (Figure 3-17). Species richness, Shannon-Weiner diversity, Pielou's evenness, and log-series alpha were about average for the period since the diversion (Figures 3-18 through 3-21). In 2021, all of these community parameters remained above the relatively low values observed in 2013 (Figures 3-17 through 3-21).

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, steadily increased to above average (801) levels in 2018 (1,333), and then declined in 2021 (223.5) to the lowest value in the time series (Figure 3-17, Table 3-2). Species richness also peaked in 2013, fluctuated near average levels (17.2) from 2016 through 2020, and then decrease in 2021 to 9.5, the second lowest value in the time series (Figure 3-18). Log series alpha reached its peak value in 2014 and then declined through 2017. The 2021 log series alpha (2.08) declined compared to 2020 (Figure 3-19). Shannon-Weiner diversity and Pielou's evenness also peaked in 2014 and then declined. The 2021 values increase compared to 2020 remaining above their respective average values of 1.8 and 0.44 (Figures 3-20 and 3-21). Despite decreasing values in some recent years, Shannon diversity and evenness remained among the highest levels observed to date. The polychaete *Micronephthys neotena* (formerly called *Nepthys cornuta* and *Bipalponephtys neotena*) had represented the majority of the infauna found at Station C019 from 2004-2011 (Figure 3-22) 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), the oligochaete *Tubificoides intermedius* dominating in 2015, and *Polydora cornuta* in 2016. *Cossura* sp 1 has dominated the community structure from 2017 through 2021. *M. neotena* and *P. cornuta*, respectively, were the next two dominant taxa in the infaunal community in 2021 (Figure 3-22, Table 3-5).

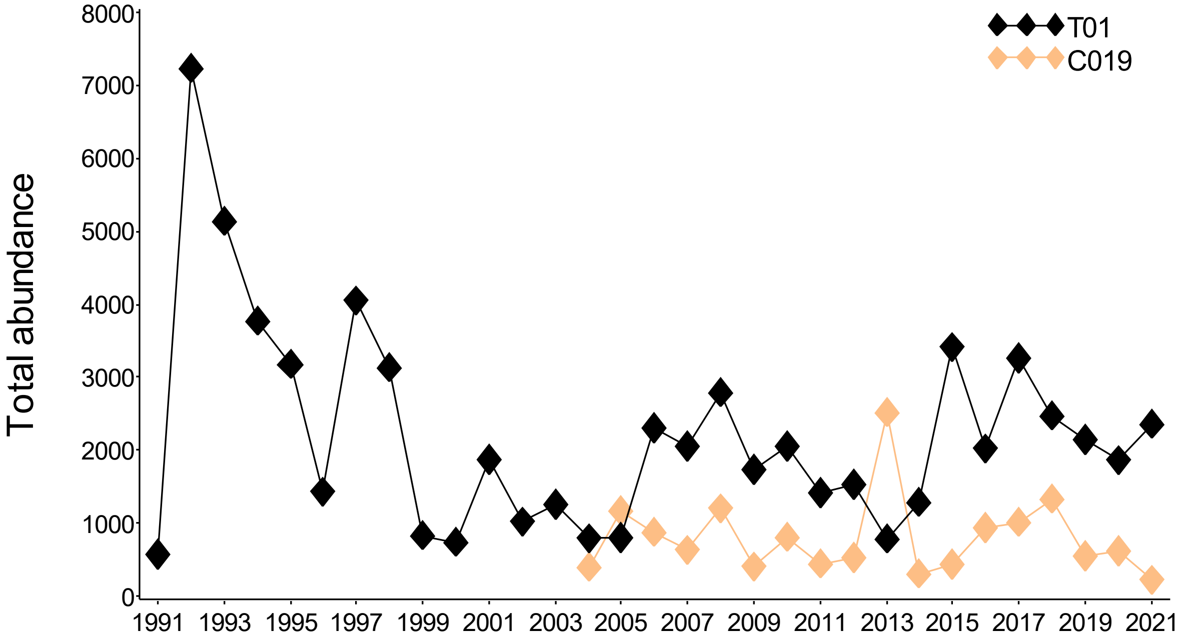

Figure 3-17. Mean total abundance at Boston Harbor Stations T01 and C019, 1991-2021.

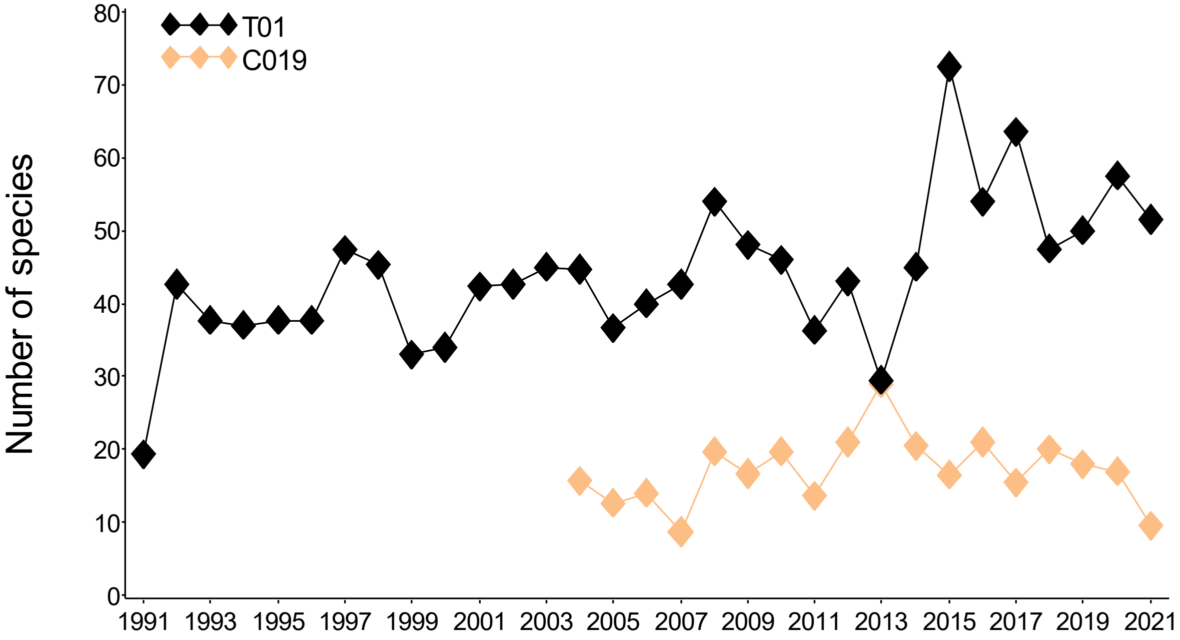

Figure 3-18. Mean species richness at Boston Harbor Stations T01 and C019, 1991-2021.

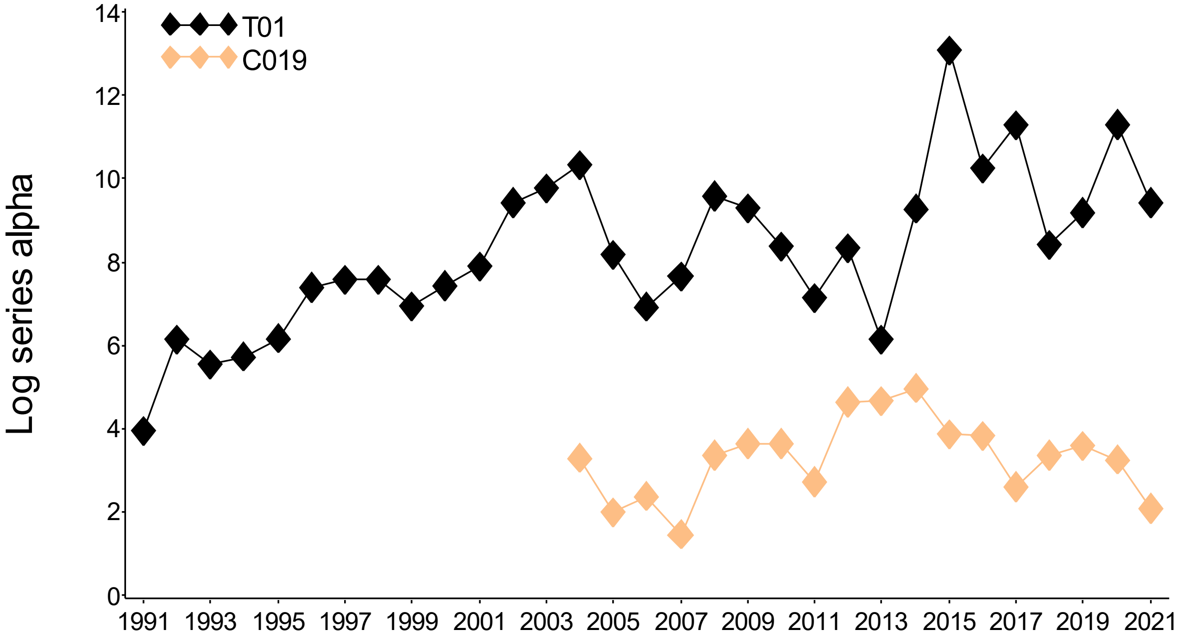

Figure 3-19. Mean log-series alpha diversity at Boston Harbor Stations T01 and C019, 1991-2021.

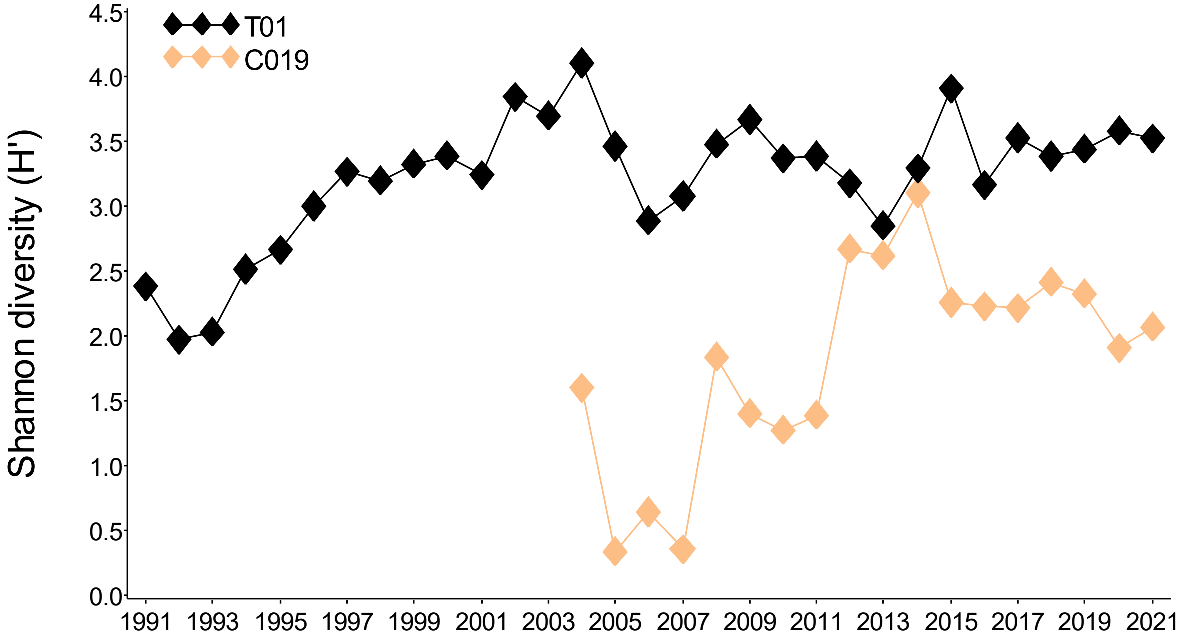

Figure 3-20. Mean Shannon-Weiner diversity at Boston Harbor Stations T01 and C019, 1991-2021.

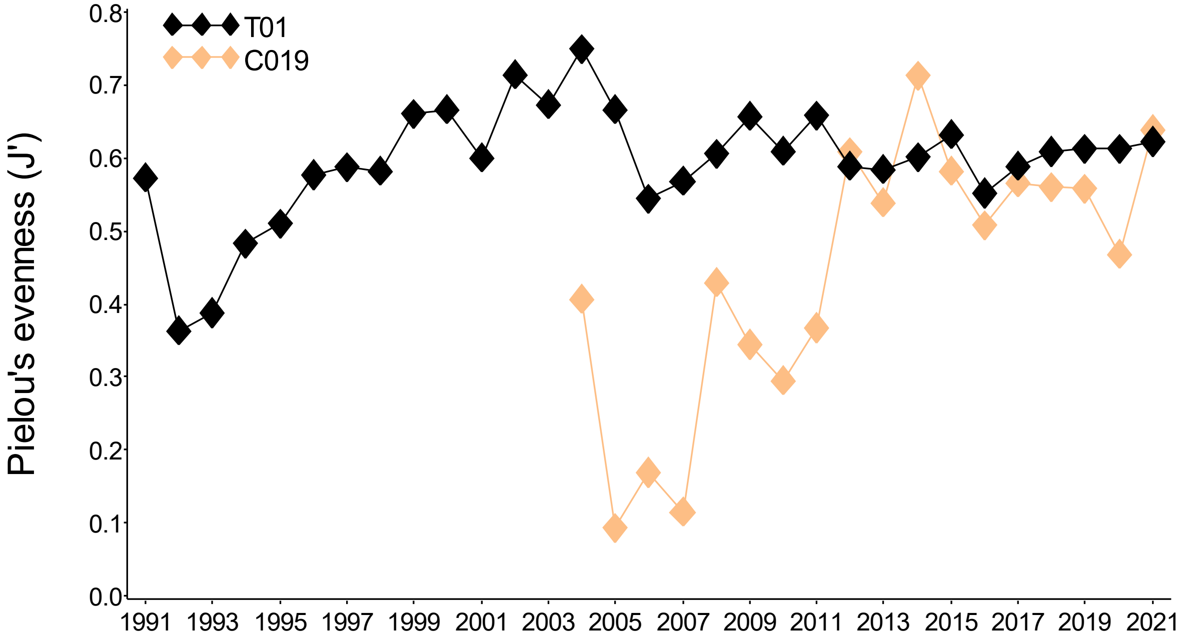

Figure 3-21. Mean evenness at Boston Harbor stations T01 and C019, 1991-2021.

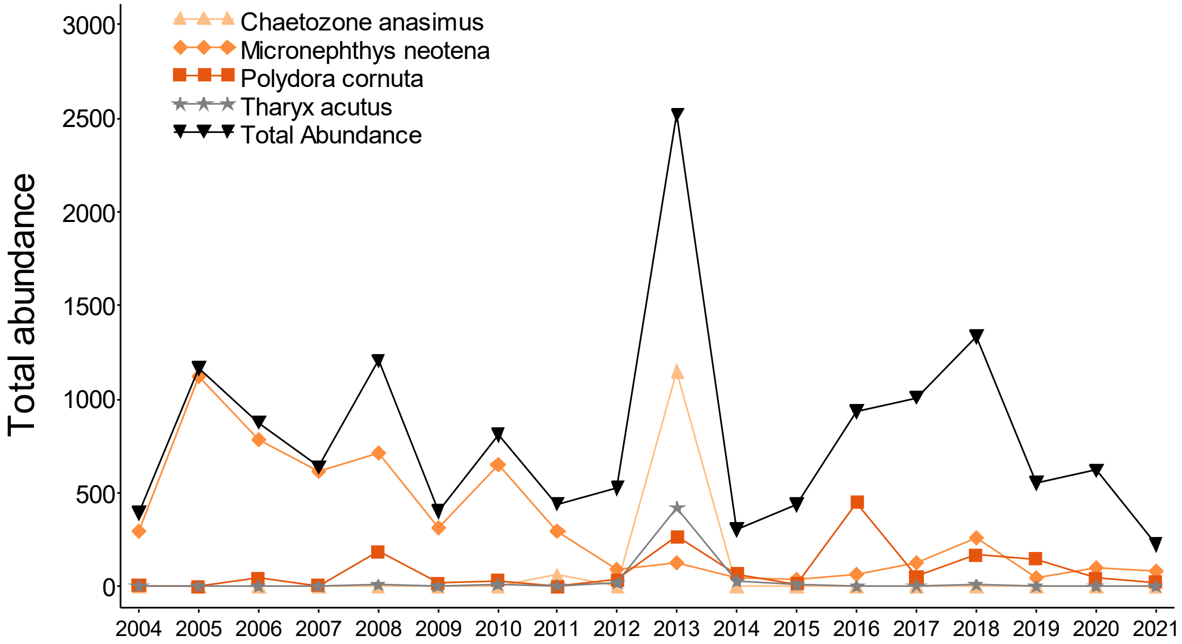

Figure 3-22. Mean abundance of *Micronephthys neotena* (formerly *Bipalponephtys neotena*) and other dominants and total community abundance at Station C019, 2004-2021.

3.2.4 Temporal Trends

Benthic community parameters for Boston 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 3-6). 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 2002-2021 were virtually the same as for 2002-2020 (Rutecki et al. 2021) so it is apparent that this trend has continued. It should be noted that the mean total abundance doubled in Period II largely as a result from sharp increases in *Ampelisca* spp. abundance in those years at some stations, especially T03, T06, and T08. For example, abundances of *Ampelisca* spp. at Station T03 were observed at > 6,000 individuals/sample during those years (Maciolek et al. 2008).

Table 3-6. Benthic community parameters for stations T01-T08, summarized by time periods defined by Taylor (2006).

Parameter	Period I (prior to Dec. 1991)		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	2,457	108
Log-series alpha	4.2	0.3	5.5	0.2	6.2	0.3	7.6	0.2
Shannon-Wiener Diversity (H')	2.1	0.1	2.4	0.1	2.8	0.1	2.9	0.05
Pielou's Evenness (J')	0.48	0.02	0.47	0.01	0.58	0.02	0.55	0.01
Number of Species	25.4	2.1	34.7	1.1	33.6	1.7	41.3	0.9
Years of Data in Period	1991-1992		1993-1998		1999-2001		2002-2021	

3.3 SEDIMENT PROFILE IMAGING

3.3.1 General Benthic Habitat Conditions

Averaged benthic habitat quality within the Harbor (all 61 SPI stations, see Figures 2-1 and 3-23 for locations), as measured by the Organism Sediment Index (OSI, Rhoads and Germano 1986), for 2021 continued a trend of higher quality that started after dips in 2015 and 2018 (Figure 3-24). The low in 2015 was related to a slight decline in averaged apparent redox potential discontinuity (aRPD) layer depth and total biogenic structures. In 2018 the dip was related to dredging of President Roads and inner harbor navigation channels that drastically lowered OSI at Stations R02 and R10. For both of these years the modal and mean OSI for the Harbor did remain above 6 (the breakpoint between stress and non-stress benthos). The last year the Harbor's benthic habitat quality dipped below 6 was 2002 (Figure 3-24) and was related to a decline in the number of stations with the highest quality habitat category (OSI = 11).

Benthic habitat and communities within the Harbor have substantially recovered from past excessive organic and nutrient loading due to improvements in wastewater treatment and diversion to the offshore outfall in September 2000 (Diaz et al. 2008, Tucker et al. 2014, Taylor et al. 2019). Much of the change occurred early in the wastewater-improvement project, associated with the biggest reductions in loadings (Blake et al. 1998, Taylor et al. 2019). Poorest habitat quality, lowest OSI scores, were linked to low dissolved oxygen (hypoxic) in Dorchester Bay region between 1994 and 1998 (Figure 3-24).

Basically, inner harbor regions improved more through time than outer harbor regions. The most pronounced improvements in habitat quality occurred between 1992 to 2002 in the inner Harbor regions (Inner Harbor/Dorchester Bay, Quincy Bay, and Hingham Bay) and also Deer Island Flats (Figure 3-25). Greatest improvements in habitat quality were directly related to improved water quality (Diaz et al. 2008, Taylor et al. 2019). Deer Island Flats was the outer harbor region most affected by wastewater and sludge disposal due to the nearby Deer Island outfalls (Taylor 2010). Even after improvements in wastewater treatment and diversion to the offshore outfall, the inner to outer harbor gradient in habitat quality remains prominent due to the Harbor's geomorphology and tidal currents that control the distribution of sediments (Signell and Butman 1992).

Habitat quality was consistently highest at the other outer harbor regions from 1992 to 2002 with no obvious trends related to improved water quality. In Nantasket Roads with wastewater outfalls operating up to April 1998, habitat quality remained high (OSI >6), except in 1994 when seven of the ten stations within Nantasket Roads had OSI vales <6 due to declines in aRPD layer depth. Similarly, in President Roads with outfalls operating up to September 2000 (Taylor 2010), habitat quality was high except in 1999 (6 of 10 stations <6 OSI), 2000 (5 of 10), and 2005 (4 of 10). Reasons for the low OSIs varied but most were related to physical disturbance and shallower aRPD layer depths. In 2021, low OSI outliers (more than two times the interquartile range for a region) occurred in Quincy Bay (R36) and Dorchester Bay (T04) primarily due to shallow aRPD layer depths (Figure 3-26).

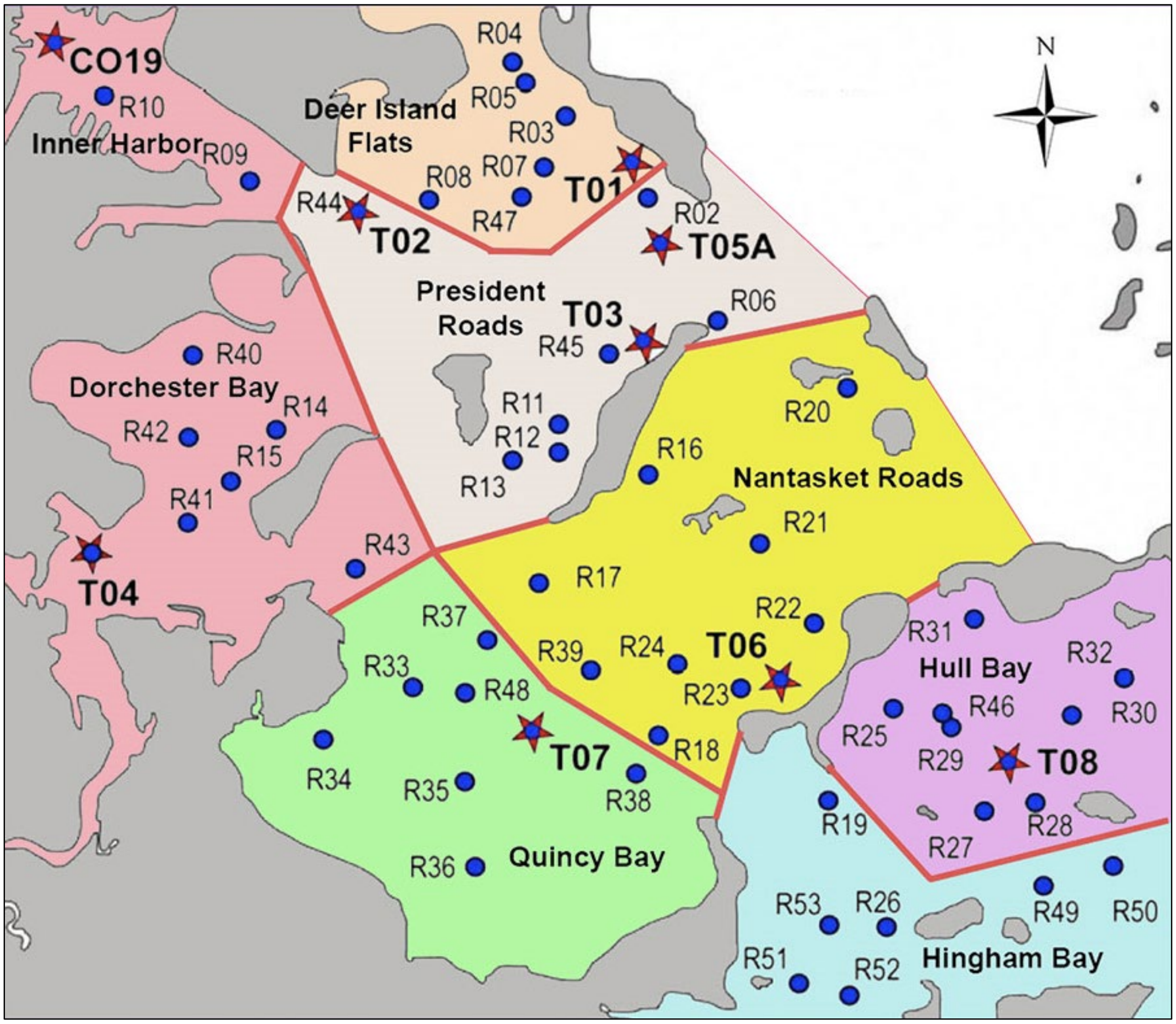

Figure 3-23. Sediment profile imaging stations (blue points) and soft-bottom sampling locations (stars) delineated by Boston Harbor regions.

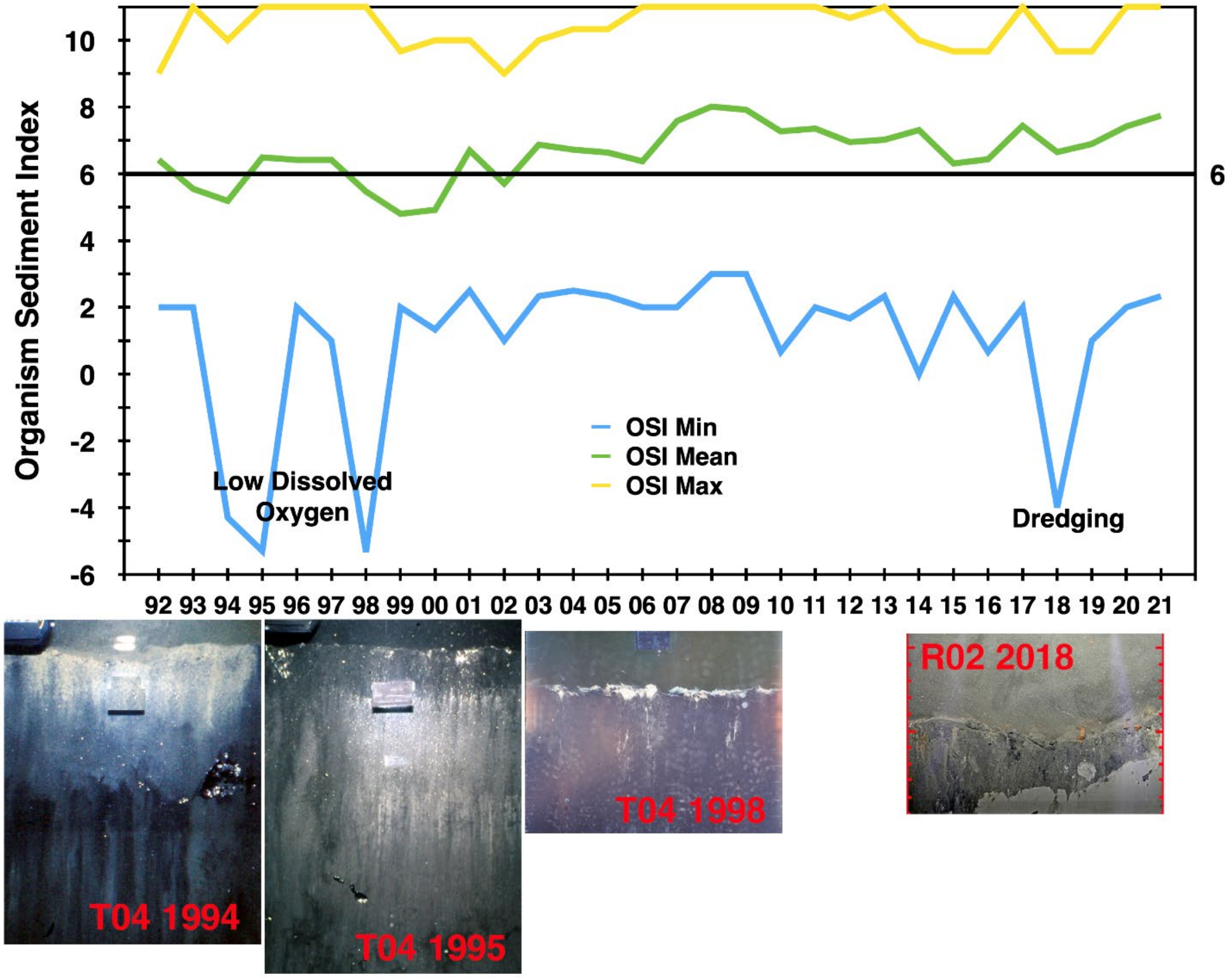

Figure 3-24. Maximum, mean, and minimum OSI for all 61 Harbor stations by year. Horizontal line at 6 is the breakpoint between stress and non-stress benthos (>6 represents good benthic habitat). Example images are 15 cm wide.

Figure 3-25. OSI anomaly (year mean - grand mean) for Boston Harbor regions. Higher than grand mean OSI years are positive and lower are negative values. Horizontal dotted line at 6 is the breakpoint between stress and non-stress benthos (>6 represents good benthic habitat). See Figure 3-25 for region boundaries.

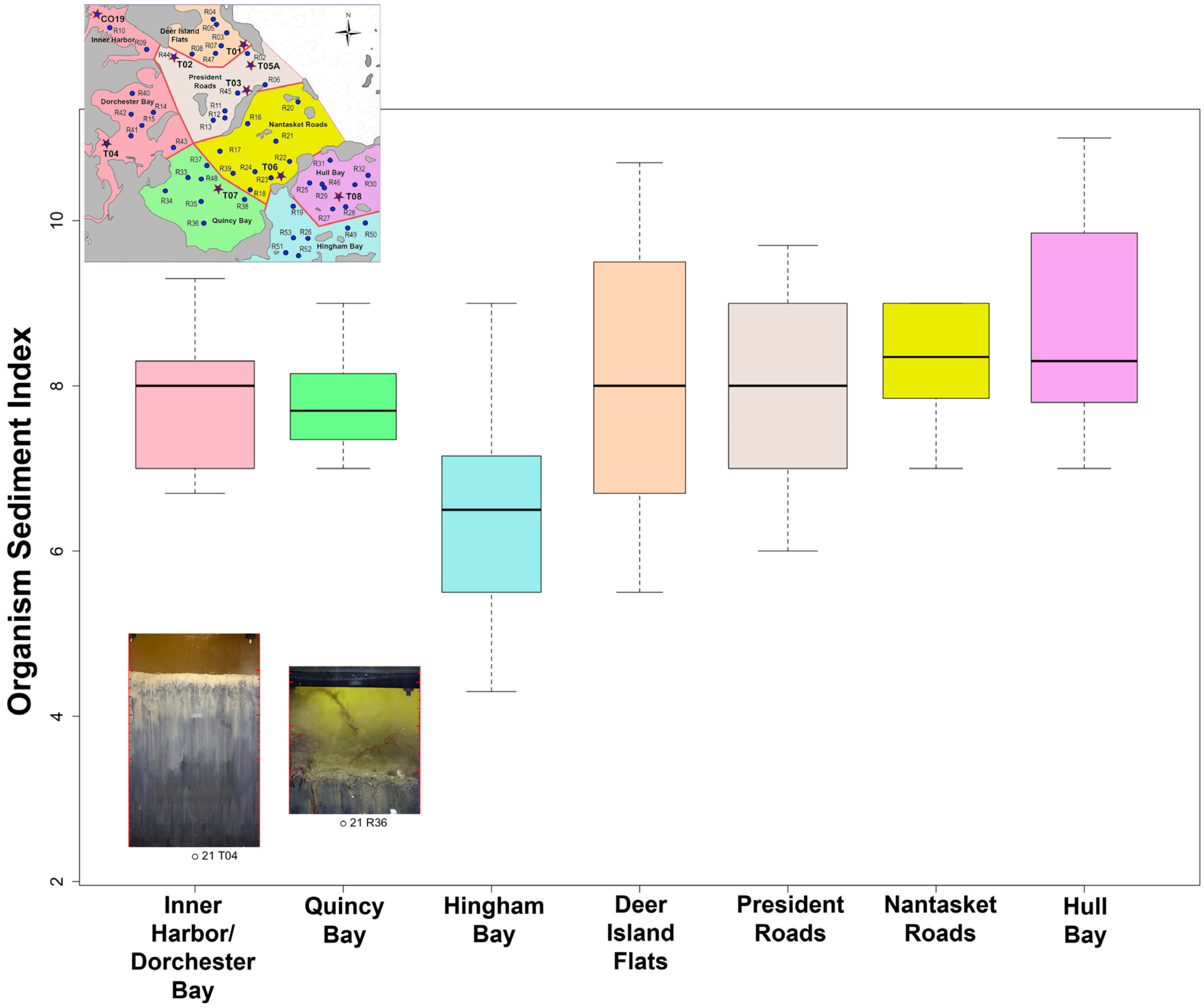

Figure 3-26. Box plot of OSI by Harbor region for 2021. Boxes are interquartile range (IR), whiskers are 2IR, outliers are labeled. Black bar in box is the region median. Images are 15 cm wide.

Between 2003 and 2006 the benthic habitat quality transition from responding to improvements in wastewater treatment and offshore outfall diversion, to responding to other broader regional driving factors. By 2006, inner to outer harbor gradients were less obvious and primarily maintained by the Harbor's complex geomorphology and hydrodynamics, and secondarily by sediment grain-size. Benthic habitat quality now appears to be driven by either harbor-wide forcing factors such as storms and climate variability, or local-scale factors such as dredging or eelgrass restoration. Climate change has already altered sea level, storminess, wind and wave energy, temperature, and salinity in the Boston region, and is expected to play a larger role in the future (USGCRP 2017, Talke et al. 2018, Voorhies et al. 2018, Reguero et al. 2019, Codiga et al. 2019, Werme et al. 2021).

Dredging operations in President Roads, part of the deep draft navigation improvement project (Massport and Corps 2013), did temporarily reduce habitat quality. Station R02, of the southwest end of Deer Island, was dredged in August 2018 just prior to SPI sampling. A year later (August 2019) the effect of dredging was still seen in SPI, but there were indications that recolonization occurred and surface sediments were starting to be reworked by a combination of physical and biological factors. In 2020, Station R02 was still disturbed from being dredged but did improve in habitat quality, and by 2021 had recovered to pre-dredging conditions (Figure 3-27). OSI at R02 was 7.3 prior to dredging, dropped to -4.0 in 2018, climbed to 3.0 in 2019, 5.0 in 2020, was 7.0 in 2021. The area around Station T05A, also of the southwest end of Deer Island, was dredged sometime after August 2018, but by the August 2019 SPI sampling it showed no signs of having been dredged. It is likely that T05A being in a deep, high tidal current area (Signell and Butman 1992) either did not need to be dredged or the sandy sediment recovered quickly and benthic habitat quality was not affected in the long-term by dredging. Long-term average OSI at Station T05A was 6.1, likely related to constant physical stresses of being located in a high tidal current area. Station R09, location in the center of the inner harbor channel, was within the dredging boundaries and continues to show signs of recent physical disturbance in 2021. Its location makes it prone to disturbance, likely from deep-draft ship traffic. Station R09 tended to have low OSI and appeared disturbed most years. Similar light-gray colored clay sediments can be seen at R09 and at R02 (Figure 3-27).

The eelgrass (*Zoestra marina*) bed planted around Station R08 on Deer Island Flats as part of a restoration efforts by MA Division of Marine Fisheries on Deer Island Flats (Evans et al. 2018) continues to do well (Figure 3-28). Prior to 2008, Station R08 was a fine-sand habitat with macroalgae. The eelgrass bed now serves as a biologically complex habitat that at one time was more widespread within Boston Harbor (Leschen et al. 2010, Costello and Kenworthy 2011).

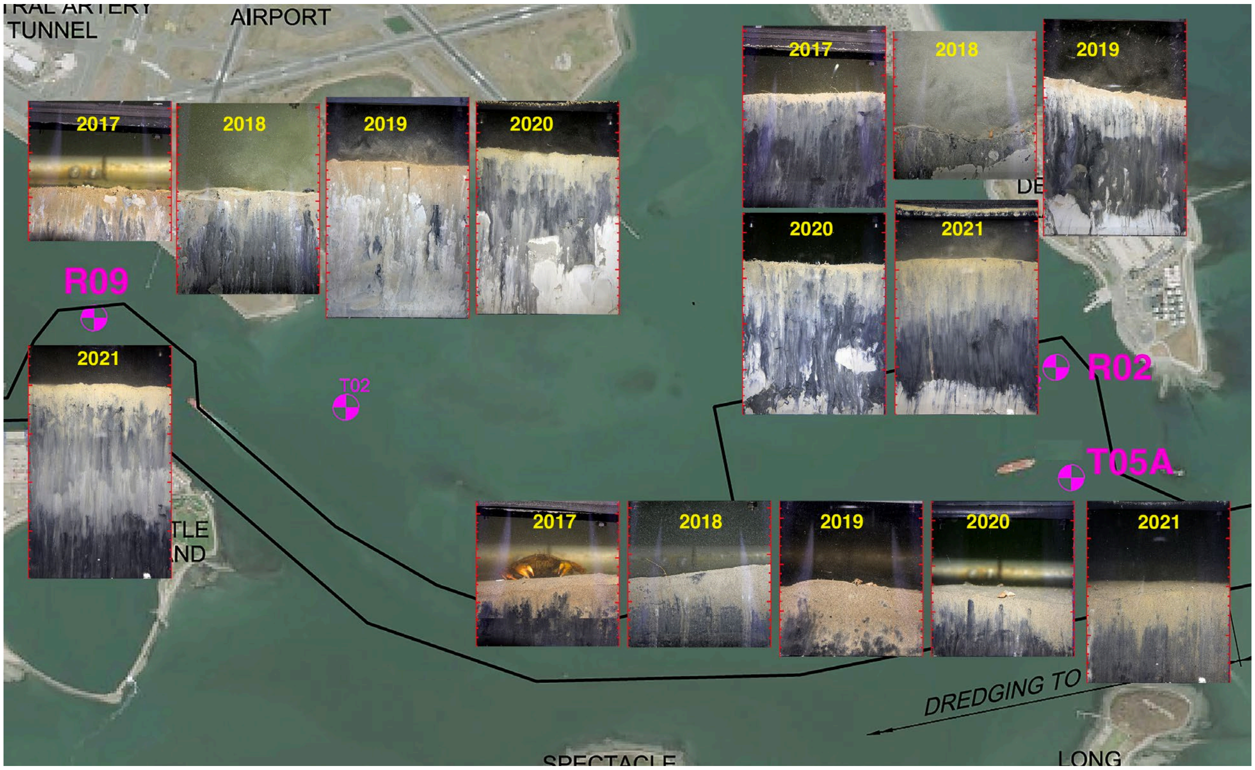

Figure 3-27. Changes at stations within the boundaries of recent President Roads dredging. Images are 15 cm wide.

Figure 3-28. Eelgrass bed at Station R08 on Deer Island Flats in 2021. Scale on side of images is in cm.

3.3.2 Long-Term Patterns

Over the 31-year Harbor SPI monitoring (1992 to 2022), data on benthic habitat quality and infaunal community structure were highly variable with a general improving trend through time (Figure 3-29). Most trends over this period reflected complex interactions of harbor-wide driving factors (summarized in Figure 3-30) with the three most important being: 1) Just prior to the start of monitoring, the October 1991 severe storm (known as the “perfect storm”, strongest storm for the region up to that year) coincided with the December 1991 cessation of sludge dumping within the Harbor. The following December, the strongest storm to hit the Boston region since 1984 also occurred; 2) subsequent treatment upgrades, and final diversion to the offshore outfall in September 2000 significantly reduced total organic carbon and nutrient inputs; and 3) regional increase in storminess that increased integrated wind stress on the bottom by about 15% per decade (Blake et al. 1998, Taylor 2010, Taylor et al. 2019, Codiga et al. 2019). The first factor played an important role in the early transition of Boston Harbor from the depauperate communities found in September 1991 to the rapidly changing fauna observed from 1992 on, which was due to the second factor (Gallagher and Keay 1998, Rutecki et al. 2020b). The influence of the third factor (changing climate) over the monitoring period was less clear because of interactions between habitat quality and community structure with past organic and nutrient loading. In addition, the Harbor’s complex geomorphology and currents lessened or amplified impacts due to storms.

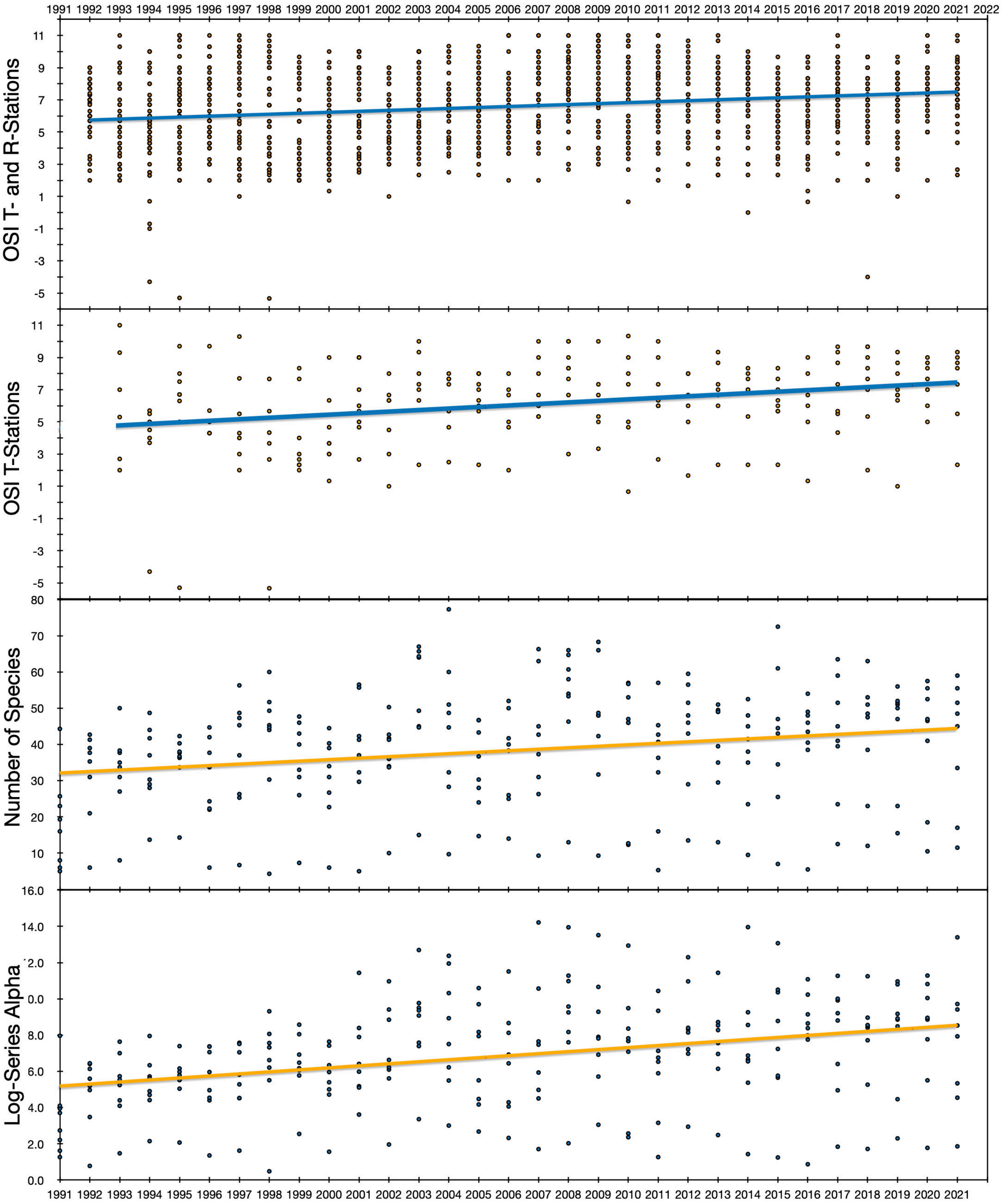

Figure 3-29. Long-term trends in benthic habitat quality as measured by OSI and community structure statistics.

3.3.3 Storms

Between 1984 and 2020 there was an increase in storminess over Massachusetts Bay and the Boston region. Both integrated wave stress (IWaveS) and integrated wind stress (IWindS) from storms increased by about 22% and 31% per decade, respectively (Codiga et al. 2019). Regional increases in winter-period IWindS storms were a result of increased storm frequency and storm duration (Codiga et al. 2019). These changes resulted in an increase in the percent of time storms were strong enough to affect the bottom at 20 m depth. To put the long-term changes in storminess into perspective, the October 1991 "perfect storm", at that time, was the most intense storm to hit Boston on record and the winter of 1991-1992 (1992 winter-period) was the stormiest year (Butman et al. 2008). Between 1984 to 2020 the "perfect storm" became the 4th highest ranked IWindS storm, and the 1992 winter-period ranked 19th of the 36-years (Codiga et al. 2019). The December 1992 storm remains the strongest storm for the region but overall, the 1992-1993 (1993 winter-period) ranked 23rd. The top ten storm years occurred between 2003 and 2020 (Figure 3-30).

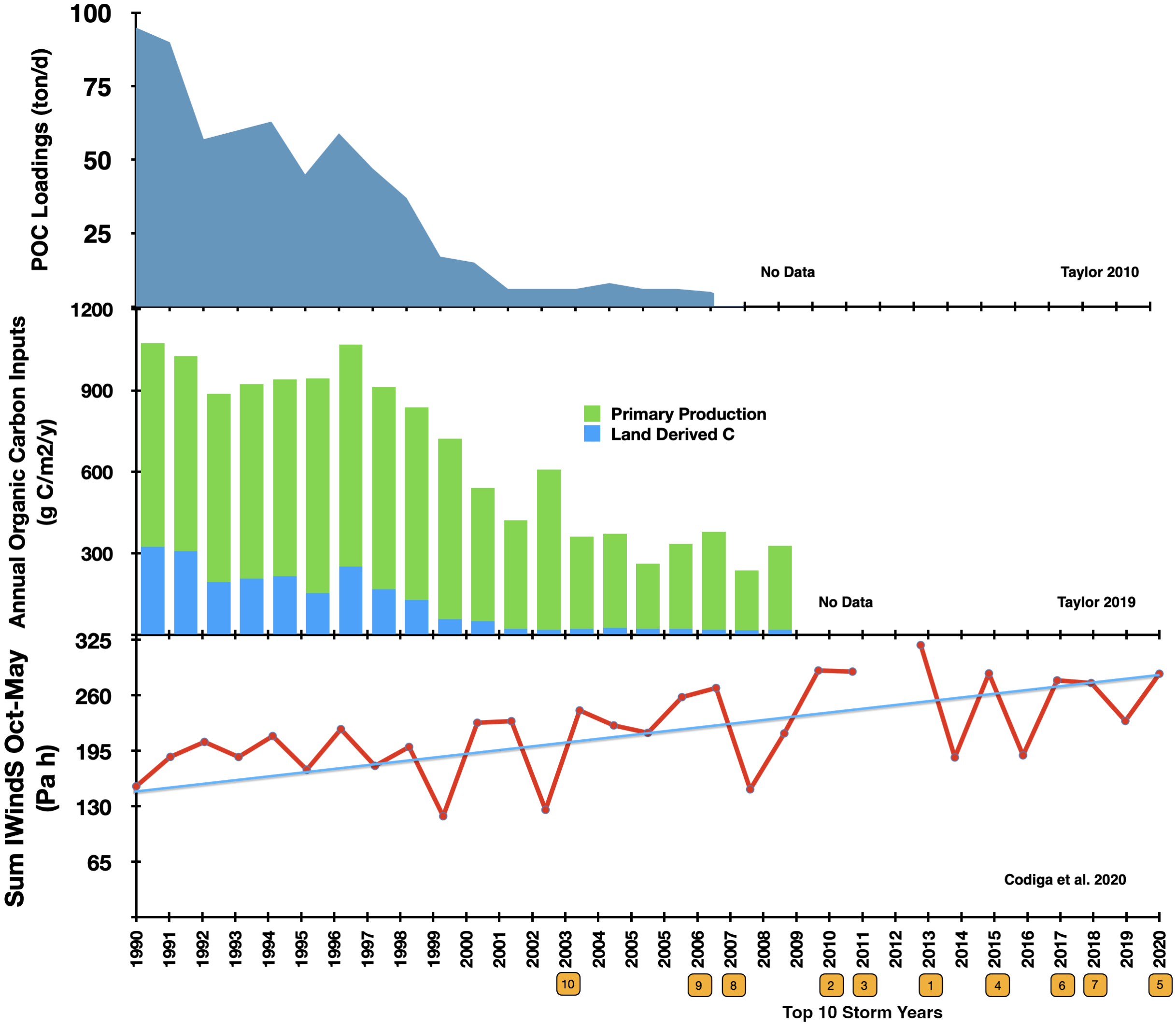

Figure 3-30. Long-term trends in annual POC loading, primary production, and annual winter-period (October to May) integrated wind strength (IWindS). Top ten stormy years are labeled.

3.3.4 Sediments

Bed Roughness. Through time there has been a shift in the relationships between processes structuring bed roughness. This was due mainly to declining particulate organic carbon (POC) loading that reduced populations of biogenic structure forming species (such as Ampelescid amphipods), and increasing winter-period storminess that increased the amount of wave energy reaching the bottom and suspending sediments (Rutecki et al. 2020b). Temporal and spatial variations in bed roughness was due to physical and/or biological processes (See Figure 3-31 for examples). Wind and tidal currents are the main physical factors that influence both sediment grain-size and bed roughness with bioturbation and biogenic structures being the main biological factors that influence bed roughness (Rhoads and Young 1970, Nowell et al. 1981, Trembanis et al. 2004).

During post sludge disposal and implementation of full primary treatment (Period II from 1992 to 1997) physical processes dominated as levels of organic and other toxic substances were likely too high for establishment of species that create biogenic structures. The influence of biological processes was strongest from 1998 to 2000 with implementation of full secondary treatment and declining organic production in the Harbor (Period III). The dominance of physical processes returned after offshore diversion (Period IV starting in 2001) and continued through to 2021. In 2021, only Stations R45 and T03, both in President Roads, had biologically dominated surface. Another 10 stations had a combination of biological and physical processes dominating bed roughness, and 49 were primarily dominated by physical processes.

For the whole Harbor the probability of bed roughness being dominated by physical processes through time was coincident with both declining organic loading (Taylor et al. 2019) and increased sum of winter-period IWindS storms (Rutecki et al. 2020b). Declining organic production, through its influence on biology, and increased winter-period storm strength, through its influence on physical bottom stress, had the strongest influences on bed roughness. Regionally, the western inner harbor (Inner Harbor, Dorchester Bay, Quincy Bay, and Hingam Bay) along with Deer Island Flats were less likely to have biologically dominated sediment surfaces. Outer harbor regions (President Roads, Nantasket Roads, and Hull Bay) were most likely to be biologically dominated and also maintained biological dominance longer (Figure 32).

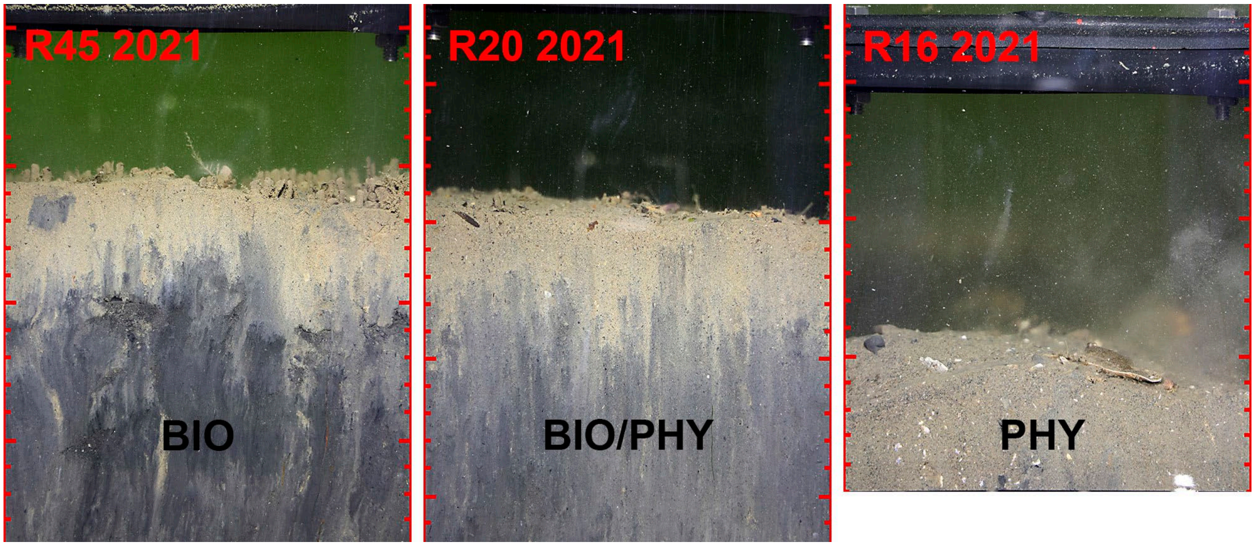

Figure 3-31 Examples of bed roughness being dominated by biological (BIO) and physical (PHY) processes. Scale on side of image is in cm.

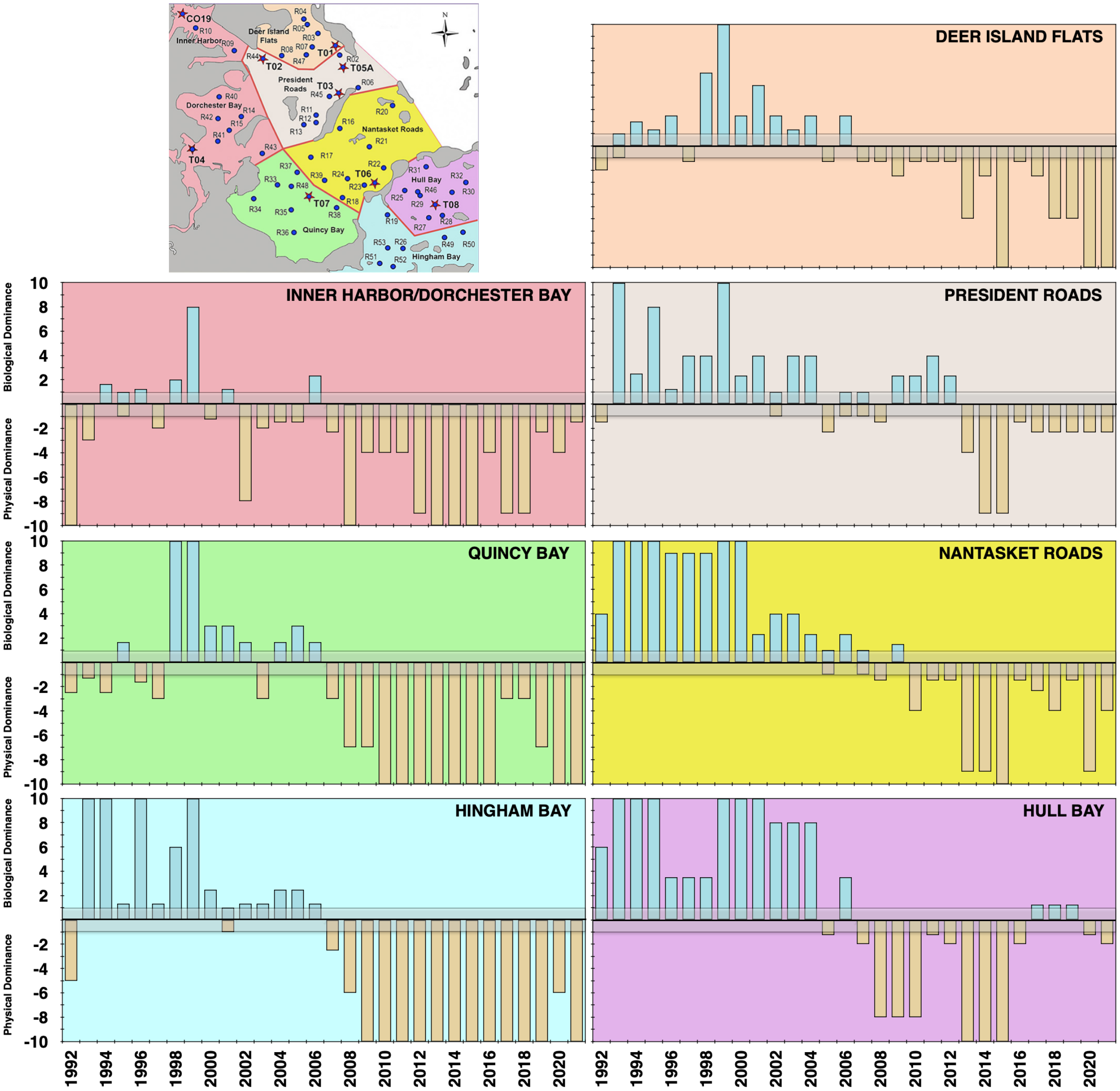

Figure 3-32 Odds of sediment surface being dominated by physical or biological processes by Harbor region. Gray area is even odds.

Grain-Size. At most Harbor stations estimated modal grain-size from SPI was consistent from year to year with a fraction of stations either coarsening or fining in modal grain-size from one year to the next (Figure 3-33). In 2021 three stations changed modal SPI grain-size class. All three were coarser in 2021 than in 2020, appearing to be sandier. Modal grain-size at Station R47 (Deer Island Flats) went from silt-clay to silty-fine-sand, Stations T01 (Deer Island Flats) and T06 (Nantasket Roads) went from fine-sandy-silt to fine-sand. Overall, coarsening of modal grain-size at T-Stations in 2021 was consistent with the long-term trend in median grain-size (from grab samples) where five of the eight stations (T01, T05A, T06, T07, and T08) significantly coarsened (Linear Regressions, n = 28, p = <0.001 for all 5 stations) by

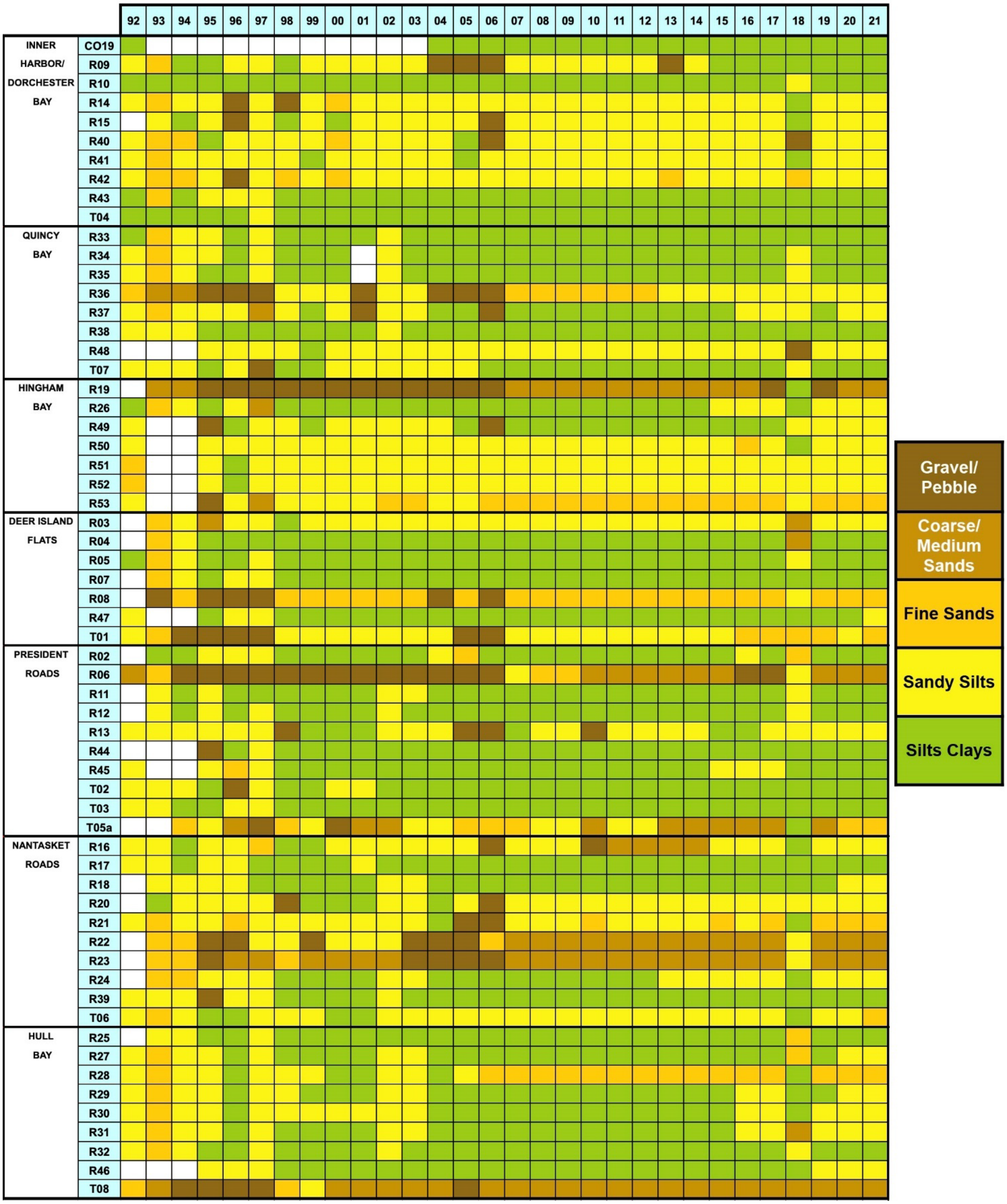

Figure 3-33. Matrix of modal grain-size estimated from SPI with stations arranged by Harbor region. Blank cells indicate station was not sampled.

about 0.4 to 0.8 Phi per decade (Figure 3-34). As a point of comparison, there is a 1.0 Phi difference between fine-sand and medium-sand. Stations T02, T03 and T04 were variable in median grain-size but no significant trend was present. The median sediment grain-size at the eight T-Stations for 2021 tended to be in the middle of the range for the monitoring period (1994 to 2021; Figure 3-35). At Station T05A both SPI and grab data indicated sediment in 2021 was on the finer end of the range, a trend that started in 2018.

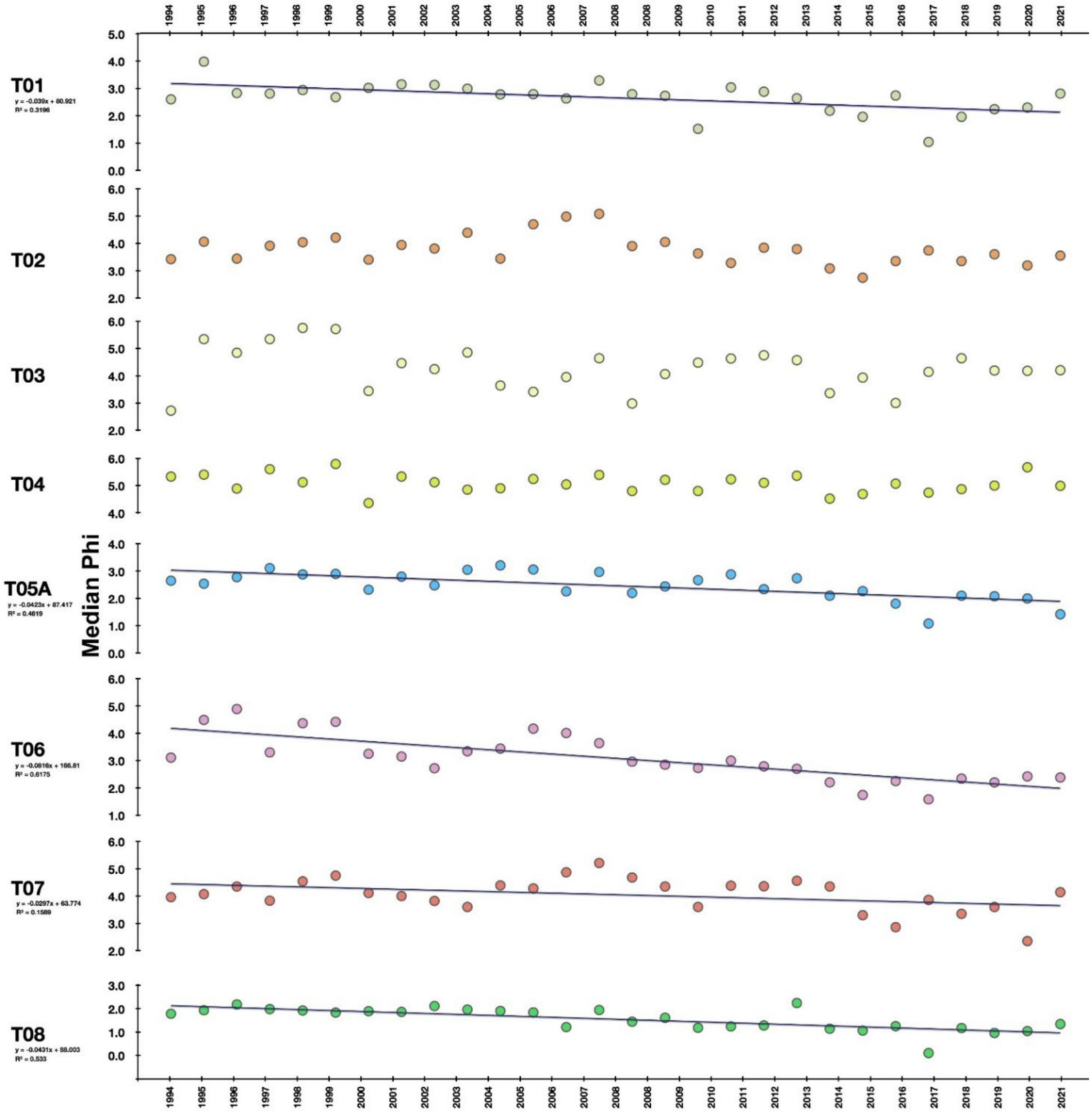

Figure 3-34. Long-term trend in median grain-size (from grab sediment analysis). Regression line indicates significant coarsening of sediment through time. Phi range for sediment classes: 4-8 for silt, 3-4 for very-fine-sand, 2-3 for fine-sand, 1-2 for medium-sand, 0-1 for coarse-sand.

Figure 3-35. Range of SPI modal grain-size and grab sediment modal and median grain-size from 1994 to 2021 at T-Stations.

3.3.5 *Ampelisca* spp. Trends

Long-term occurrence of *Ampelisca* spp. tubes was related to both POC loading (Diaz et al. 2008) and intensity of winter period storms (Rutecki et al. 2020b). As POC loading declined from 1991 to 2001, tube mats also declined, with a lag of about four years, from about 60% of stations, to 0% in 2005 (Figure 3-36). The periods of high, but declining, POC loading (Periods I, II, and III of Taylor 2010) were coincident with six of the ten lowest sum of winter period IWindS storm years (Figure 3-30). Between 2006 and 2021 with essentially low but constant annual organic loading and production, mats peaked again, twice occurring at about 30% of stations. Nine of the top ten IWindS winter period storm years occurred between 2006 to 2020 (Figure 3-30), and all ten stormiest years occurred after the September 2000 diversion (Period IV of Taylor 2010).

Ampelisca spp. occurred at all eight T-stations in 2021 and increased by a factor of about two over the previous three years, with *Ampelisca vadorum* being more abundant (Figure 3-37). Prior to 2013, *Ampelisca abdita* was the more abundant species. In SPI, only three T-stations had *Ampelisca* spp. tubes in 2021 (T03, T05A, and T06). While mat densities of *Ampelisca* spp. tubes occurred at four stations across the Harbor, overall, the number of stations with tubes declined to about a third (18 of 61 stations) in 2021. *Ampelisca* spp. mats occurred at outer harbor stations: R23 and T06 in Nantasket Roads, and R45 and T03 in President Roads. The other two-thirds of stations did not have *Ampelisca* spp. tubes (Figure 3-36). Deer Island Flats had no *Ampelisca* spp. tubes again in 2021. Inner Harbor/Dorchester Bay and Quincy Bay were the other two regions to have years with no *Ampelisca* spp. tubes. Western Harbor regions lost most tube mats early as organic loading declined. Eastern Harbor regions held on to tube mats till mid 2000s and oscillated in numbers up to 2021 (Figure 3-38). Worm tube mats were present at 10% (6 of 61) of stations in 2020, but in 2021 only Station C019 in the Inner Harbor had a tube mat.

From 2005 on, the combination of lower food availability (internal and external organic sources) and increasing storminess were the likely factors leading to lower mat numbers and higher variability of mats from year to year. Diaz et al. (2008) estimated that the optimal annual organic load for maintaining large areas of amphipod tube mats was around 500 g C m-2 yr-1. Above and below this level the area of tube mats in Boston Harbor declined. From 1990 to 2000, total organic load in the Harbor declined from over 1000 g C m-2 yr-1 to about 500 g C m-2 yr-1, and between 2003 to 2009 it averaged about 300 g C m-2 yr-1 (Taylor et al. 2019). While not a measure of primary production, annual averaged phytoplankton abundance measured at the mouth of the Harbor (Station F23 south of Deer Island, Libby et al. 2021) was well below the long-term average. For the monitoring region phytoplankton abundance has been on a downward trend from 2008 to 2015. From 2015 to 2021 abundance has been stable with 2021 being 27th lowest out of 30 years (Libby et al. 2022, D. Borkman personal communication). It is also likely that fewer stations with *Ampelisca* spp. tube mats from 2018 to 2021 could be related to increasing storminess across the region, which would tend to disrupt tube mats.

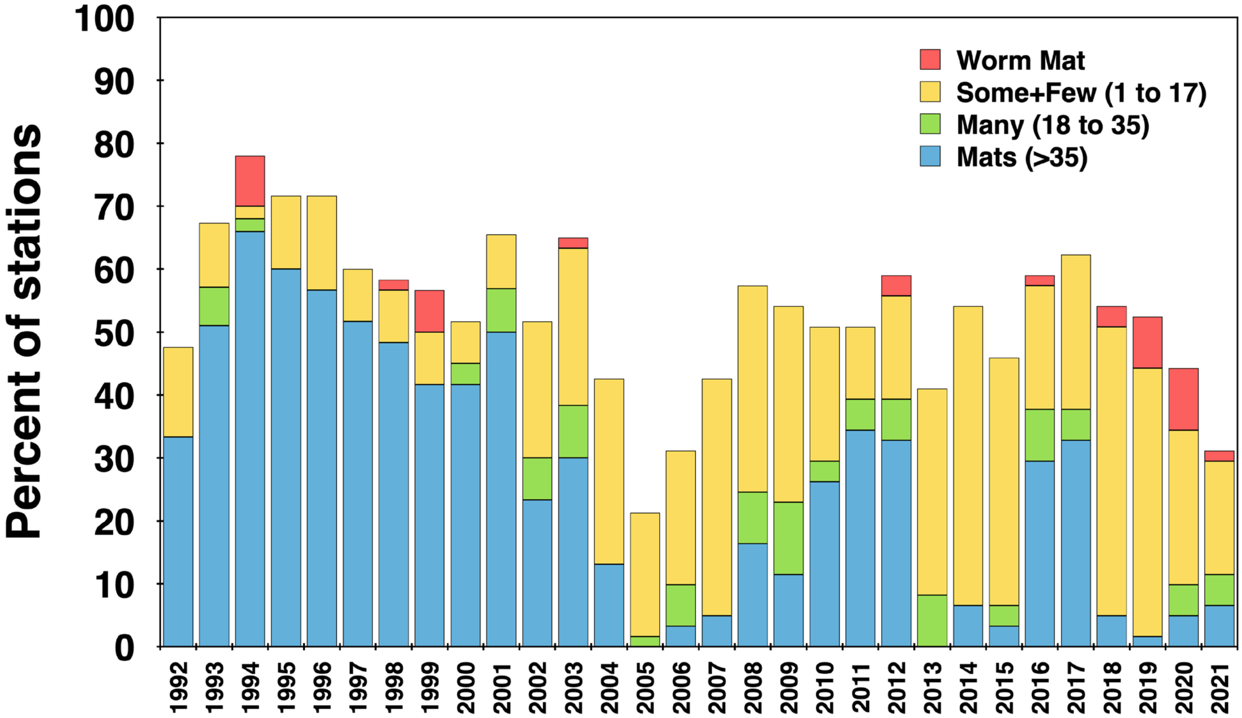

Figure 3-36. Histogram of *Ampelisca* spp. tubes and tube mats, and worm tube mats for all 61 Harbor stations.

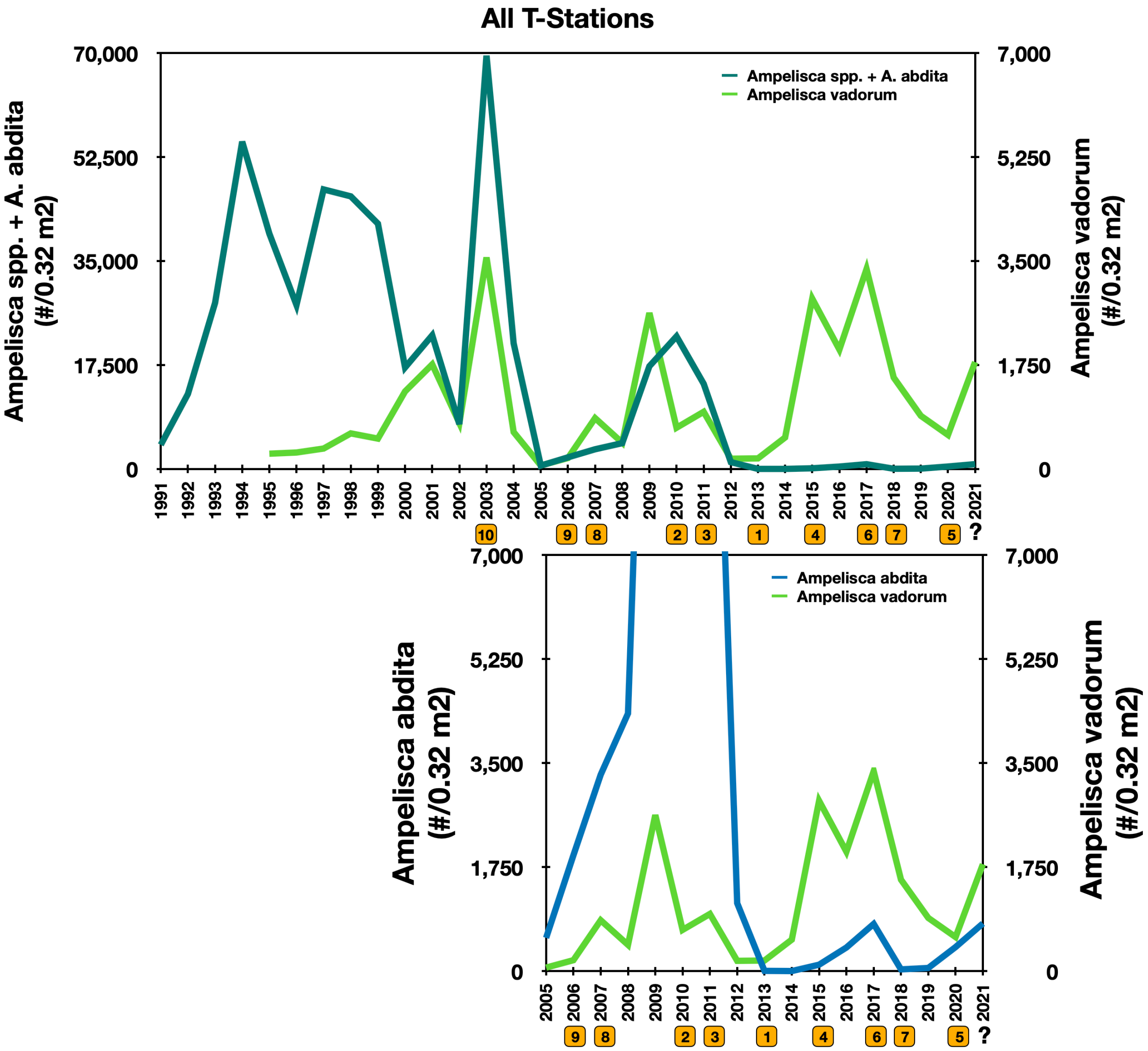

Figure 3-37. Long-term trends in the occurrence of *Ampelisca abdita* and *Ampelisca vadorum* at T-Stations. Top ten stormy years are labeled.

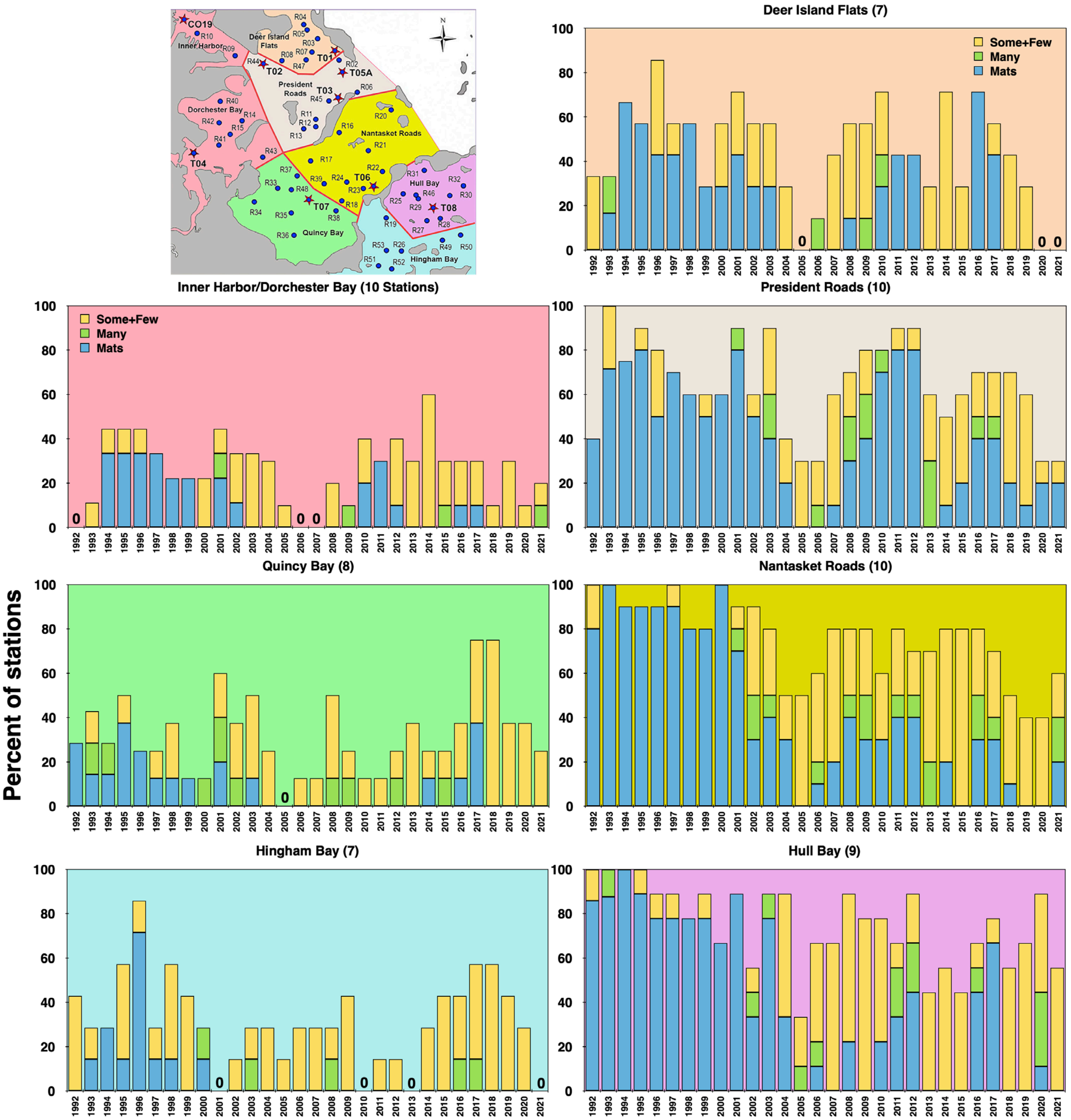

Figure 3-38. Histogram of *Ampelisca* spp. tubes and tube mats by Harbor regions.

SPI Summary

Overall, benthic habitats continue to maintain good ecological conditions as assessed by the Organism Sediment Index (OSI). OSI trended up in all Harbor regions except Hingham Bay (Figure 3-25). The inner to outer harbor habitat quality gradient remains prominent primarily due to hydrodynamics and secondarily to sediment grain-size. The continued tendency for OSI to trend upward in recent years, particularly in western harbor regions is likely related to long-term oxidation of legacy sediment organic matter (Tucker et al. 2014), declines in organic inputs (Taylor 2010), and lowered primary production (Taylor et al. 2019). Stations R03 and R09 appear to have recovered from the 2018 dredging disturbance. Strength of winter period storms in 2021 was likely above average based on dominance of physical processes structuring surface sediments and limited distribution of *Ampelisca* spp. tube mats.

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 (see Tucker et al. 2014 and Taylor et al. 2019 for details on sediment recovery). Physical and biological properties of the soft substrate in Boston Harbor in 2021 exhibited minor changes from recent years but were consistent with longer-term trends (Rutecki et al. 2021). 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 have 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 2021 survey are consistent with the recovery of benthic habitats from decades of inadequately treated sewage discharges.

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