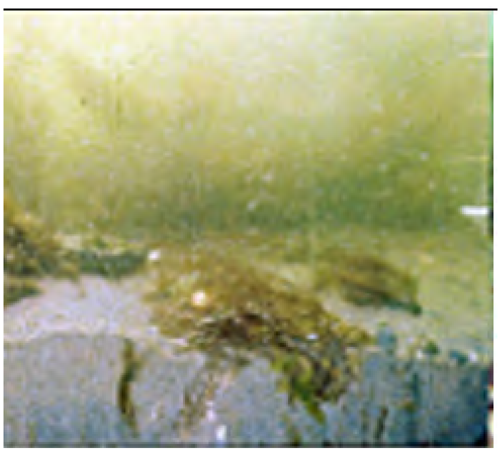
2020 Boston Harbor Benthic Monitoring Report



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2020 Boston Harbor Benthic Monitoring Report

Submitted to

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EXECUTIVE SUMMARY

The Massachusetts Water Resources Authority (MWRA) has conducted ongoing benthic monitoring in Boston Harbor since 1991 to evaluate changes to the ecosystem, particularly the benthic community, resulting from reductions in wastewater discharges over time. This report provides a summary of the results of the benthic surveys that were conducted in 2020.

Benthic monitoring in Boston Harbor during 2020 included soft-bottom sampling for sediments and infauna at 9 stations and sediment profile imaging (SPI) at 61 stations.

Sediment conditions were characterized based on analyses of sediment grain size composition, total organic carbon (TOC), and spore counts of the anaerobic bacterium *Clostridium perfringens*. 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 2020 were observed in Savin Hill Cove and the Inner Harbor. *C. perfringens* concentrations during 2020 were generally low. The physical properties of the soft substrate in Boston Harbor in 2020 exhibited normal year-to-year variability but were consistent with longer-term trends (Rutecki et al. 2020a). Concentrations of both TOC and *C. perfringens* have remained low compared to the levels in the early 1990s.

Benthic infauna mean total abundance and species richness in 2020 were consistent with values seen in previous post-offshore diversion years. These and other community structure measures continue to point to improving benthic conditions in 2020. 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 have other measures of biodiversity. 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 in abundance relate more to normal physical disturbances than organic stress in the years since wastewater impacts to the harbor have been reduced. Sediment profile imaging showed overall habitat conditions for 2020 trended higher relative to 2019, as measured by the Organism Sediment Index. The trends observed in previous years, including reduction of indicators of organic enrichment and increases in species diversity continued in the 2020 survey and are consistent with the recovery of benthic habitats from decades of inadequately treated sewage discharges.

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 ecological conditions. Through litigation, the EPA 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, an upgrade to secondary treatment, and relocation of wastewater discharge through an offshore diffuser located 9.5 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).

Overall, the upgrades in wastewater treatment and moving the outfall offshore have led to improvements in water 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 be able 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 2020 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 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 Rutecki et al. (2020a) for previous monitoring years. Detailed descriptions of the methods are contained in the Quality Assurance Project Plan (QAPP) for Benthic Monitoring (Rutecki et al. 2020b). 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 2020 (Figure 2-1). Soft-bottom stations were sampled for grain size composition; total organic carbon (TOC); the sewage tracer

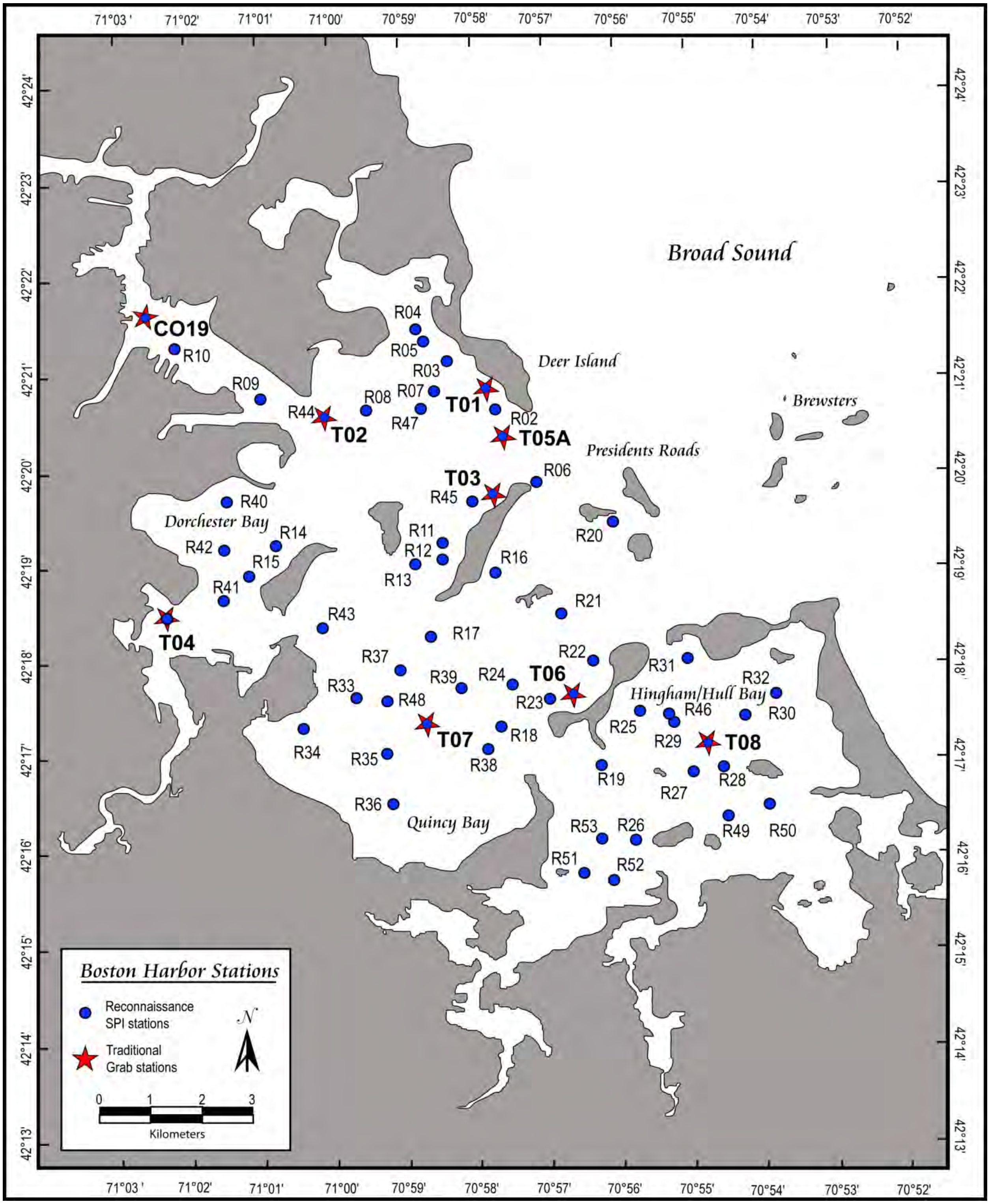

Figure 2-1. Locations of soft-bottom sampling and sediment profile imaging stations for 2020.

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 4, 2020.

SPI samples were collected in triplicate at 61 stations from August 2-3, 2020 (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. 2020). 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).

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. 2020b) 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 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). 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. Alpha probabilities (p-values) of multiple correlation analysis were corrected with Holm-Bonferroni method to control the family-wise error rate (Holm 1979). 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 2020 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 2020 included a wide range of sediment types (Table 3-1, Figure 3-1). Grain size profiles ranged from predominantly sand (e.g., T08) to almost entirely silt and clay (i.e., 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 than sand from 2017 through 2020. This could be an effect of the Boston Harbor maintenance dredging that occurred in the nearby President Roads Anchorage in 2018. The grain size composition at each station in 2020 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 fairly large drops in percent fines (Figure 3-2).

Total Organic Carbon. Concentrations of total organic carbon (TOC) in 2020 were generally similar to or lower than values reported in 2019 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 (silt + clay; Figures 3-2 and 3-3). During 2020, Stations T03, T04, and C019 had among the highest concentrations of TOC and also 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 2020 are consistent with this trend. The lowest TOC concentrations for 2020 were reported at Stations T08, T01, 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 2020 (Table 3-1) were generally low and comparable across all monitoring stations, especially when compared to historic data (Figure 3-4). Though concentrations at Stations T01 and T08 were higher than in the last three years. 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 2020 (Figure 3-4). Normalized *C. perfringens* counts at Station T08 have consistently been low since 2010 with an exception in 2016 that was largely an artifact of the atypically low percent fines at T08 that year. Except at Inner Harbor station C019, *C. perfringens* counts at other 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 (Figure 3-4). This 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.

Table 3-1. Monitoring results for sediment condition parameters in 2020.

Parameter		C019	T01	T02	T03	T04	T05A	T06	T07	T08
Grain Size	Gravel (%)	0	7.8	0	0	0	0	0.2	5.1	0.8
	Sand (%)	4.6	74.2	61.0	39.8	4.4	70.4	76.6	59.0	94.9
	Silt (%)	55.4	12.4	25.2	37.7	52.8	20.6	14.5	22.6	2.4
	Clay (%)	40.0	5.7	13.8	22.5	42.8	9.0	8.7	13.3	1.9
	Percent Fines (Silt + Clay)	95.4	18.0	39.0	60.2	95.6	29.7	23.2	35.9	4.4
Total Organic Carbon	TOC (%)	2.1	0.4	0.9	1.8	3.0	0.6	0.9	2.1	0.2
Clostridium perfringens	Not Normalized	2540	1160	762	1070	4350	356	2090	2470	544
	Normalized (cfu/g dry/%fines)	26.6	64.3	19.5	17.8	45.5	12.0	90.1	68.8	124.8

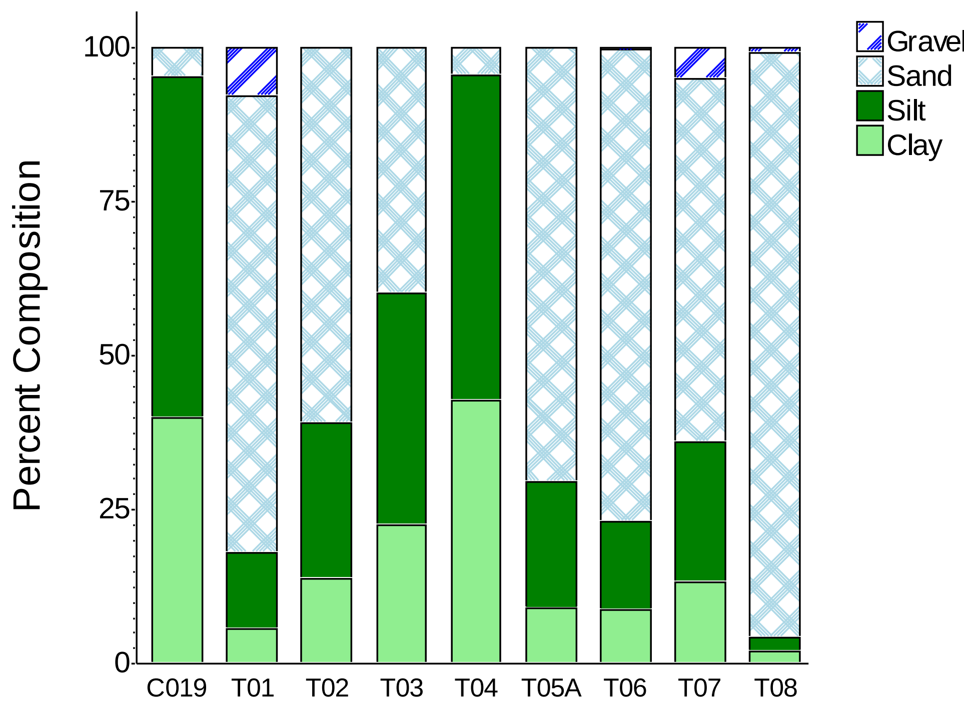

Figure 3-1. Monitoring results for 2020 sediment grain size in Boston Harbor.

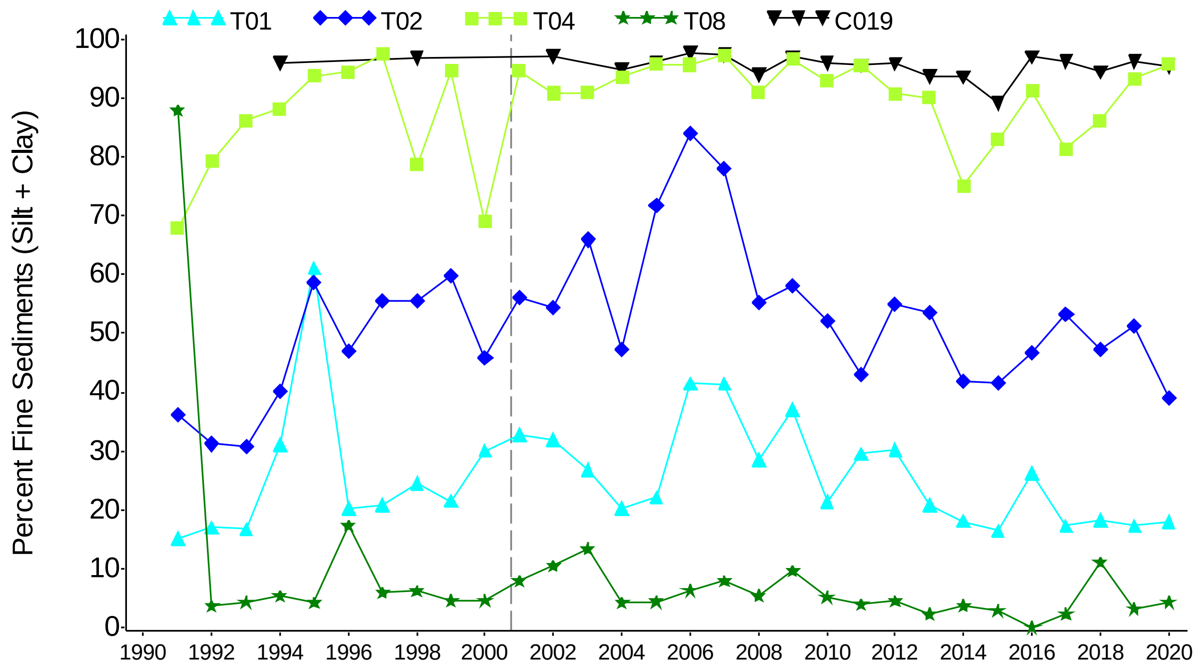

Figure 3-2. Mean percent fine sediments at five stations in Boston Harbor, 1991 to 2020. Five stations selected to illustrate the trends in percent fine sediments at stations in the outer harbor (T08), mid harbor (T01 and T02), and inner harbor (T04 and C019).

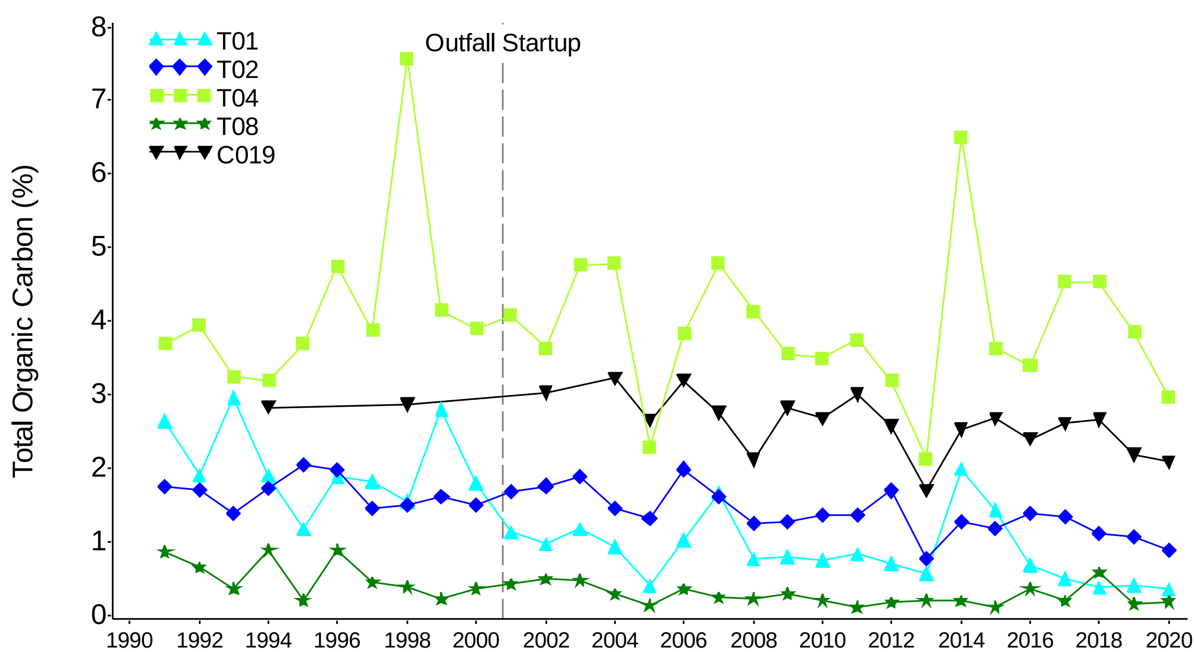

Figure 3-3. Mean concentrations of TOC at five stations in Boston Harbor, 1991 to 2020. Five stations selected to illustrate the trends in TOC at stations in the outer harbor (T08), mid harbor (T01 and T02), and inner harbor (T04 and C019).

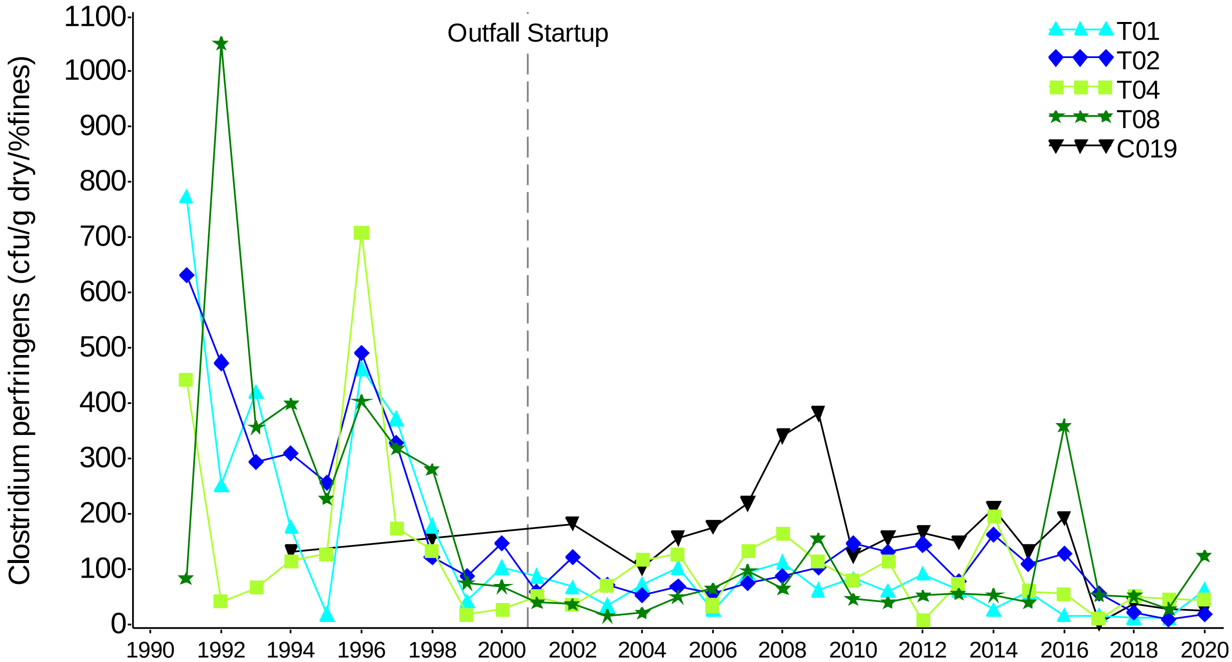

Figure 3-4. Mean normalized concentrations of *Clostridium perfringens* at five stations in Boston Harbor, 1991 to 2020. Five stations selected to illustrate the trends in *Clostridium perfringens* at stations in the outer harbor (T08), mid harbor (T01 and T02), and inner harbor (T04 and C019).

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 2020 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. 2020a). 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).

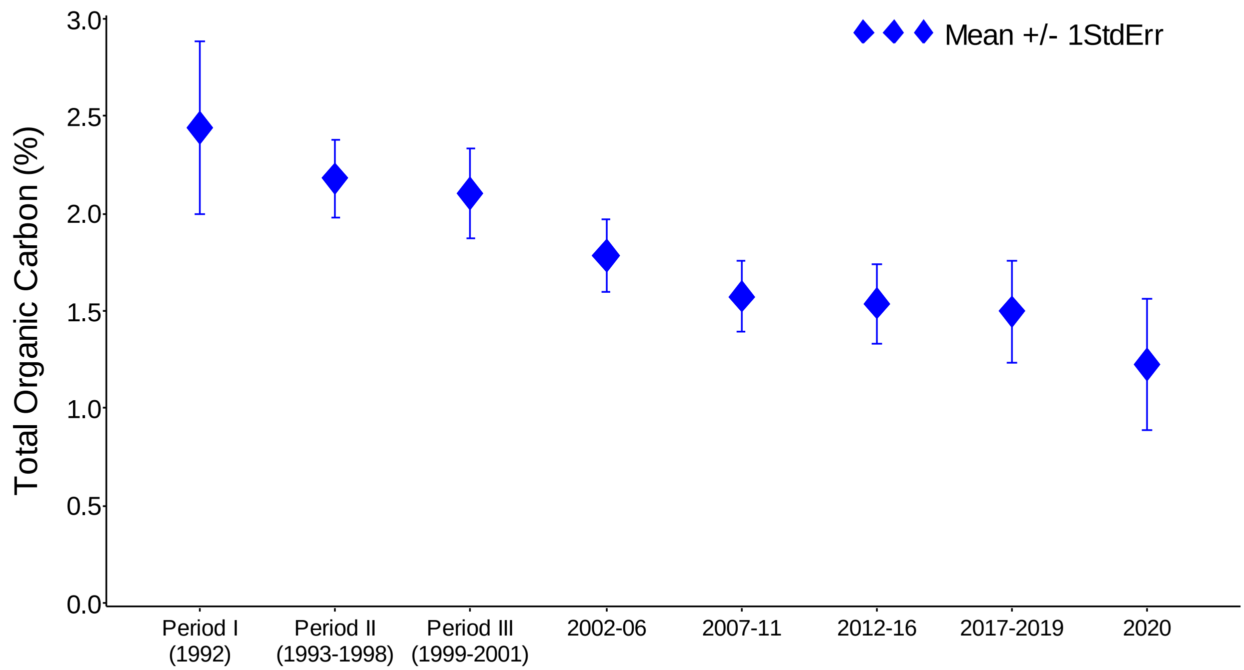

Figure 3-5. Comparison of TOC across time periods (offset by one year) at Boston Harbor stations (T01-T08) from 1992 to 2020 (1991 excluded).

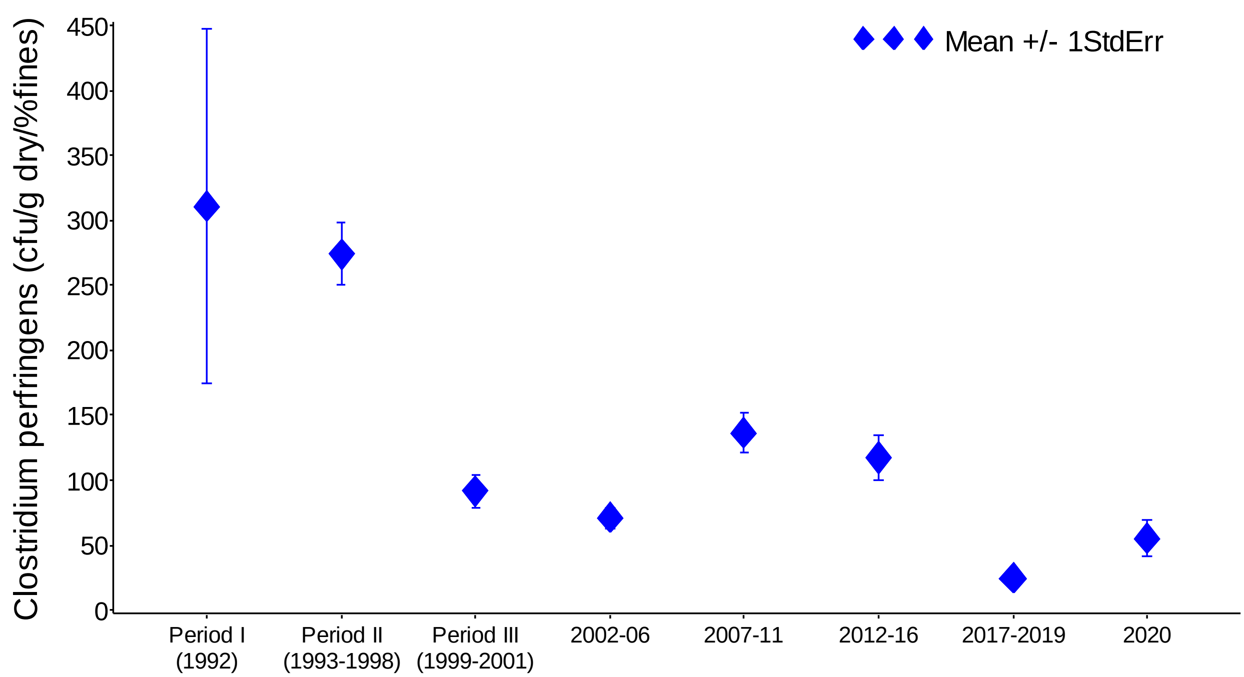

Figure 3-6. Comparison of *Clostridium perfringens* across time periods (offset by one year) at Boston Harbor stations (T01-T08) from 1992 to 2020 (1991 excluded).

3.2 BENTHIC INFAUNA

3.2.1 Community Parameters

A total of 26,265 infaunal organisms were counted from the 18 samples processed in 2020. Organisms were classified into 146 discrete taxa, 136 of which were species-level identifications. Ninety-eight 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 2020 infaunal community parameters by station.

Station	Total Abundance	Number of Species	Pielou's Evenness (J')	Shannon-Wiener Diversity (H')	Log-series alpha
C019	620.5	17.0	0.47	1.91	3.25
T01	1,863.5	57.5	0.61	3.58	11.29
T02	2,217.5	46.5	0.65	3.59	8.86
T03	1,547.5	41.0	0.54	2.87	7.77
T04	670.0	10.5	0.39	1.31	1.77
T05A	1,821.0	55.5	0.68	3.93	10.82
T06	3,153.0	52.5	0.55	3.11	8.95
T07	159.0	18.5	0.68	2.84	5.50
T08	1,080.5	47.0	0.58	3.20	10.05

Mean total abundance at the eight traditional Harbor stations reported for 2020 were lower than values in 2019 but comparable to values reported since 2011. Decreases in mean abundance occurred at all traditional stations except Station T02, and ranged from less than 1% at Station T05A to 79% at Station T07. Total mean abundance at Station T02 increased by 23% compared to the 2019 value (Rutecki et al. 2020a). Abundances in 2020 were within the range observed during the post-offshore diversion period but relatively low compared to pre-diversion values (Figure 3-7). The eight most abundant species in 2020 each contributed 4.0% or more of the animals counted, and together they provided 64% 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 2020 (Table 3-3) although the rank order changed. Six species of polychaetes were among the most abundant taxa in 2020. The five most abundant taxa in 2020 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). As in the early 2010s, Station T02 supported among the highest abundances among the harbor stations, although Station T06 had the highest abundance in 2020.

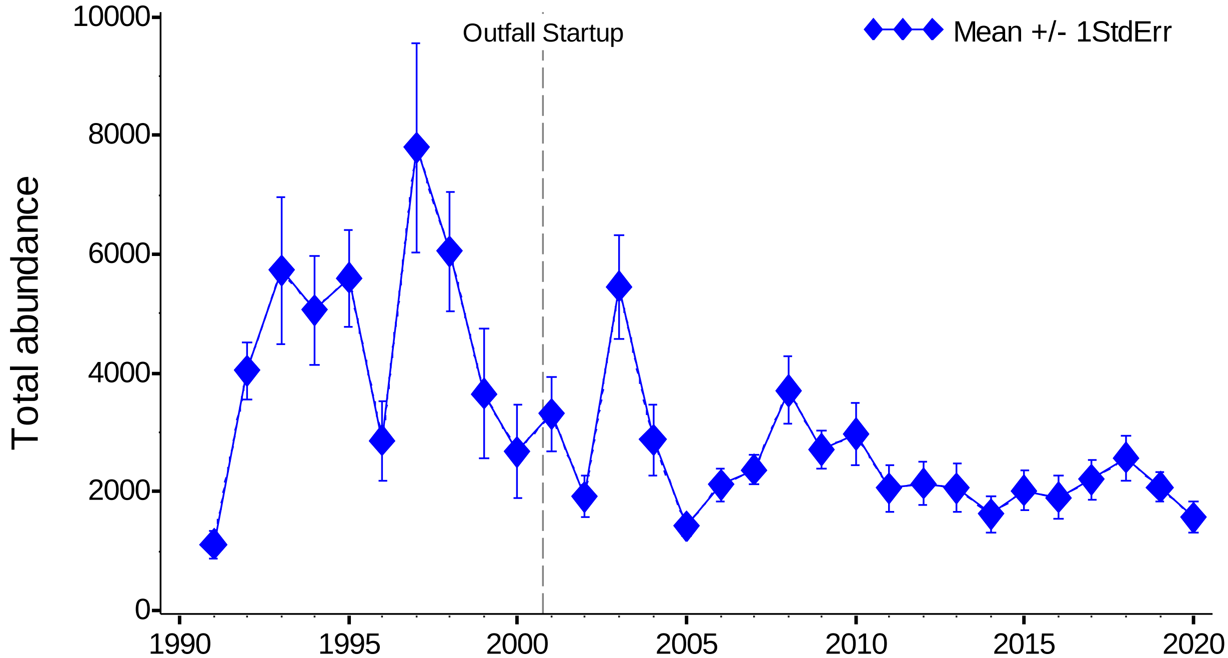

Figure 3-7. Mean abundance of benthic infauna at eight Boston Harbor stations (T01-T08), 1991-2020.

Table 3-3. Dominant taxa at eight grab stations (T01-T08) in Boston Harbor in August 2020.

Taxon	Total 2020 Abundance (compared with 2019)[a]
Aricidea catherinae	4,852 (similar)
Tubificoides intermedius	2,421 (similar)
Limnodriloides medioporus	2,117 (decrease)
Polydora cornuta	2,030 (decrease)
Tharyx acutus	1,481 (decrease)
Scoletoma hebes	1,066 (decrease)
Spiophanes bombyx	1,060 (increase)
Ampelisca spp.	976 (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. 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).

Table 3-4. Mean abundance per sample of dominant taxa during four discharge periods at eight Boston Harbor stations (T01-T08), 1992-2020.

Phylum	Higher taxon	Family	Species[a]	Period I	Period II	Period III	Period IV	2020
Mollusca	Bivalvia	Tellinidae	*Ameritella agilis*	9.8	9.5	18.0	14.4	43.9
Annelida	Polychaeta	Capitellidae	*Capitella capitata* complex	65.2	88.8	3.4	6.1	5.1
		Cirratulidae	*Tharyx acutus*	50.6	111.8	52.4	58.5	92.6
		Lumbrineridae	*Scoletoma hebes*	3.4	10.5	4.2	77.5	66.6
		Maldanidae	*Clymenella torquata*	34.7	17.6	10.6	25.6	59.6
		Nephtyidae	*Micronephthys neotena*[b]	-	11.4	10.3	165.7	55.5
		Paraonidae	*Aricidea catherinae*	325.0	237.4	204.3	250.0	303.3
		Spionidae	*Polydora cornuta*	525.8	1053.0	269.6	265.3	126.9
			Spiophanes bombyx	16.2	41.4	65.9	39.4	66.3
			Streblospio benedicti	236.0	298.6	27.7	91.5	55.8
	Oligochaeta	Tubificidae	*Limnodriloides medioporus*	484.7	297.9	315.2	231.0	132.3
			Tubificoides intermedius	42.6	101.4	231.2	235.7	151.3
Arthropoda	Amphipoda	Ampeliscidae	*Ampelisca* spp.	354.3	1698.3	1205.9	489.4	61.0
		Corophiidae	*Corophiidae* spp.	16.1	336.2	23.0	1.5	1.8
			Crassicorophium bonellii	7.9	217.3	37.3	6.6	1.0
			Leptocheirus pinguis	29.0	117.4	66.0	69.7	27.6
		Photidae	*Photis pollex*	11.4	77.0	86.8	26.9	3.4
		Phoxocephalidae	*Phoxocephalus holbolli*	28.0	116.9	125.9	5.8	0.8

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

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

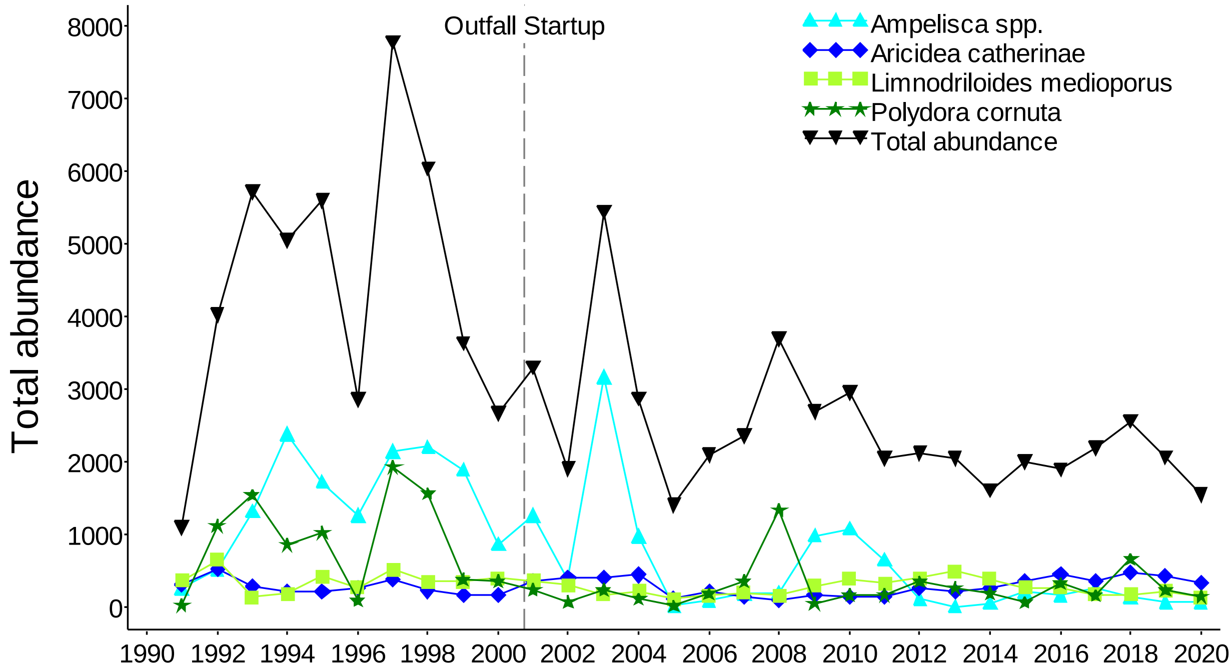

Figure 3-8. Total abundance of four dominant taxa at eight Boston Harbor stations (T01-T08), 1991-2020.

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 2020 was similar to 2019 (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 in 2019 and 2020, but declined at Station T03. In 2020, Station T06 supported the largest population of this species for the first time since 2012.

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 2020, *A. abdita* accounted for approximately 40% 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 2020 (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. (2020a).

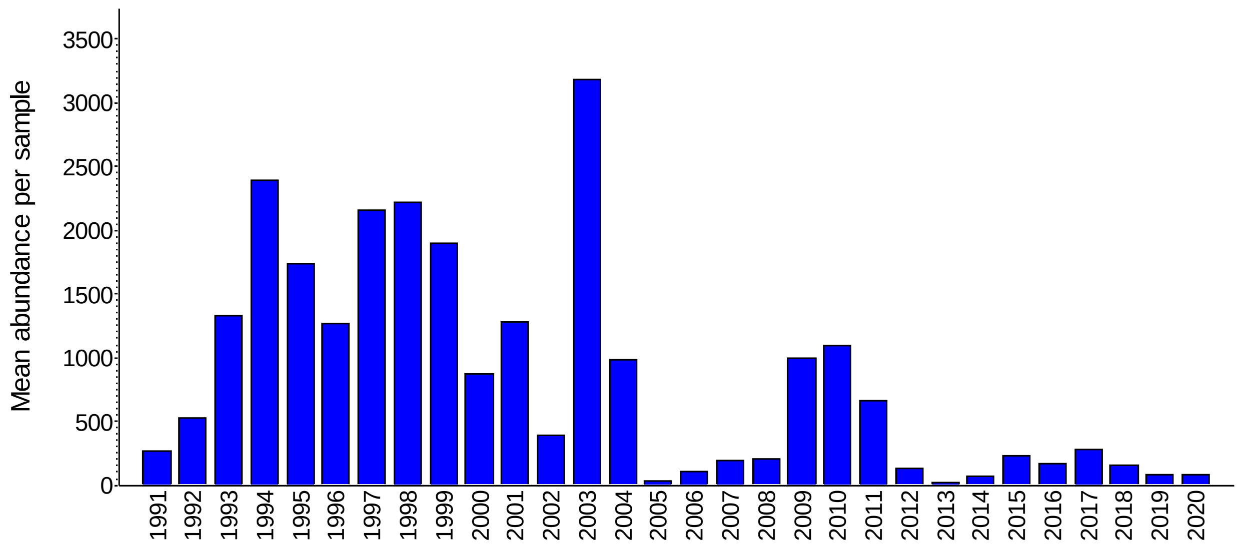

Figure 3-9. Mean annual abundance of *Ampelisca* spp. averaged over eight Boston Harbor stations (T01-T08), 1991-2020.

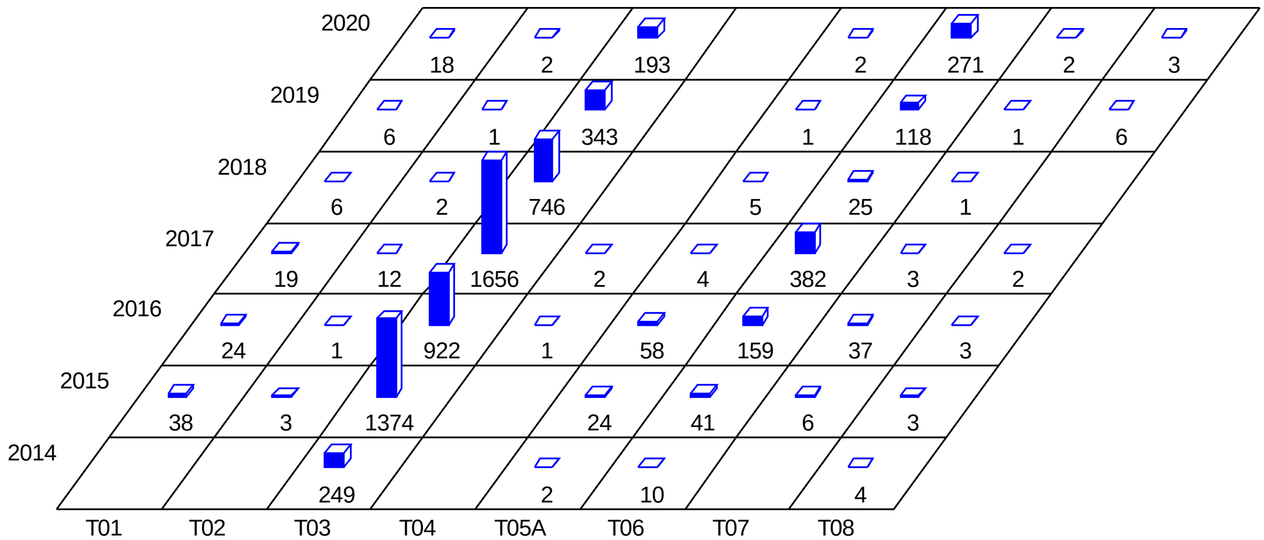

Figure 3-10. Spatial distribution of *Ampelisca* spp. at eight Boston Harbor stations (T01-T08), 2014-2020.

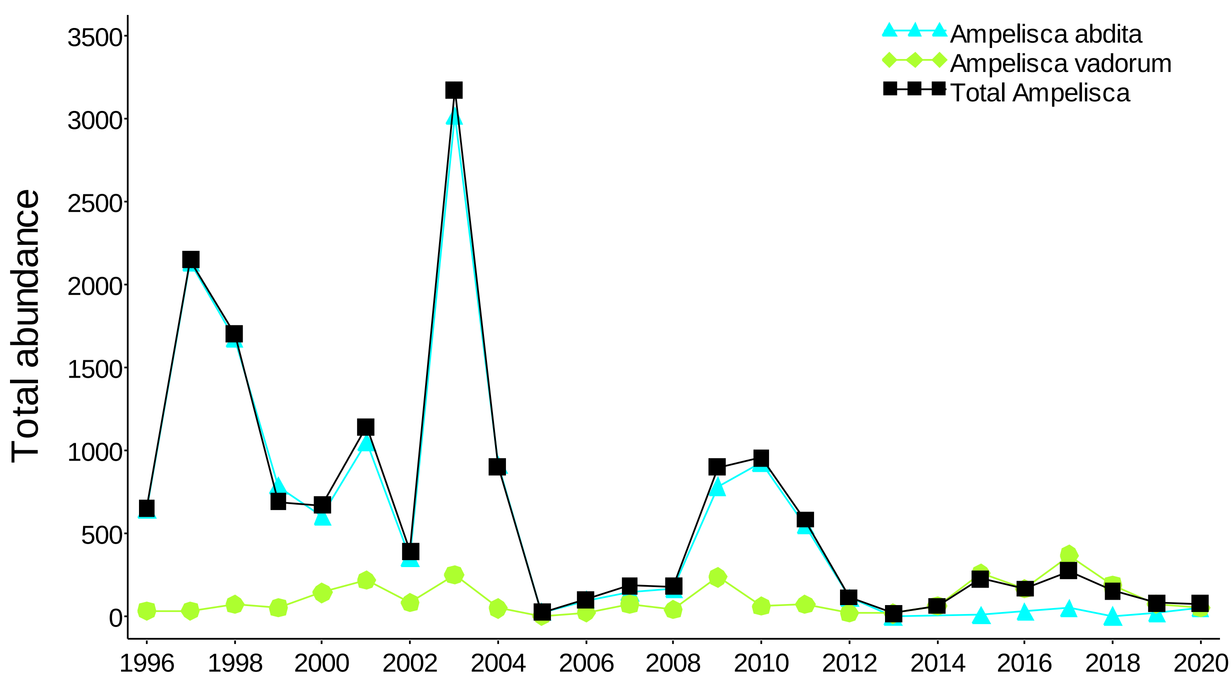

Figure 3-11. Mean total abundance of the two dominant *Ampelisca* taxa at eight Boston Harbor stations (T01-T08), 1995-2020.

The numbers of species reported for 2020 ranged from 10.5 to 57.5 per station and averaged 41 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 2020 than in 2019 (Figure 3-12). Stations T02, T03, and T08 were among the most species-rich stations from 2011 through 2019 (Rutecki et al. 2020a); in 2020 species richness at each these three stations was at or above the average for the Harbor. Station T04 has consistently supported the lowest species richness in this time frame. Stations T01, T05A, T06 and T08 also exhibited species richness above the average for the Harbor in 2020.

When averaged across the eight outer harbor stations Pielou's evenness and Shannon-Weiner diversity, two measures of community structure, declined in recent years. Average Pielou's evenness declined from 0.60 in 2015 to 0.52 in 2019, but increased in 2020 to 0.58. Average Shannon-Weiner diversity declined from 3.11 in 2015 to 2.81 in 2019; diversity increased in 2020 to 3.05 (Figures 3-13 and 3-14, Table 3-2). Within each station, differences in these metrics between 2019 and 2020 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, was similar in 2020 (8.1) compared to 2019 (8.0, Rutecki et al. 2020a), and was well above pre-diversion values (1991-2000; Figure 3-15). The highest log-series alpha diversity in 2020 occurred at Station T01, which is typical as Stations T01 or T08 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 2020 (Table 3-2; Pembroke et al. 2017, Rutecki et al. 2020a). The largest change in log-series alpha compared to 2019 was the increase at T07.

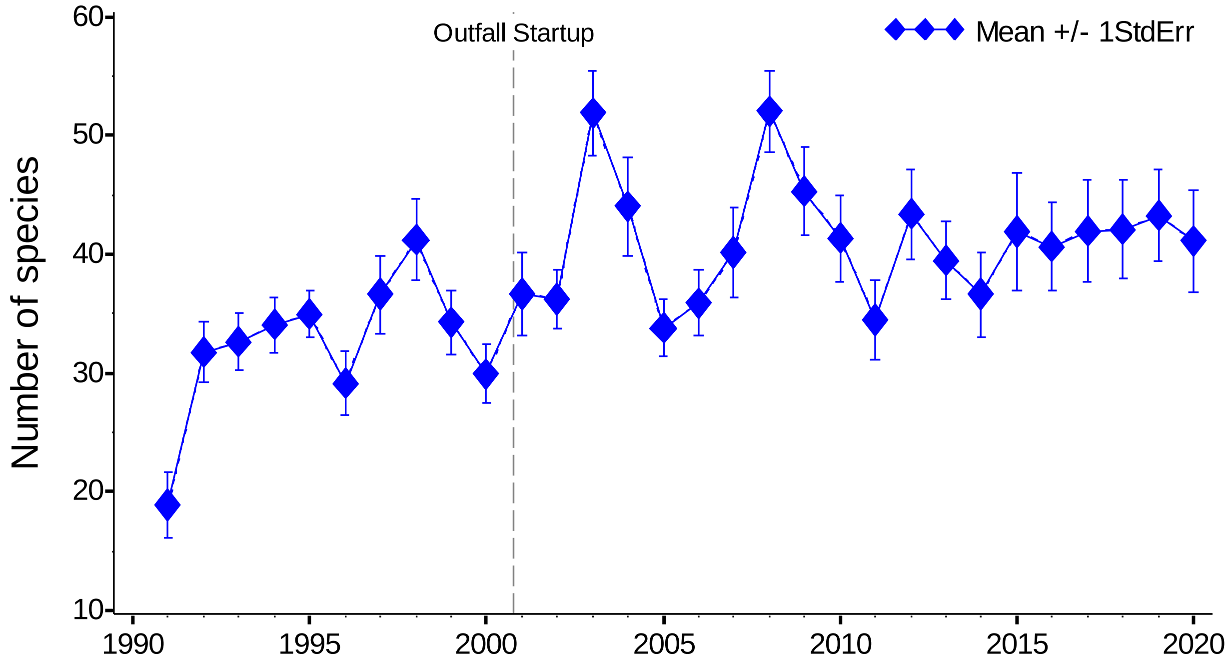

Figure 3-12. Mean species richness at eight Boston harbor stations (T01-T08), 1991-2020.

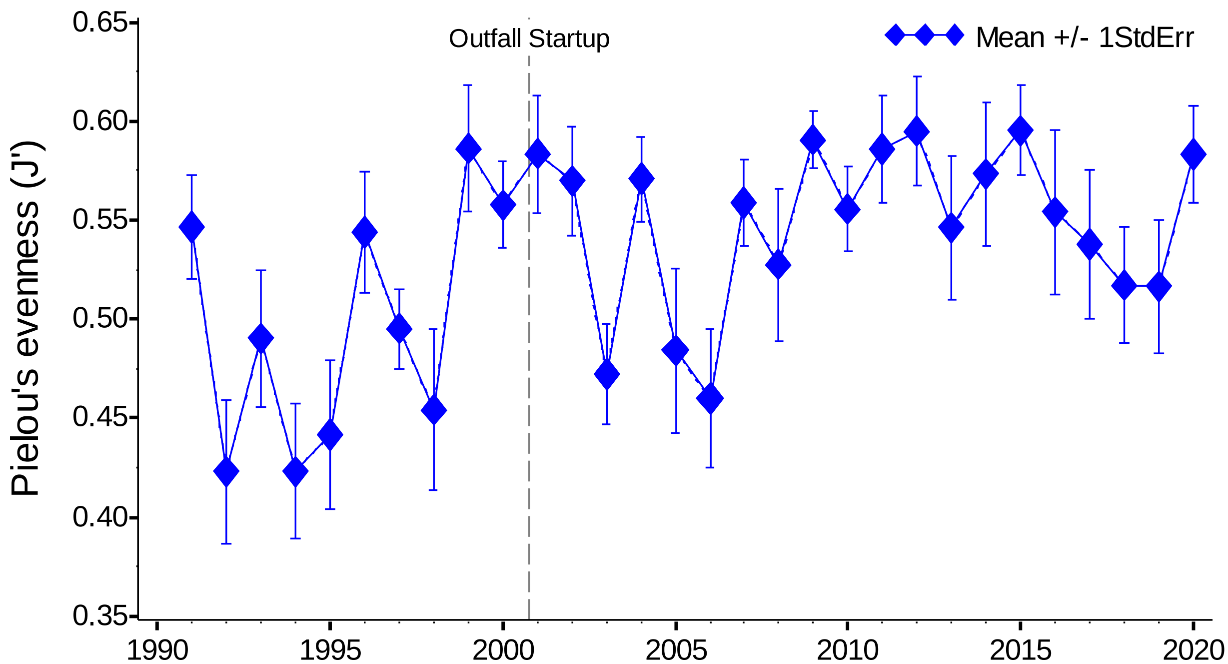

Figure 3-13. Mean community evenness at eight Boston Harbor stations (T01-T08), 1991-2020.

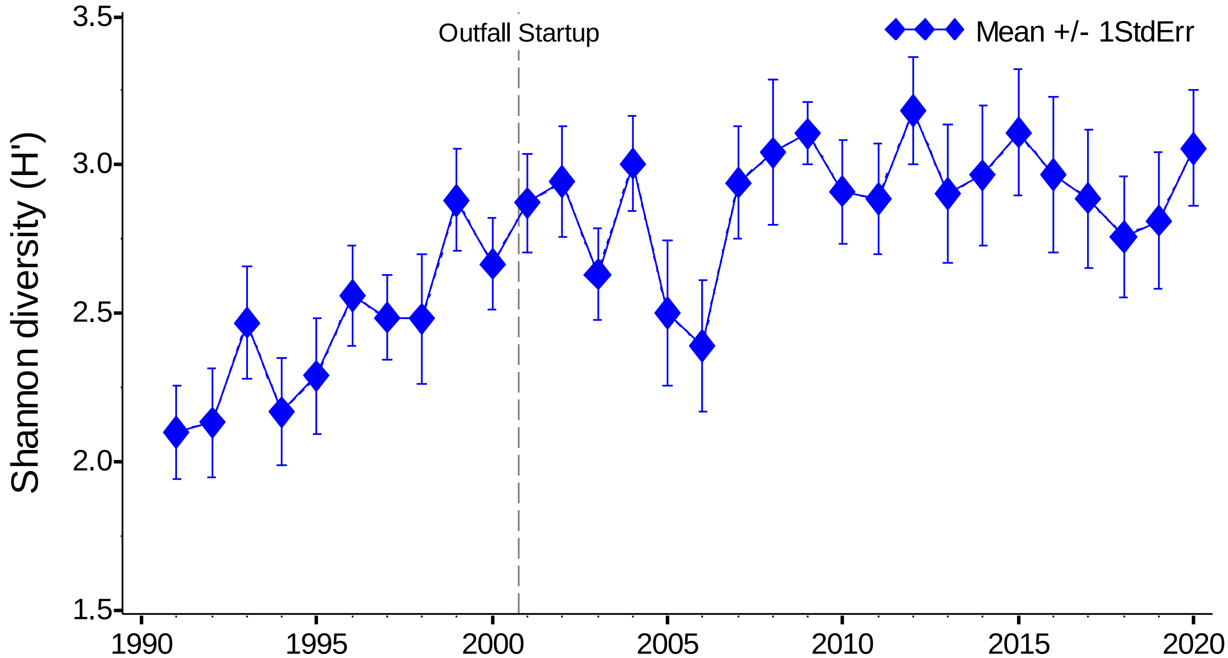

Figure 3-14. Mean Shannon-Weiner diversity at eight Boston harbor stations (T01-T08), 1991-2020.

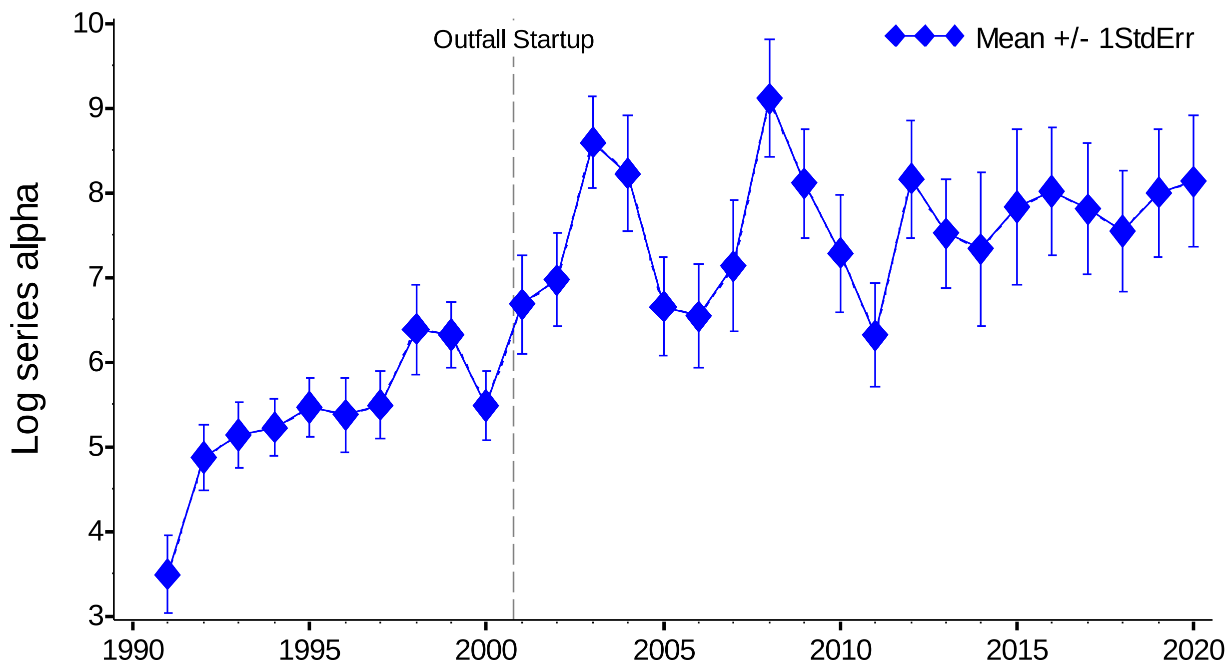

Figure 3-15. Mean log-series alpha diversity at eight Boston Harbor stations (T01-T08), 1991-2020.

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 2020 (Figure 3-16). Patterns identified through cluster analysis were confirmed in the MDS ordination plot for the 2020 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 1,947 individuals) and species richness (averaging 50 species per collection). Five species of polychaetes and oligochaetes (*Aricidea catherinae*, *Tubificoides intermedius*, *Limnodriloides medioporus*, *Polydora cornuta*, and *Tharyx acutus*) had relatively high abundances (Table 3-5). Within Group I, Stations T05A and T08 were distinct enough to form Subgroup IA dominated by *Spiophanes bombyx*, *T. acutus*, *Polygordius jouinae*, *Ameritella agilis*, and *P. cornuta*, and were characterized by high species richness (averaging 51 species per collection). Subgroup IB was comprised of Stations T01, T02, T03, and T06 characterized by high abundance and species richness (averaging 49 species per collection). Dominants included *A. catherinae*, *L. medioporus*, *T. intermedius*, *P. cornuta*, and *S. hebes.* The main Group II consisted of Stations C019, T04, and T07 and were dominated by five species, *Streblospio benedicti*, *Cossura* sp. 1, *Micronephthys neotena*, *Tubificoides* sp. 2, and *P. cornuta* (Table 3-5). Each station in main Group II was distinct enough to form its own subgroup. Station T07 formed Subgroup IIA and was dominated by *T. intermedius*, *M. neotena* and *P. cornuta*. This subgroup was characterized by low abundance and species richness (averaging 18.5 species per collection). Station C019 formed Subgroup IIB dominated by *Cossura* sp. 1 and *M. neotena*; total abundance was moderate and species richness was low. Station T04 formed Subgroup IIC dominated by *S. benedicti* and *Tubificoides* sp. 2, 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. Subgroup IA (T05A and T08) was predominantly sand and very low TOC. Sediments at stations in Subgroup IB ranged from approximately 40 to 77% sand and moderate to low TOC (0.4 to 1.8%). Sediments at Station T07 (Subgroup IIA) were approximately 36% fines with a moderate TOC (2.0%). Sediments at C019 (Subgroup IIB) were predominantly fines (95%) with a moderate TOC (2.1) and sediments at Station T04 (Subgroup IIC) were predominantly fines and TOC was higher than at other locations (Table 3-1).

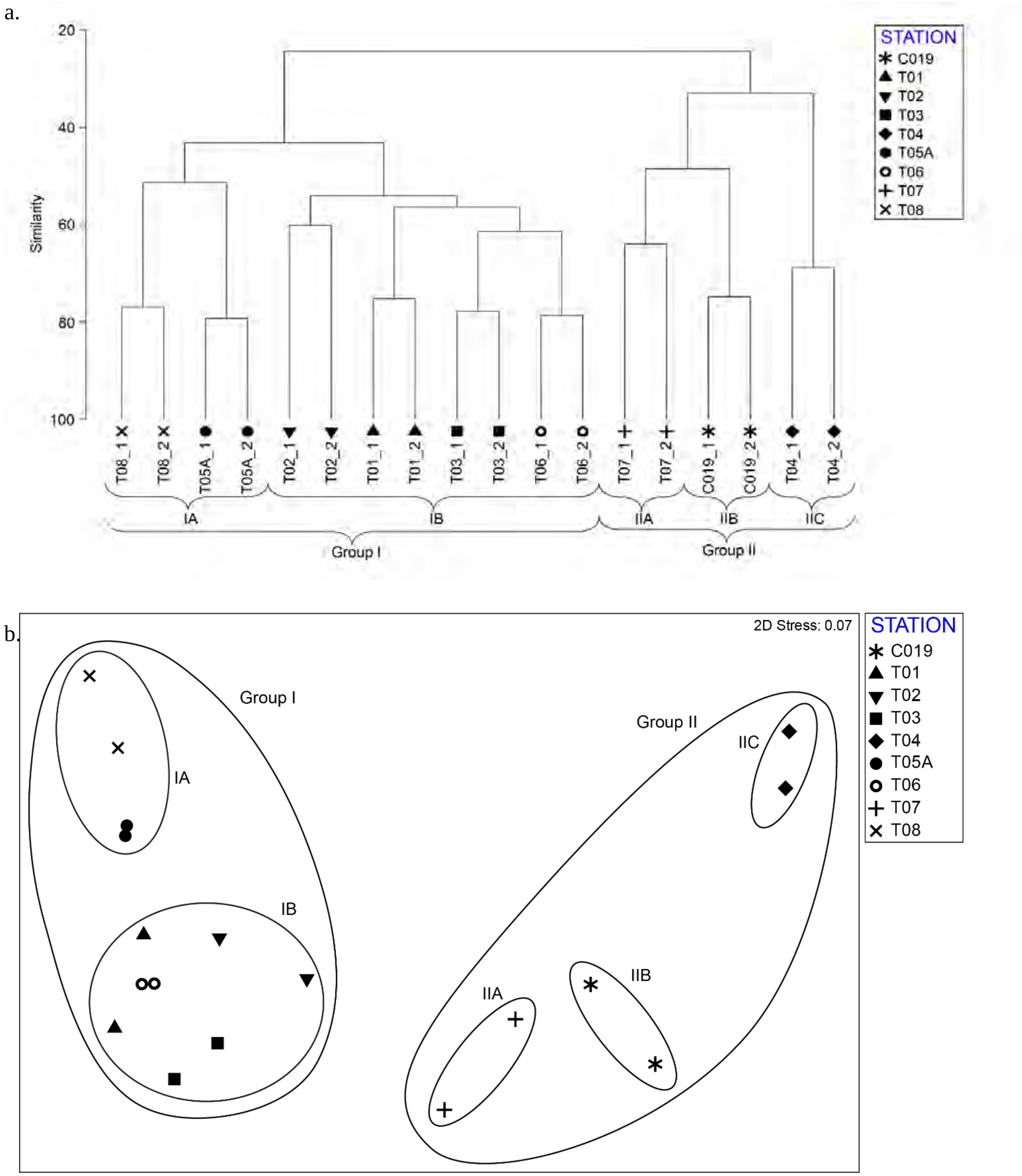

Figure 3-16. Results of (a) cluster analysis and (b) multidimensional scaling analysis of the 2020 infauna samples.

Table 3-5. Mean abundance of dominant taxa in 2020 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]
Bivalvia	Tellinidae	*Ameritella agilis*	**56.8**	135.0	17.8	**3.7**	10.0	0.5	0.5
	Yoldiidae	*Yoldia sapotilla*	**-**	0.8	0.3	**-**	0.5	3.5	0.5
Polychaeta	Cirratulidae	*Tharyx acutus*	**120.1**	248.3	56.0	**8.0**	3.0	4.0	17.0
	Cossuridae	*Cossura* sp. 1	**11.1**	-	16.6	**125.5**	-	376.5	-
	Hesionidae	*Microphthalmus pettiboneae*	**-**	1.8	3.9	**-**	1.0	2.0	1.5
	Lumbrineridae	*Scoletoma hebes*	**88.4**	1.0	132.1	**0.8**	2.5	-	-
	Maldanidae	*Clymenella torquata*	**79.5**	30.5	104.0	**-**	-	-	-
		Sabaco elongatus	**-**	0.3	3.0	**-**	4.0	-	-
	Nephtyidae	*Micronephthys neotena*	**61.3**	1.3	91.4	**59.2**	38.0	101.5	38.0
		Nephtys incisa	**1.1**	1.8	0.8	**3.7**	-	10.0	1.0
	Nereididae	*Neanthes virens*	**-**	-	0.1	**-**	-	-	0.5
	Orbiniidae	*Leitoscoloplos robustus*	**3.6**	1.8	4.5	**2.0**	4.0	1.5	0.5
	Paraonidae	*Aricidea catherinae*	**403.9**	8.3	601.8	**0.8**	2.0	-	0.5
	Pholoidae	*Pholoe spp.*	**-**	1.8	19.5	**-**	1.0	4.5	-
	Phyllodocidae	*Hypereteone heteropoda*	**-**	-	0.6	**-**	-	-	2.0
	Polygordiidae	*Polygordius jouinae*	**-**	148.0	0.1	**-**	-	-	-
	Spionidae	*Polydora cornuta*	**163.8**	116.8	187.3	**25.5**	32.5	44.0	-
		Spiophanes bombyx	**88.3**	254.8	5.1	**-**	-	-	-
		Streblospio benedicti	**1.9**	-	2.9	**150.7**	1.0	17.0	434.0
Oligochaeta	Tubificidae	*Limnodriloides medioporus*	**175.7**	3.0	262.0	**1.5**	4.5	-	-
		Naidinae sp. 1	**-**	82.5	29.4	**-**	2.0	-	**-**
		Tubificoides intermedius	**195.1**	102.0	241.6	**28.8**	40.0	46.5	-
		Tubificoides sp. 2	**-**	-	-	**56.8**	-	-	170.5
Amphipoda	Ampeliscidae	*Ampelisca* spp.	**81.2**	2.3	120.6	**0.3**	1.0	-	-
	Corophiidae	*Crassicorophium crassicorne*	**-**	38.5	-	**-**	-	-	-
		Leptocheirus pinguis	**-**	2.8	53.9	**-**	-	0.5	-
Cumacea	Diastylidae	*Diastylis sculpta*	**-**	29.0	-	**-**	-	-	-

[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 2020, species richness, Shannon-Weiner diversity, evenness, and log-series alpha were high at T01. All of these community parameters increased slightly compared to 2019 but remained within the ranges of values recorded in recent years (Rutecki et al. 2020a). Mean abundance in 2020 decreased compared to 2019 but was 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 2020, 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 (848) levels in 2018 (1,165), and then declined in 2019 (552.5). Mean abundance was 620.5 in 2020 (Figure 3-17, Table 3-2). Species richness also peaked in 2013 and has fluctuated near average levels (17.6) since 2016 with a slight decrease in 2020 compared to the previous year (Figure 3-18). Log series alpha reached its peak value in 2014 and then declined through 2017. The 2020 log series alpha (3.25) declined slightly compared to 2019 (Figure 3-19). Shannon-Weiner diversity and Pielou's evenness also peaked in 2014 and then declined. The 2020 values declined slightly compare to 2019 but remained above their respective average values of 1.8 and 0.43 (Figures 3-20 and 3-21). Despite decreasing values in some recent years, the diversity measures 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 2020. *M. neotena* and *T. intermedius*, respectively, were the next two dominant taxa in the infaunal community in 2020 (Figure 3-22, Table 3-5).

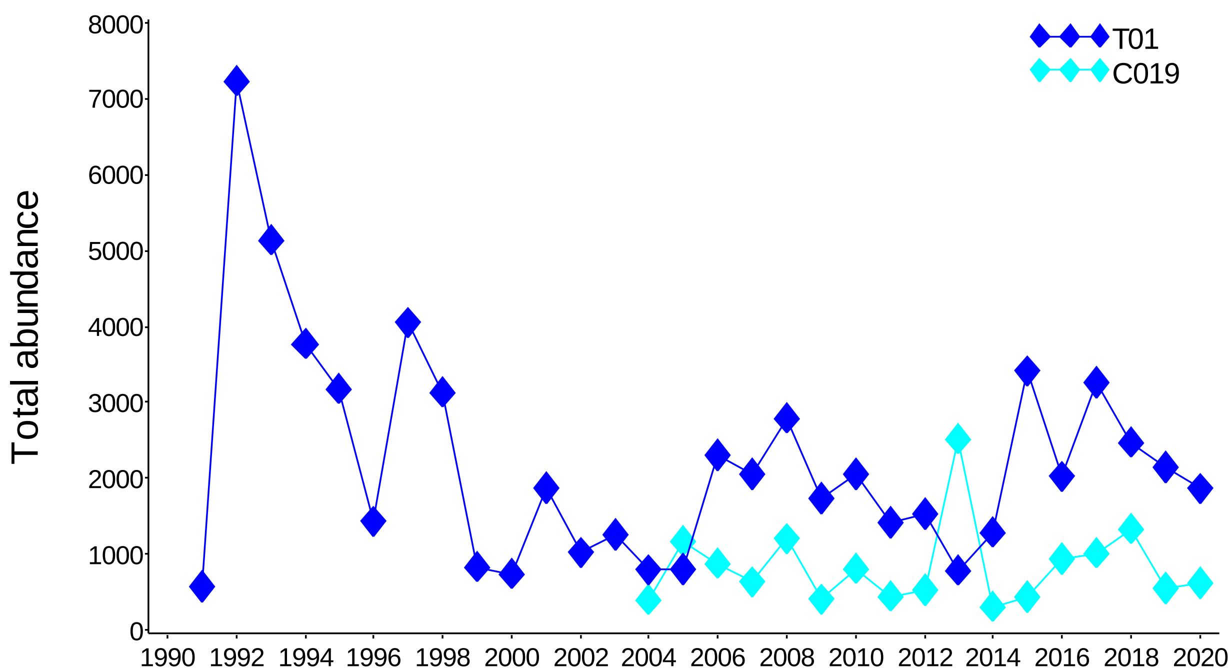

Figure 3-17. Mean total abundance at Boston Harbor Stations T01 and C019, 1991-2020.

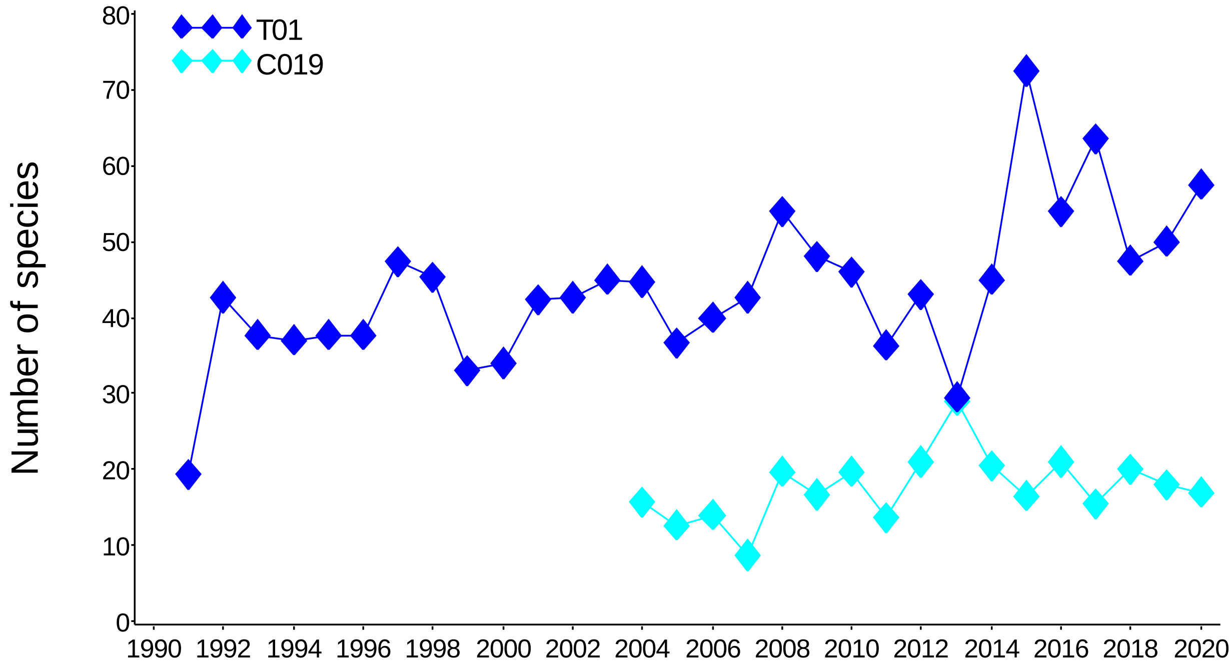

Figure 3-18. Mean species richness at Boston Harbor Stations T01 and C019, 1991-2020.

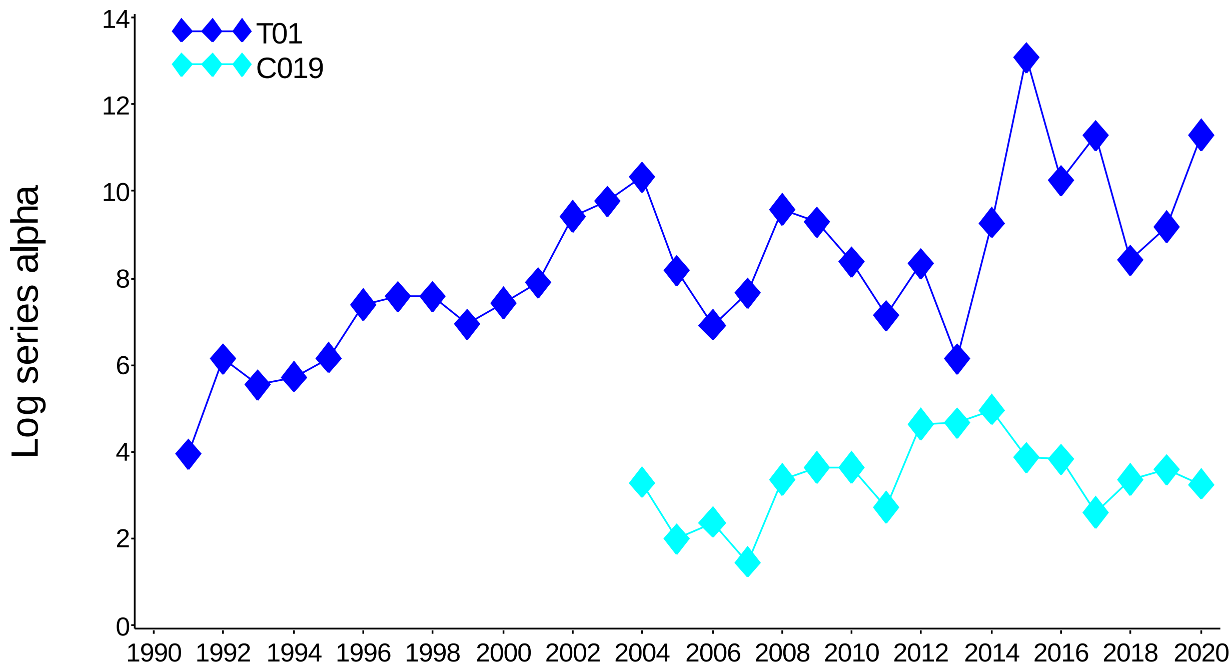

Figure 3-19. Mean log-series alpha diversity at Boston Harbor Stations T01 and C019, 1991-2020.

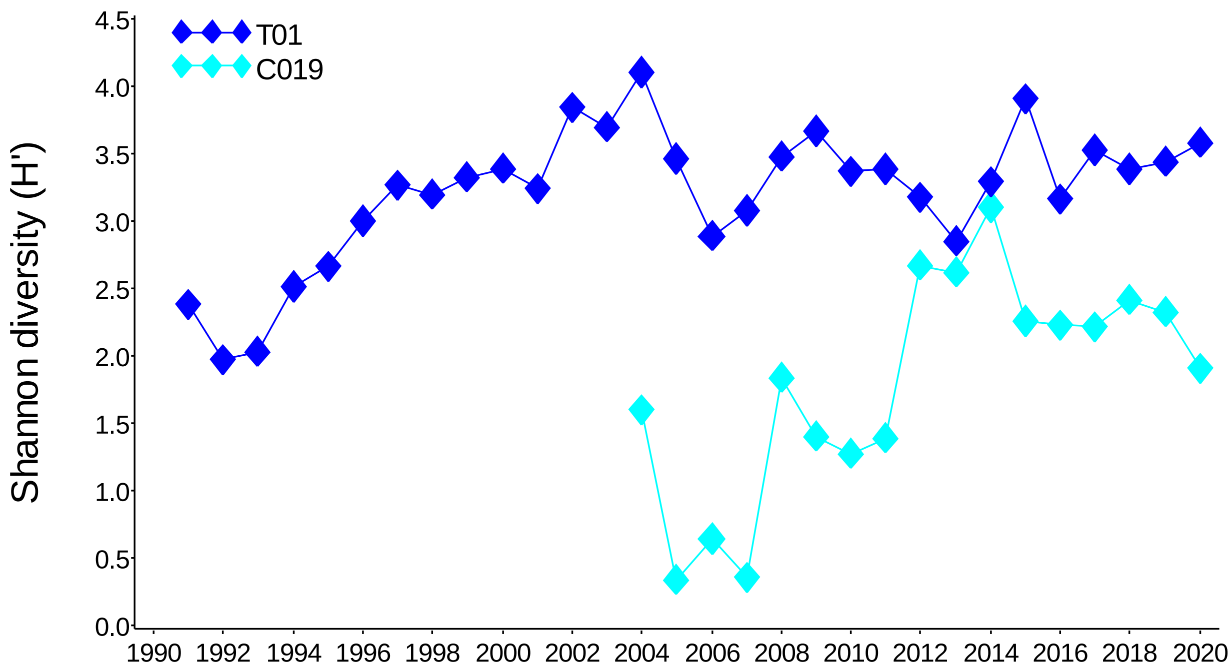

Figure 3-20. Mean Shannon-Weiner diversity at Boston Harbor Stations T01 and C019, 1991-2020.

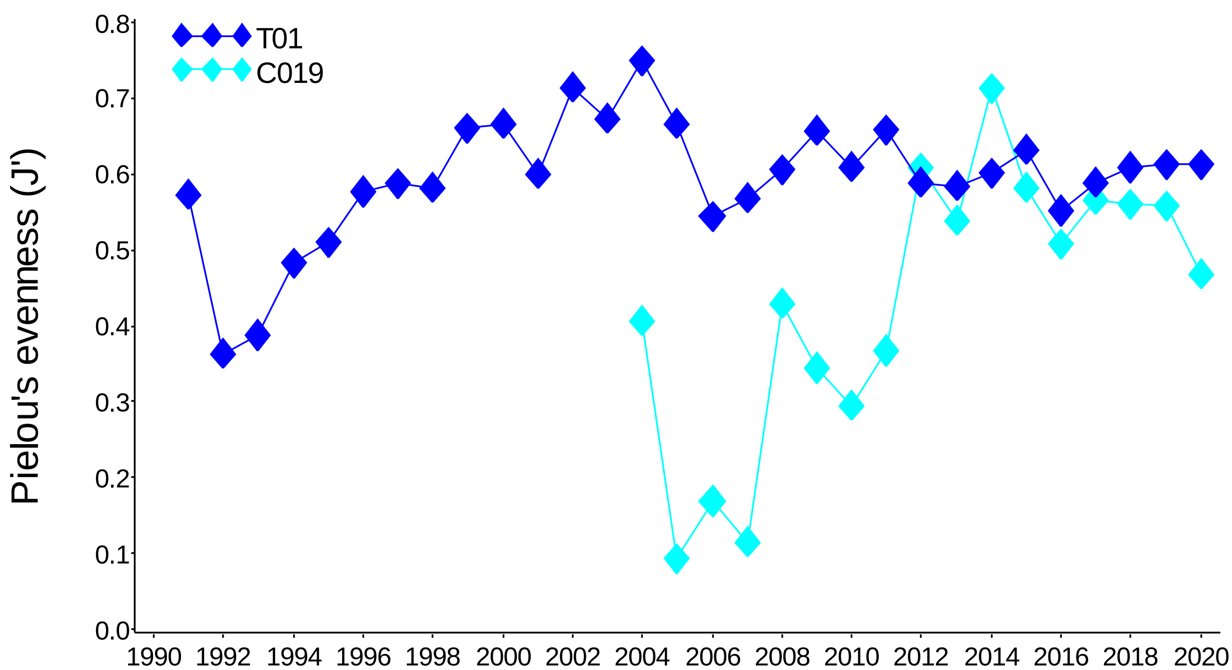

Figure 3-21. Mean evenness at Boston Harbor stations T01 and C019, 1991-2020.

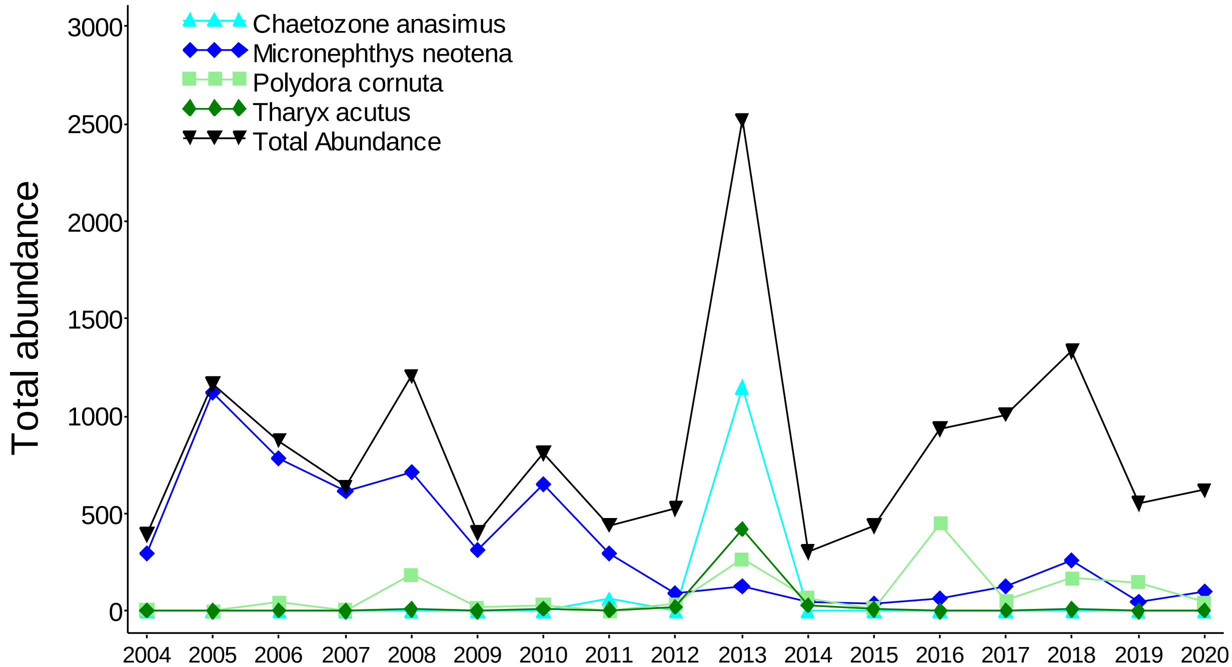

Figure 3-22. Mean abundance of *Micronephthys neotena* (formerly *Bipalponephtys neotena*) and other dominants and total community abundance at Station C019, 2004-2020.

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 2002-2020 were virtually the same as for 2002-2019 (Rutecki et al. 2020a) 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	2,478	112
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	<0.1
Pielou's Evenness (J')	0.48	0.02	0.47	0.01	0.58	0.02	0.55	0.01
Number of Species	25.4	2.1	34.7	1.1	33.6	1.7	41.4	0.9
Years of Data in Period	1991-1992		1993-1998		1999-2001		2002-2020	

3.3 SEDIMENT PROFILE IMAGING

3.3.1 General Benthic Habitat Conditions

Overall benthic habitat quality for 2020, as measured by the Organism Sediment Index (OSI) of Rhoads and Germano (1986), continued a trend of higher quality that started after a dip in 2015 (Figure 3-23). The low in 2015 was related to a slight decline in aRPD layer depth and total biogenic structures, but still the modal and mean OSI for the Harbor remained above 6 (the breakpoint between stressed and non-stressed benthos). The last year the Harbor's benthic habitat quality dipped below 6 was 2002 (Figure 3-23).

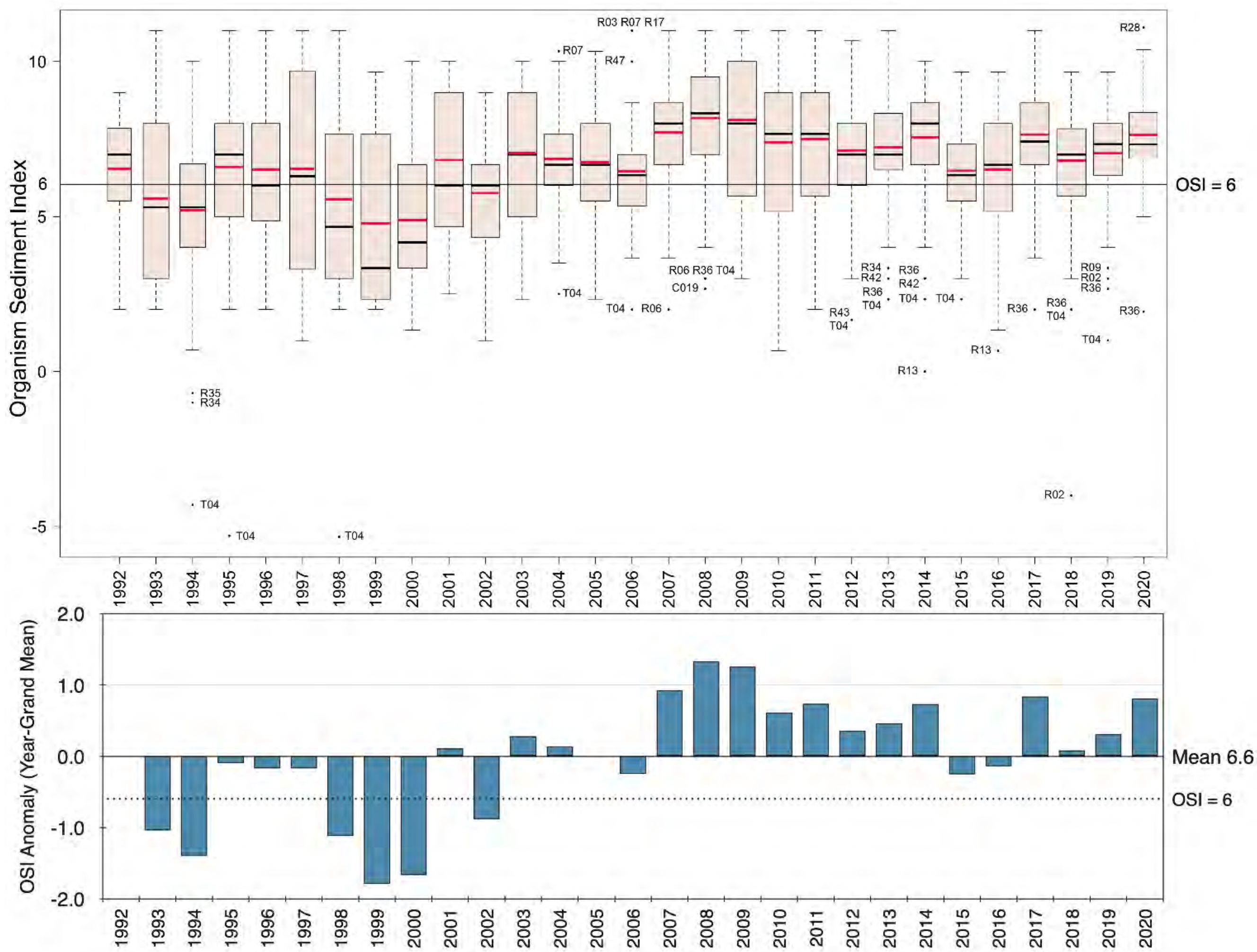

Figure 3-23. Box plot (top) and anomaly (year mean - grand mean; bottom) of OSI for all 61 Harbor stations by year. Boxes are interquartile range (IR), whiskers are 2IR, and outliers are labeled. The black bar in the box is the annual median and the red bar is the mean. Higher than grand mean OSI years are positive and lower are negative anomalies. Horizontal line at 6 is the breakpoint between stress and non-stress benthos (>6 represents good benthic habitat.

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 as the biggest reductions in loadings happened then. The most pronounced negative OSI anomalies (year - grand mean) were prior to 2000 (Blake et al. 1998, Taylor et al. 2019; Figure 3-24).

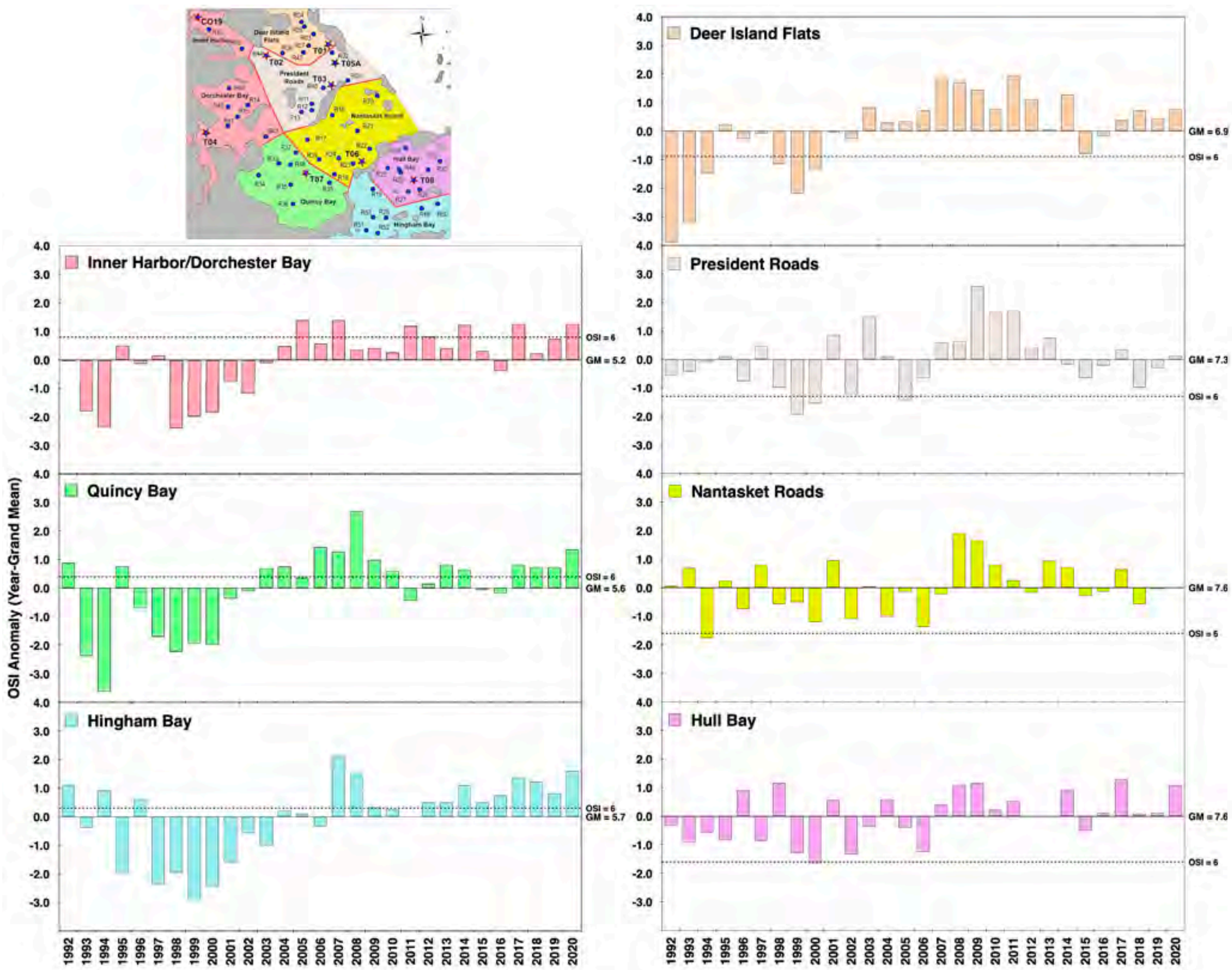

Figure 3-24. OSI anomaly (year mean - grand mean) for Boston Harbor regions. Higher than grand mean OSI years are positive and lower are negative values. The horizontal dotted line at 6 is the breakpoint between stress and non-stress benthos (>6 represents good benthic habitat).

However, 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). The inner harbor (western side) consistently had lowest habitat quality and the outer harbor (eastern side) the highest (Figure 3-25). Inner Harbor/Dorchester Bay, Quincy Bay, and Hingham Bay were lower in habitat quality than Deer Island Flats, President Roads, Nantucket Roads, and Hull Bay (ANOVA and Tukey's HSD, harbor regions $F = 67.6$, $p = <0.001$, year as covariate $F = 10.7$, $p = <0.001$). The significant interaction between harbor regions and year ($F = 1.3$, $p = 0.004$) indicated that all regions did not respond the same through time.

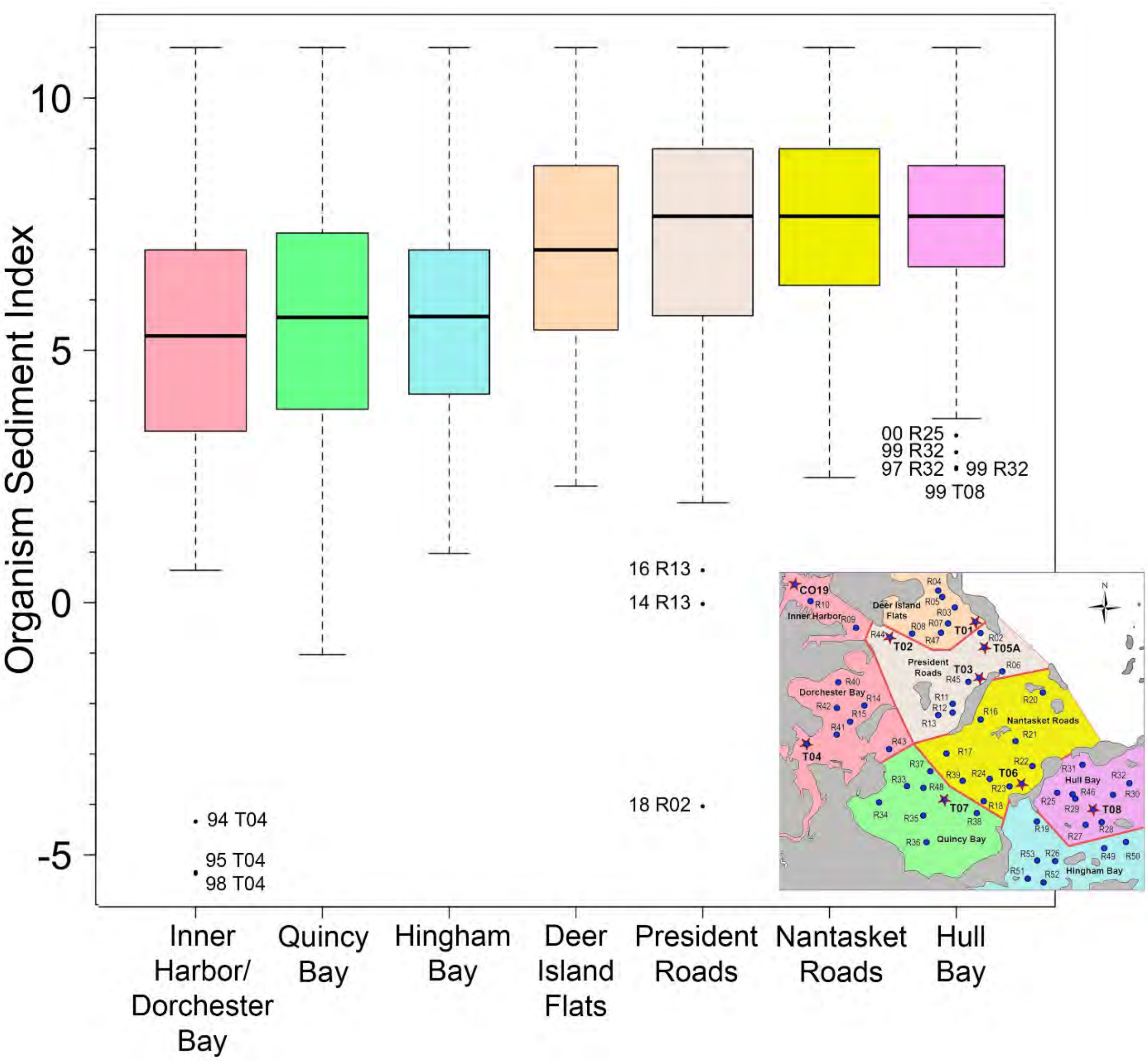

Figure 3-25. Box plot of OSI for Harbor regions summarized for all years. Boxes are interquartile range (IR), whiskers are 2IR, and outliers are labeled. The black bar in the box is the region median.

Basically, inner harbor regions improved more through time than outer harbor regions. This can be seen in the OSI anomaly through time (Figure 3-24). Greatest improvements in habitat quality occurred within inner harbor regions and also Deer Island Flats from 1992 to 2002, being 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).

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, except in 1994. Similarly, in President Roads with outfalls operating up to September 2000 (Taylor 2010), habitat quality was high except in 1999, 2000, and 2002. In 2020, low OSI outliers (more than two times the interquartile range for a region) occurred in Quincy Bay (R36) and Hingham Bay (R53) primarily due to shallow aRPD layer depths. High OSI outliers also occurred in Hingham Bay (R26), Nantasket Roads (R21), and President Roads (R28; Figure 3-26) primarily due to a combination of deeper aRPD layers and advanced estimated successional stage fauna.

Between 2003 and 2006 the benthic habitat quality transitioned 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. 2019).

Dredging operations in President Roads, part of the deep draft navigation improvement project (Massport and Corps 2013), did locally reduce habitat quality. Station R02 was dredged in August 2018 just prior to SPI sampling. A year later (August 2019) the effect of dredging were 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. OSI at R02 was above 7 prior to dredging, dropped to -4 in 2018, climbed to 3 in 2019, and in 2020 was 5. The area around Station T05A was also dredged, sometime after August 2018, but by the August 2019 SPI sampling, T05A showed no signs of having been recently 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. Station R09 was within the dredging boundaries and continues to show signs of recent physical disturbance. Its location in the center of the channel 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 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 Masachusetts 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. It 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).

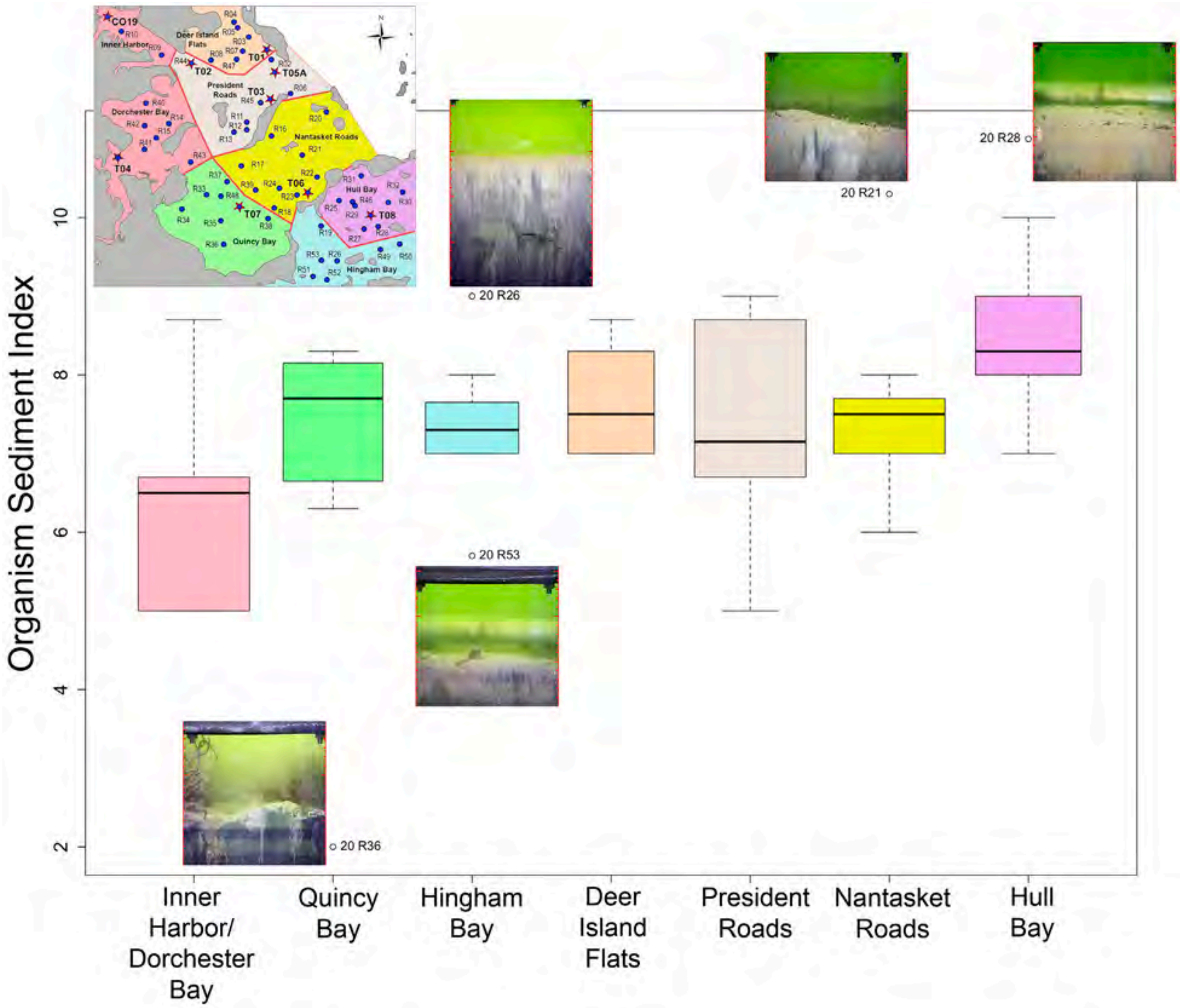

Figure 3-26. Box plot of OSI for Harbor regions for 2020. Boxes are interquartile range (IR), whiskers are 2IR, and outliers are labeled. The black bar in the box is the region median.

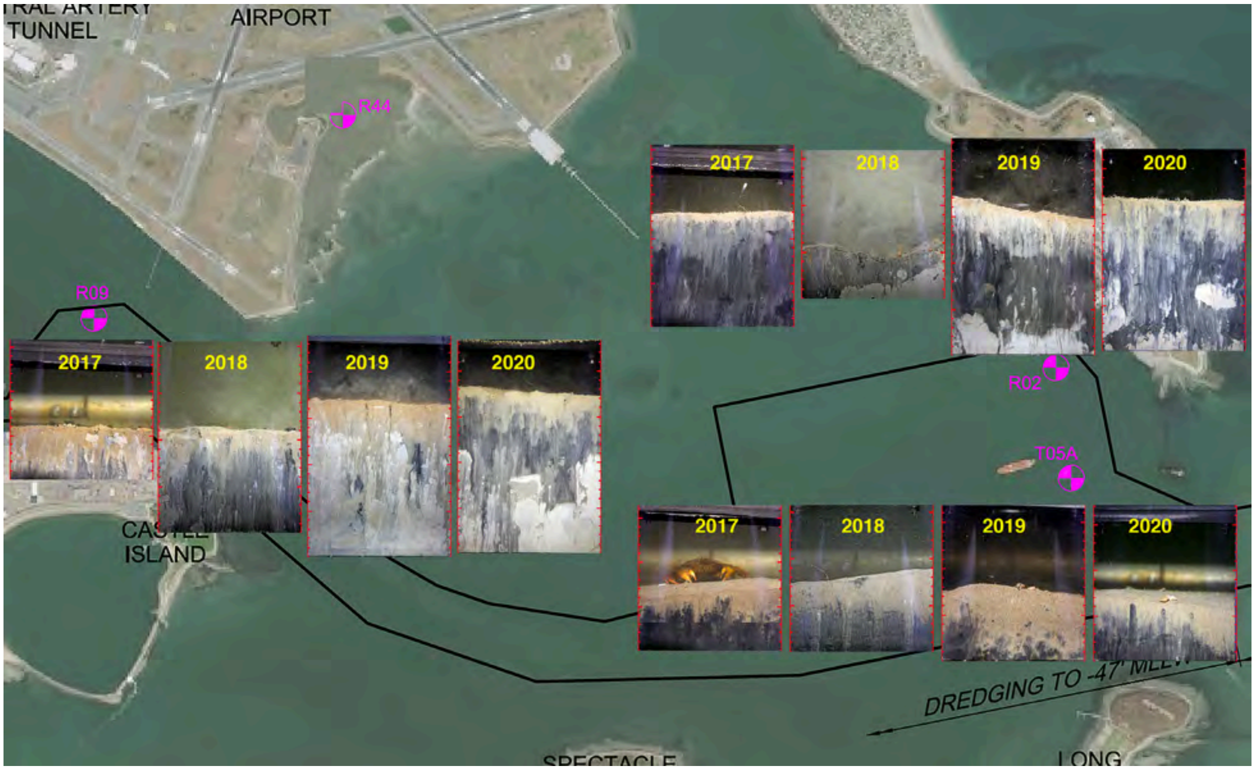

Figure 3-27. Changes at stations within the boundaries of President Roads dredging.

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

3.3.2 2020 Recruitment

Benthic recruitment appeared to be strong in 2020 based on SPI images with worm tube mats at six muddy sediment stations. The three Inner Harbor stations (CO19, R09, R10) had worm tube mats, plus T04 in Dorchester Bay, R02 in President Roads and R04 on Deer Island Flats (Figures 3-29, 3-30, and 3-31). However, infaunal abundance at CO19 and T04 were not elevated in 2020 relative to recent years. The tubes builders may have been small recently recruited individuals that were not retained on the 0.3 mm sieve.

At Station CO19 the worm tubes were about 1 mm diameter and likely belonged to *Polydora cornuta* (44 /0.04 m^2), the dominant tube building species at CO19. *Cossura* sp 1 (376 / 0.04 m^2) was the most abundant taxon at CO19, but it is a burrower and not a tube builder. Tubes were also visible on sediment surface of the grab sample from CO19. Abundance at CO19 in 2020 was about the same as in 2019 and certainly not close to peak abundance years of 2013 and 2018 (Figure 3-30). The tubes at Station R02 were similar to those at CO19 and likely belonged to *Polydora cornuta*. Dense aggregates of worm tubes (worm tube mat) were also seen on the sediment surface at Station T04 in Inner Dorchester Bay. These tubes were smaller, about 0.5 mm diameter and likely belonged to the tube building *Streblospio benedicti*, which was the dominant species (434 / 0.04 m^2). Tubes were so small that they were not visible on the sediment surface of the grab sample (Figure 3-31). Infaunal abundance at Station T04 in 2020 was much lower than in 2019.

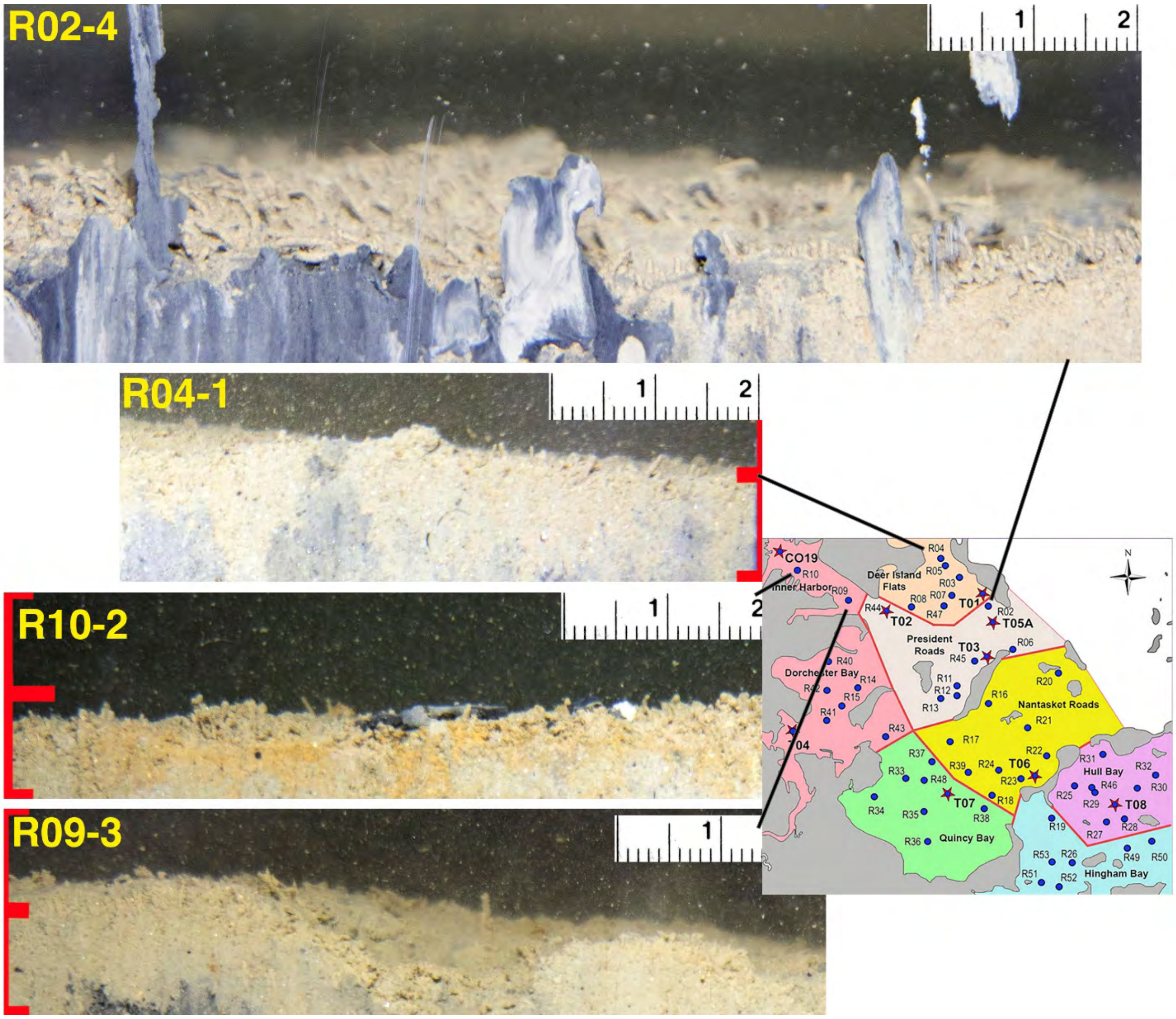

Figure 3-29. Worm tube mats observed in SPI in 2020.

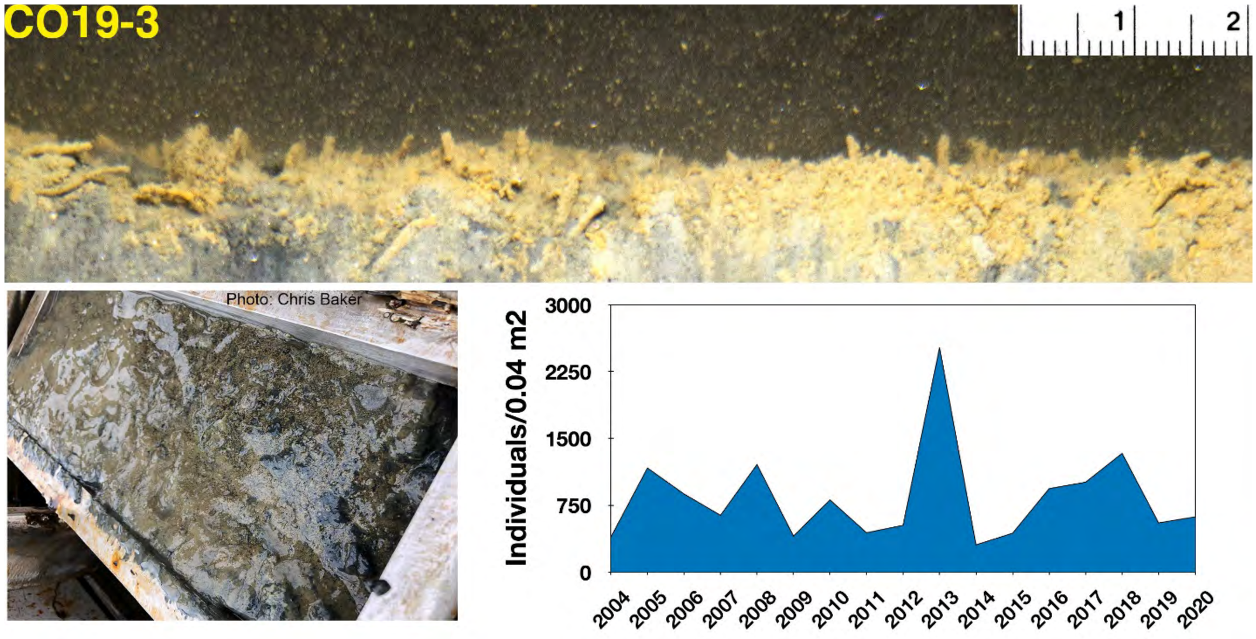

Figure 3-30 Worm tube mats observed in SPI and infaunal grab sample in 2020 at Station CO19 in the Inner Harbor. Total infaunal abundance did not have a large increase for 2020.

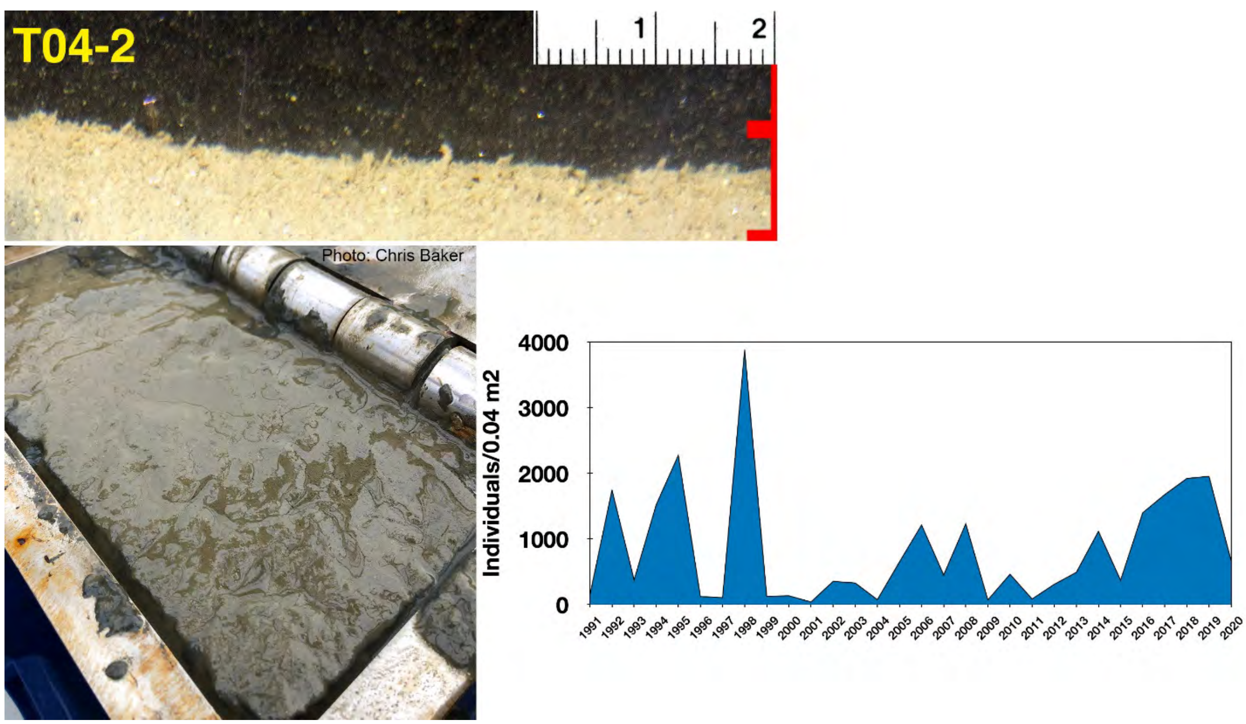

Figure 3-31 Worm tube mats observed in SPI and infaunal grab sample in 2020 at Station T04 in Dorchester Bay. Total infaunal abundance had a decline for 2020.

3.3.3 Long-Term Patterns

Over the 29 years of Harbor SPI monitoring (1992 to 2020), data on benthic habitat quality (OSI, Figure 3-24) and infaunal community structure (Diversity, Figure 3-14) were highly variable with a general improving trend through time. Most trends over this period reflected complex interactions of harbor-wide driving factors with the three most important being: 1) Just prior to the start of monitoring, the October 1991 severe storm (known as the "perfect storm", as it was the strongest storm for the region up to that year) coincided with the December 1991 cessation of sludge dumping within the Harbor, followed by the strongest storm to have occurred in December 1992; 2) subsequent treatment upgrades and final diversion to the offshore outfall in September 2000 significantly reduced total organic carbon inputs; and 3) regional increase in storminess that increased integrated wind stress on the bottom (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. 2019). 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.

3.3.4 Storms

Between 1985 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 was 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 (Figure 3-32). 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 (Butman et al. 2008). From 1985 to 2020 it was the 4th highest ranked IWindS storm, and up to that time, the winter of 1991-1992 (1992 winter-period) was the stormiest year. The 1992 winter-period is now 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) ranks 23rd. The top ten storm years occurred between 2003 and 2020 (Figure 3-32).

3.3.5 Sediments

Bed Roughness. Through time there has been a shift in the relationships between processes structuring bed roughness due mainly to declining particulate organic carbon (POC) loading and increasing winter-period storminess (Rutecki et al. 2019). Temporal and spatial variations in bed roughness, which is due to physical and/or biological processes (See Figure 3-33 for examples), affects bottom drag and sediment stability. 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 2020. In 2020, only Stations T03 and R45, both in President Roads, had biologically dominated surfaces. Another 9 stations had a combination of biological and physical processes dominating bed roughness, and the other 50 stations 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 increased sum of winter-period IWindS storms (Rutecki et al. 2019). The probability declined with increasing percent of time that was stormy, which is the reverse of what we predicted, and likely due to the nonlinear interaction of organic carbon production (POC loading + primary production) and storminess thought time. The addition of 2020 data, which was the 5th stormiest winter-period (Figure 3-32), strengthened these relationships. 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.

Grain-Size. At most of the 61 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 3-34). In 2020, seven (7 of 61) stations changed modal SPI grain-size class, four became coarser (R37 in Quincy Bay, R18 in Nantasket Roads, and R27 and R29 in Hull Bay), and three became finer (R19 in Hingham Bay, T01 on Deer Island Flats, and T05A in President Roads).

The median sediment grab grain-size tended to be on the coarser end of the range for the monitoring period (1994 to 2020; Figure 3-35). At station T08 both SPI and grab data indicated sediment in 2020 was on the coarse end of the range (Figure 3-36). At station T07 grab median grain-size was the coarsest recoded while the SPI modal grain-size was the finest (Figure 3-37). This discrepancy is likely related to the grab grain-size coming from the top several cm of sediment while in the SPI modal estimate the entire image area is assessed for grain-size.

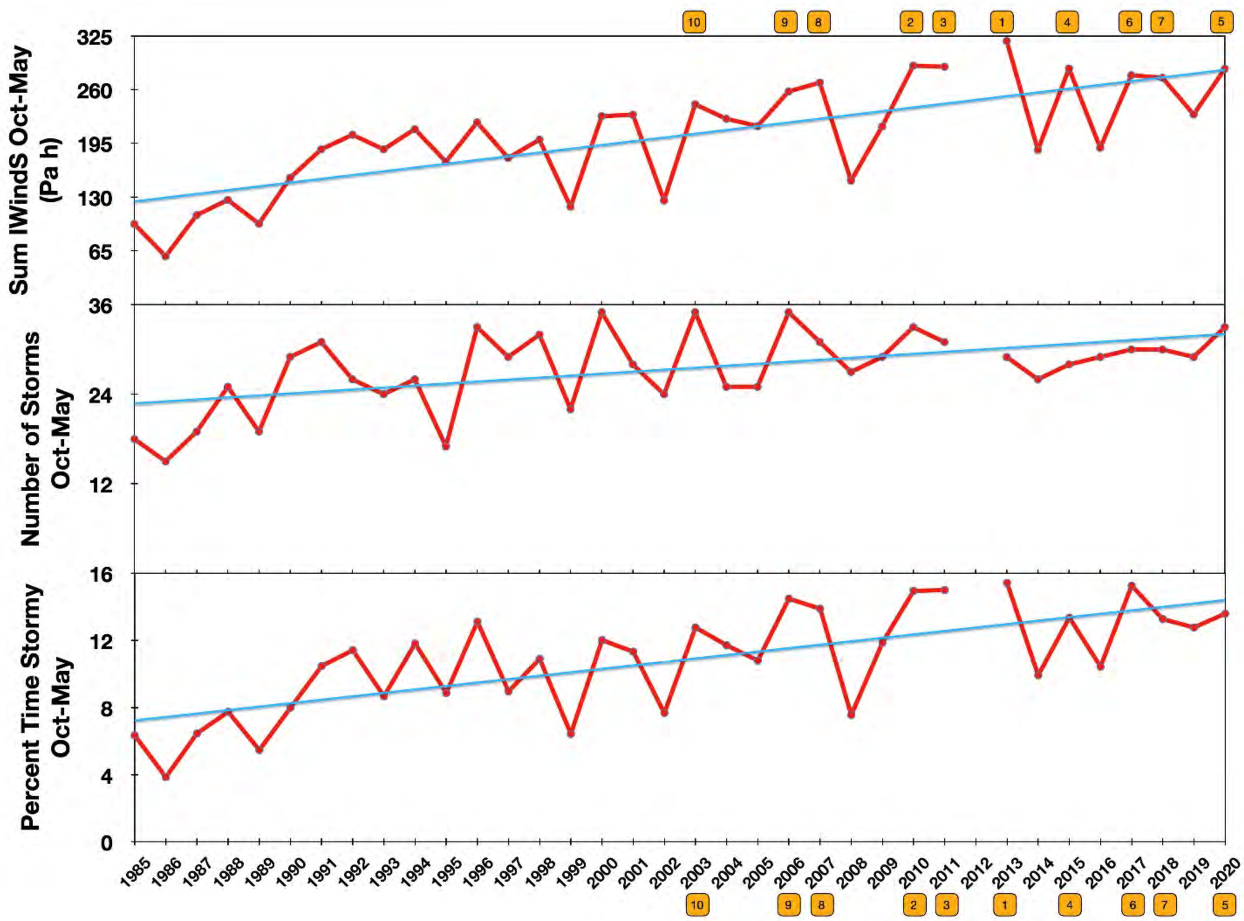

Figure 3-32. Trends in annual winter-period (October to May) integrated wind strength (IWindS) storm parameters from 1985 to 2020. Top ten storm year are labeled. Data updated from Codiga et al. (2019).

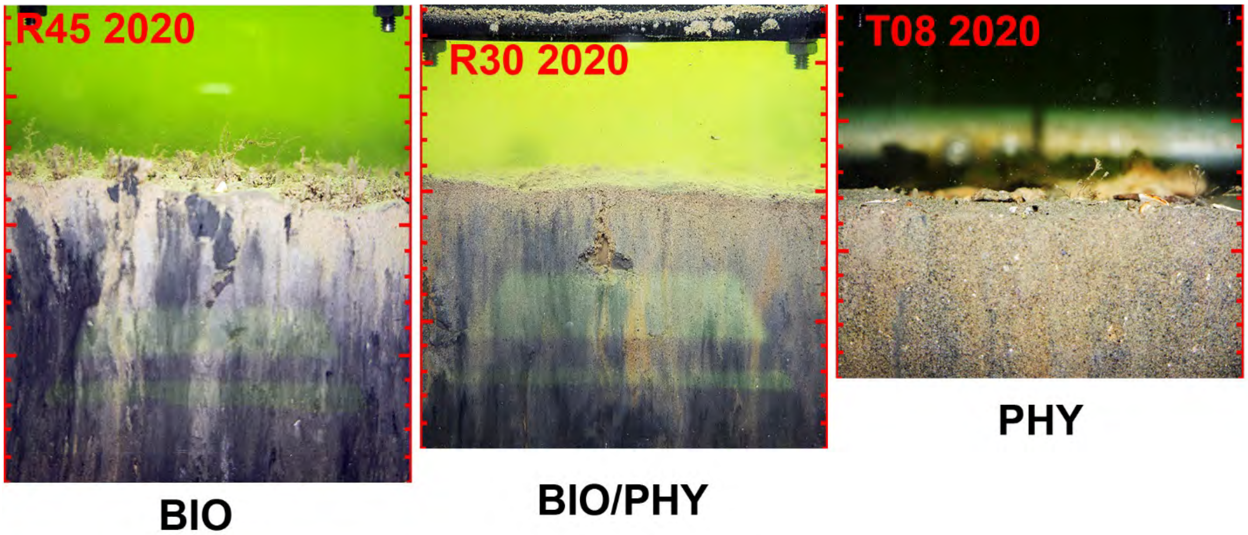

Figure 3-33. Examples of bed roughness being dominated by biological (BIO) and physical (PHY) processes. Scale on the side of the image is in cm.

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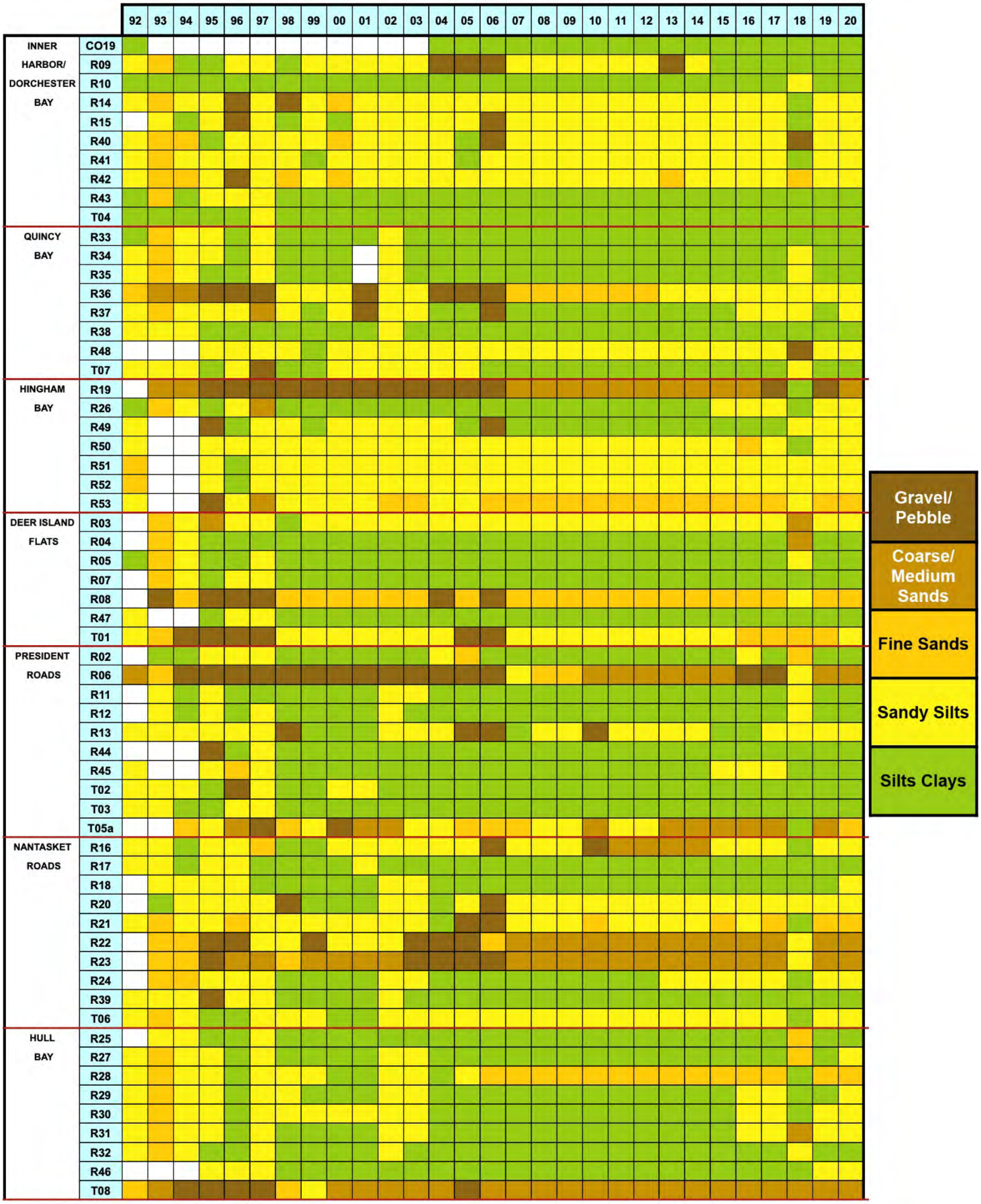

Figure 3-34. Matrix of modal grain-size estimated from SPI with stations arranged by Harbor region. Blank cells indicate station was not sampled.

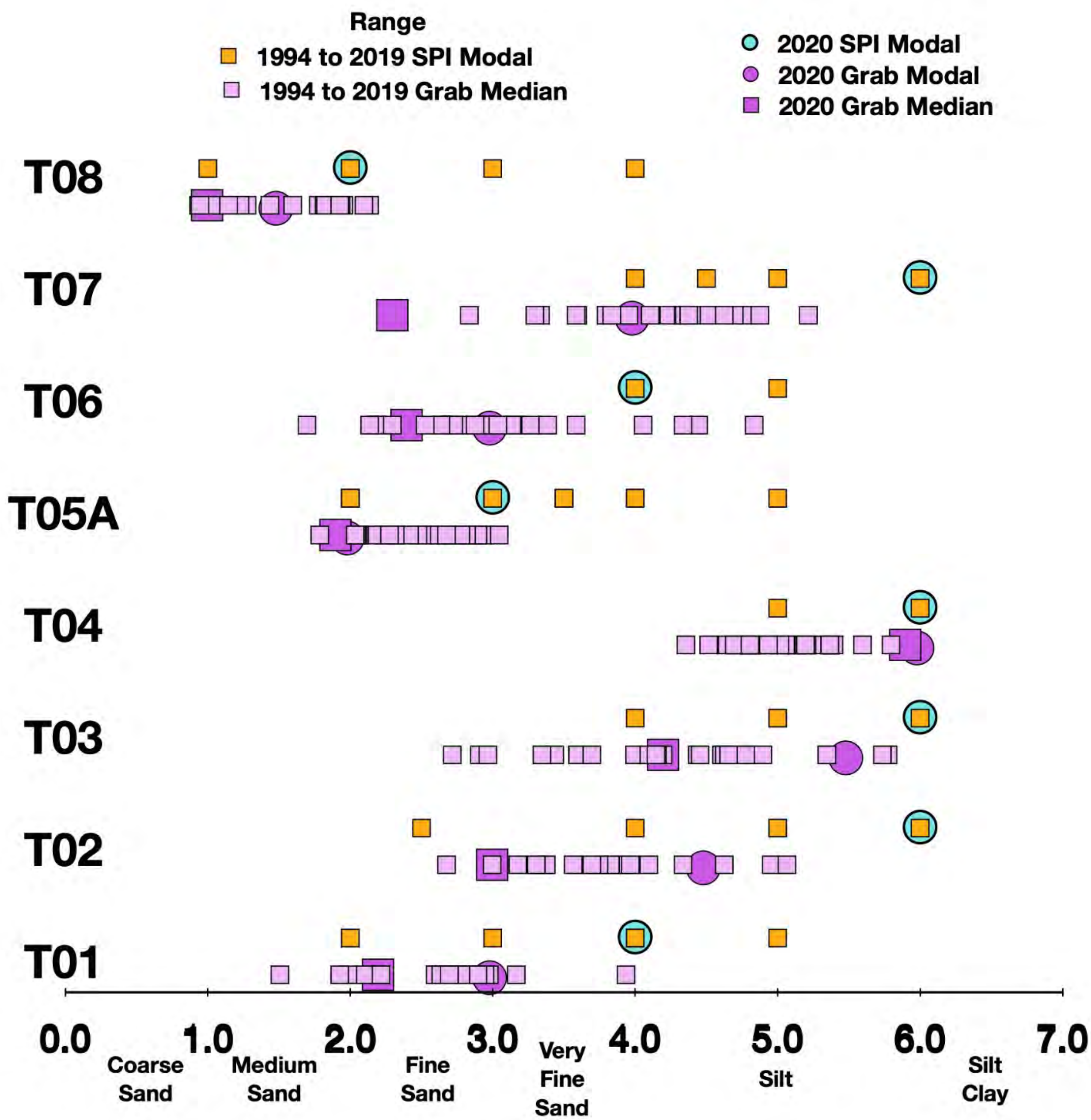

Figure 3-35. Range of SPI modal grain-size and grab sediment modal and median grain-size from 1994 to 2020 for T-Stations.

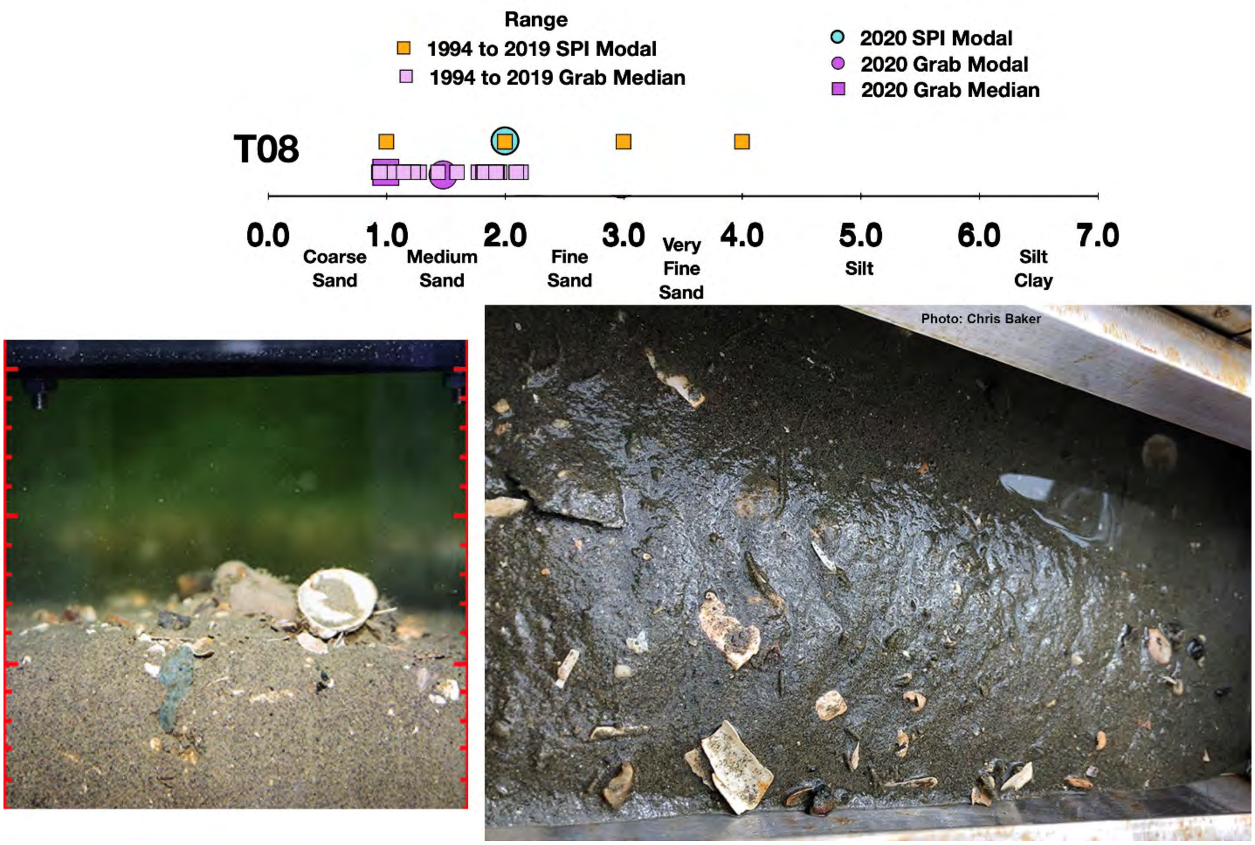

Figure 3-36. Range of SPI modal grain-size and grab sediment modal and median grain-size from 1994 to 2020 at Station T08. Scale on the side of SPI is in cm. Grab sample image is not scaled.

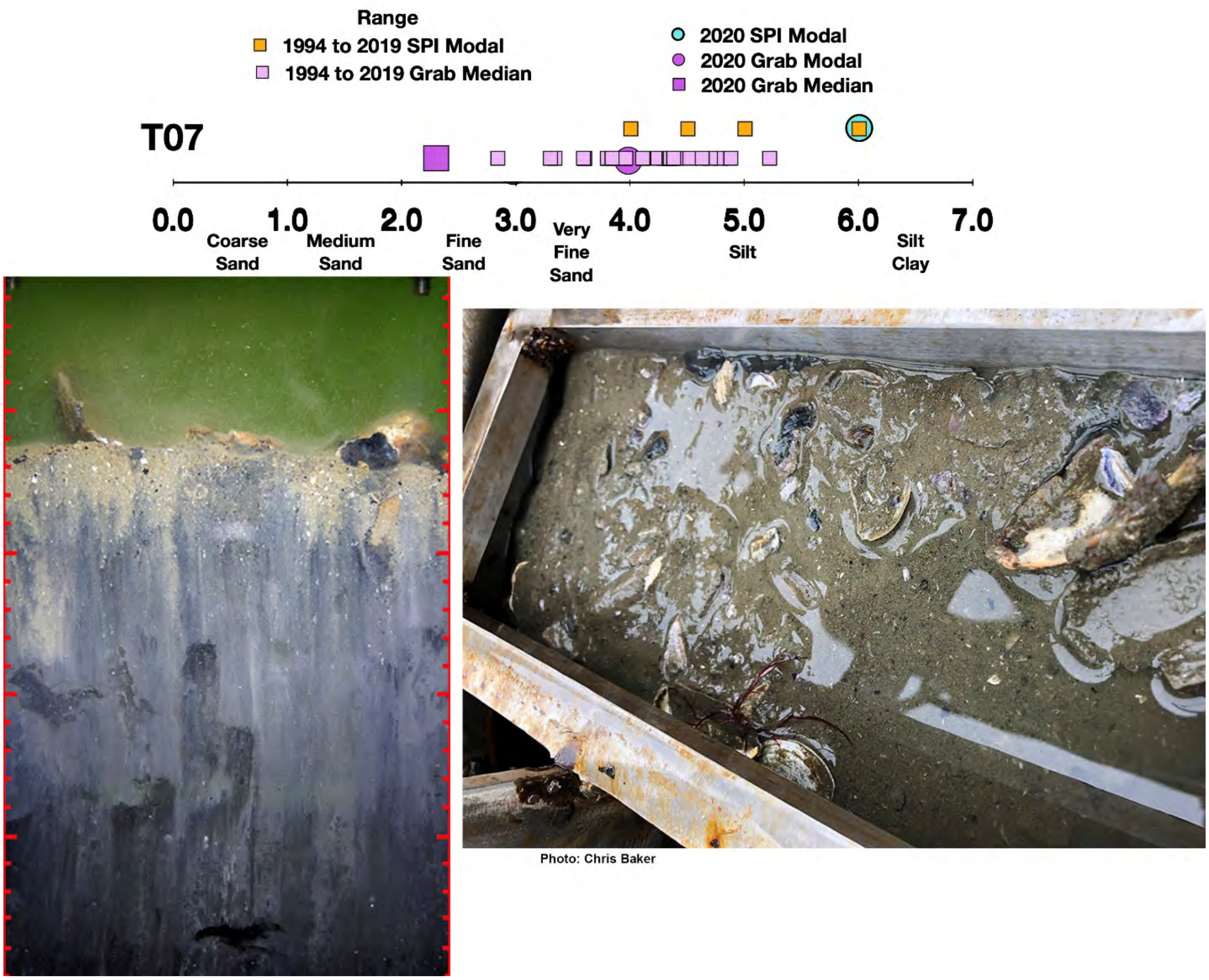

Figure 3-37. Range of SPI modal grain-size and grab sediment modal and median grain-size from 1994 to 2020 at Station T07. Scale on the side of SPI is in cm. Grab sample image is not scaled.

3.3.6 *Ampelisca* spp. Trends

The occurrence of *Ampelisca* spp tubes was related to both POC loading and intensity of winter period storms (Rutecki et al. 2019). 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 3-38). 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 3-32). Between 2006 and 2019 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 3-32), and all ten stormiest years occurred after the September 2000 diversion (Period IV of Taylor 2010).

Abundance of *Ampelisca* spp has remained low at the T-stations for the last few years (Rutecki et al. 2019) and 2020 continued that trend. There were also fewer *Ampelisca* spp tubes in SPI with about two-thirds (40 of 61) of all stations not having *Ampelisca* spp tubes (Figure 3-38). The other third of stations had *Ampelisca* spp tubes, with mat densities at three stations. *Ampelisca* spp mats occurred at outer harbor stations: R29 (Hull Bay), and R45 and T03 (President Roads). It is notable that in 2020 Deer Island Flats had no *Ampelisca* spp tubes for the second time since 1992. 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 2020 (Figure 3-39).

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 and 2009 it averaged about 300 g C m-2 yr-1 (Taylor et al. 2019). The few stations with *Ampelisca* spp tube mats in 2020 also fits with 2020 being the 5th stormiest year. While not a measure of primary production, annual averaged phytoplankton abundance measured at the mouth of the Harbor (Station F23, Libby et al. 2020) were well below the long-term average. For the monitoring region, phytoplankton abundance has been on a downward trend since 2008 with 2020 being 27th lowest out of 29 years (Libby et al. 2020).

Most tubes at outer harbor stations in 2020 were likely *Ampelisca vadorum* and not *Ampelisca abdita*. *A. vadorum* tubes are shorter and wider than *A. abdita* tubes which are longer and thinner (Figure 3-40). At station T03 most tubes in the SPI image seem to be *A. abdita*, but grab data indicated most were *A. vadorum*. *A. vadorum* has dominated at T03 since 2012 (Figure 3-40). Station T03 is near the Harbor mouth with higher salinity, which would favor *A. vadorum*. But small-scale spatial variation likely plays a role in which species was sampled. Being in mid harbor, Station T06 in Nantasket Roads has lower salinities, which would favors *A. abdita* (Mills 1967). *Ampelisca* spp abundance at T06 has been low since the early 2010s (Figure 3-41) but it had mat densities for 17 of 29 years (1992-2020) with 2018 the last year with tube mat.

Dense aggregates of small worm tubes (worm mats), likely all polychaetes, have also increased over the last three year being present at 10% (6 of 61) of stations in 2020 (Figures 3-38 and 3-39). This increase in small-tube worm mats could be related to a trend of later recruitment or shifting species dominance driven by changing climatic factors and patterns in primary production or stochastic population variations.

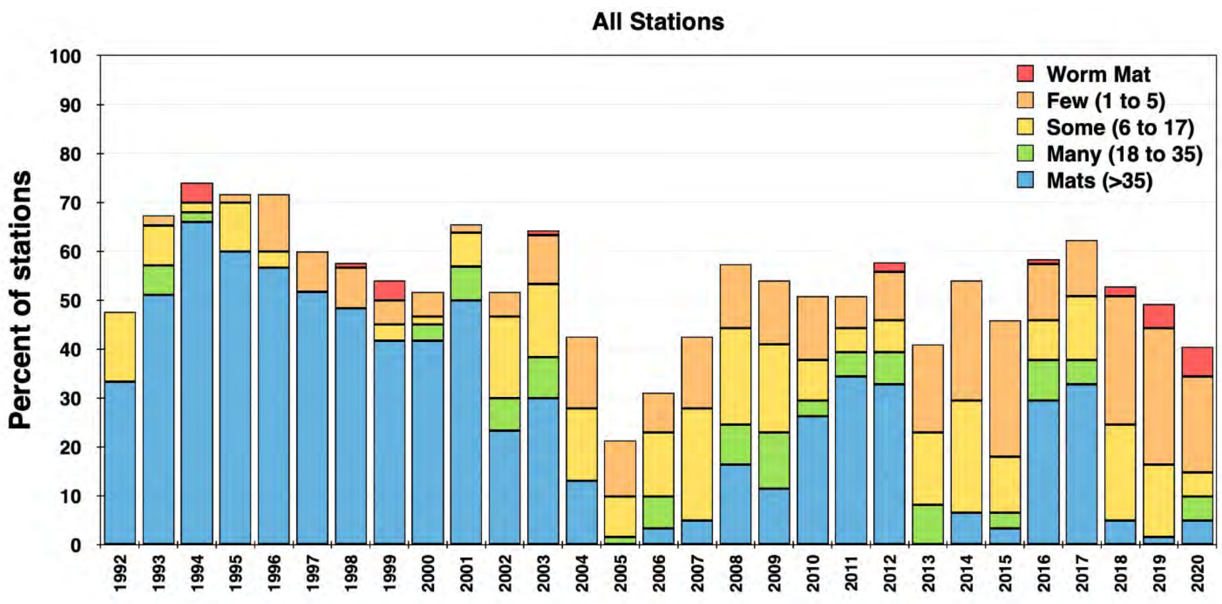

Figure 3-38. Histogram of the occurrence of *Ampelisca* spp. tubes (number/image) and worm tube mats for all 61 Harbor stations.

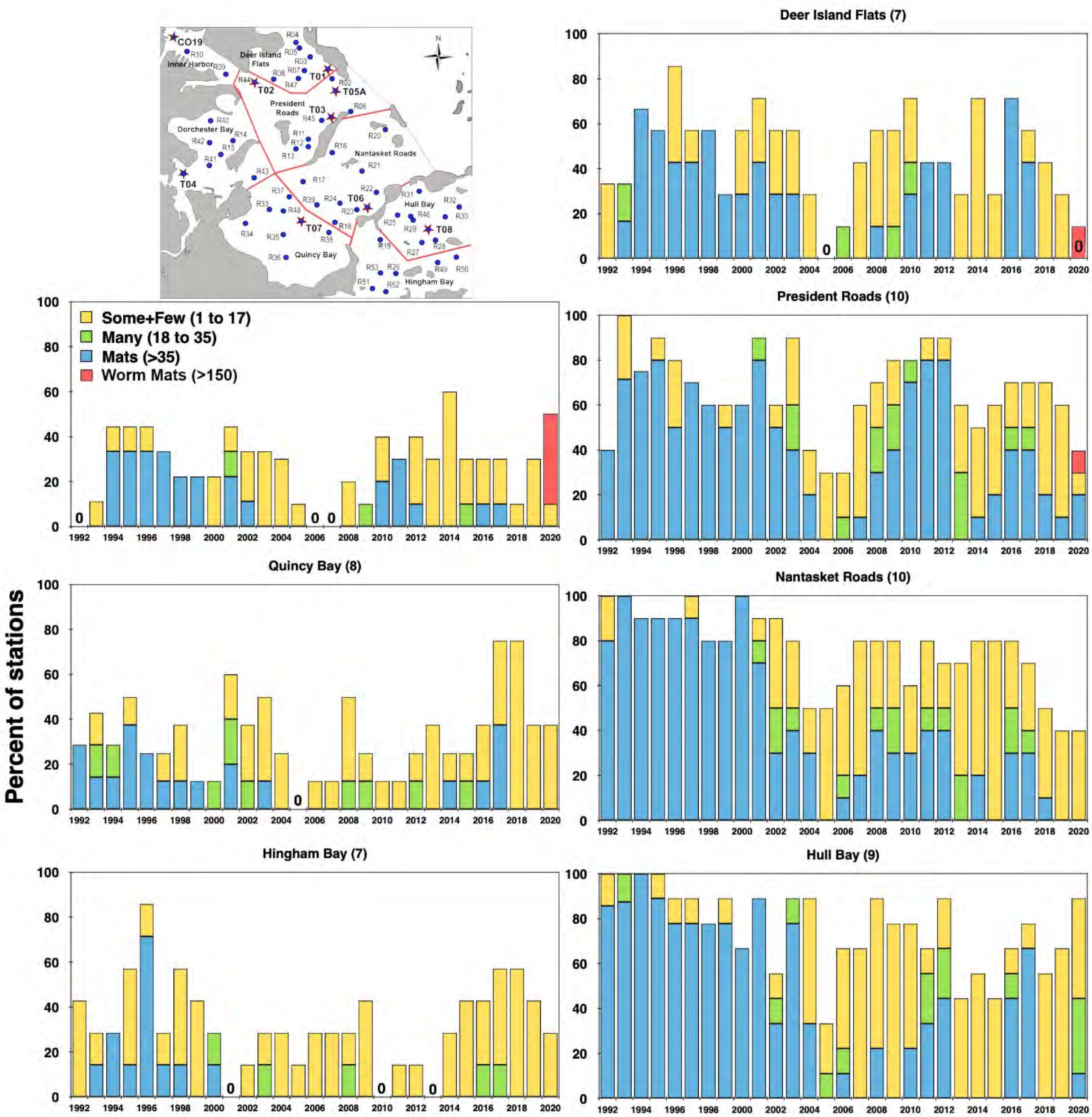

Figure 3-39. Histogram the occurrence of Ampelisca spp. tubes (number/image) and worm tube mats by Harbor regions.

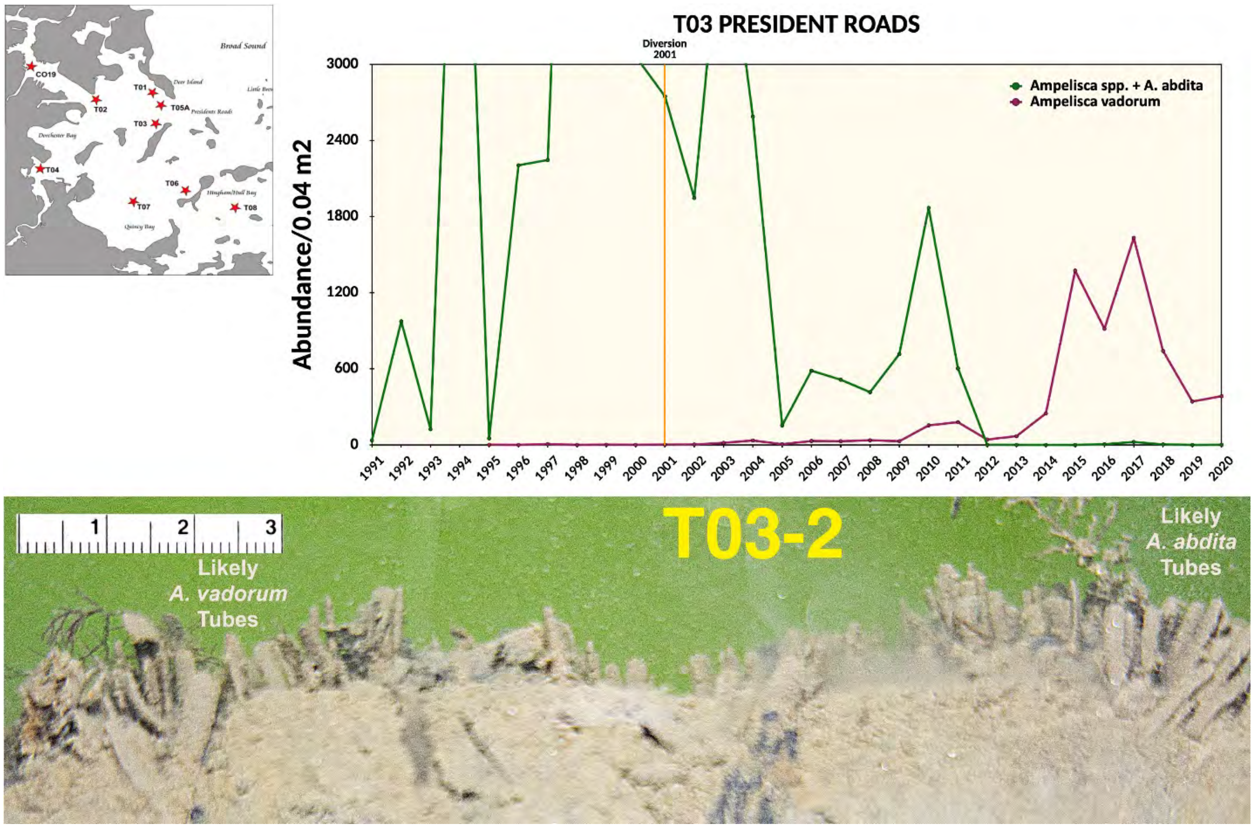

Figure 3-40. Shift in *Ampelisca* species from *A. abdita* to *A. vadorum* at Station T03 starting in 2014. Tubes of *A. abdita* are longer and thinner than *A. vadorum*.

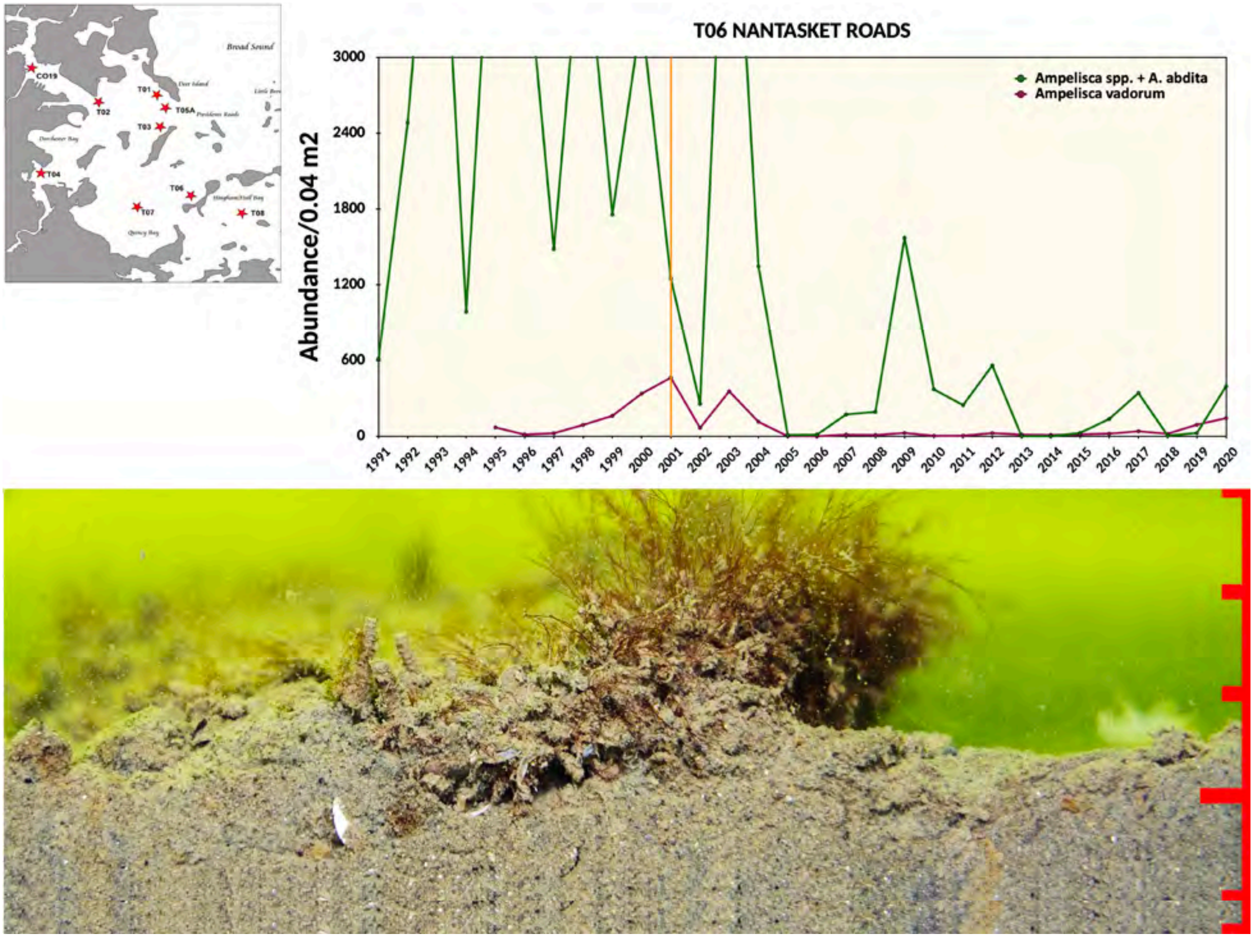

Figure 3-41. Continued dominance of *Ampelisca abdita* tubes at Station T06.

SPI Summary

Benthic habitats continue to reflect good ecological conditions across Boston Harbor. The inner to outer harbor habitat quality gradient remains prominent primarily due to hydrodynamics and secondarily to sediment grain-size.

Overall habitat conditions for 2020 trended higher relative to 2019, as measured by the Organism Sediment Index (OSI). OSI trended up in most Harbor regions (Figure 3-24). This points to more biogenic structures associated with higher successional stage fauna (feeding voids, burrows, large infauna). The continued tendency for OSI to trend upward in recent years, particularly in western harbor regions could be related to a continuing oxidation of sediments, and decline in organic inputs and primary production. Relative to 2019, Inner Harbor regions had the largest gains in OSI, followed by Hull Bay.

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 2020 exhibited minor changes from recent years but were consistent with longer-term trends (Rutecki et al. 2020a). 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 2020 survey are consistent with the recovery of benthic habitats from decades of inadequately treated sewage discharges.

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