2019 Boston Harbor Benthic Monitoring Report

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2019 Boston Harbor Benthic Monitoring Report

Submitted to

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EXECUTIVE SUMMARY

Boston Harbor was once considered among the most degraded urban estuaries in the country. Direct discharge of wastewater with limited treatment into the harbor had affected both water quality and ecological conditions. Both the EPA and the Courts prevailed upon the Commonwealth of Massachusetts to take actions to improve these conditions substantially and the Massachusetts Water Resources Authority (MWRA) was created in response. In 1985, MWRA initiated a multi-faceted plan to meet these mandates, most significantly including an upgrade to secondary treatment, elimination of sludge disposal into the harbor, and relocation of wastewater discharge through an offshore outfall located 9.5 miles off Deer Island in Massachusetts Bay. Subsequently, improvements have been made to numerous Combined Sewer Overflows (CSOs) reducing another source of water quality concern.

Conditions in the sediments and the associated benthic infaunal community reflect cumulative water quality exposures. In order to evaluate changes to the ecosystem, particularly the benthic community, resulting from reductions in contaminated discharges over time, MWRA has conducted benthic monitoring in Boston Harbor on an ongoing basis since 1991. This report provides a summary of the results of the benthic surveys that were conducted in 2019. These include sediment conditions, benthic infauna, and sediment profile imagery.

Overall, the improvements in wastewater treatment and moving the outfall offshore have led to improvements in water quality and benthic habitat quality within Boston Harbor by reducing organic and nutrient loading. These reductions have enabled processes that enhance the mixing of sediment by organisms. At one time, the sediment organic matter in Boston Harbor was derived primarily from sewage but once changes in wastewater treatment and disposal were initiated, marine-derived organic material has become prevalent in the sediment. The infaunal community has responded to this change and subsequent biological activity has led to more aerobic and 'healthy' sediment conditions. Physical and biological properties of the soft substrate in Boston Harbor in 2019 exhibited normal year-year variability but were consistent with longer-term trends (Rutecki et al. 2019a). Concentrations of both total organic carbon (TOC) and *Clostridium perfringens*, indicators of organic enrichment and deposition from municipal wastewater discharge, have remained low compared to the levels occurring in the early 1990s.

Community structure measures also continue to point to improving benthic conditions. As municipal wastewater and sludge discharges were eliminated from the harbor, total abundance has trended downward, particularly for opportunistic species such as *Capitella capitata*, reaching a fairly stable level for about the last decade. Species richness, while variable, has trended upward as 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 relate more to normal physical disturbances than organic stress in the years since wastewater impacts to the Harbor have been reduced. The trends observed in previous years, including reduction of indicators of organic enrichment and increases in species diversity that continued in the 2019 survey 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. Both the EPA and the Courts prevailed upon the Commonwealth of Massachusetts to take actions to improve these conditions substantially and the Massachusetts Water Resources Authority (MWRA) was created in response. In 1985, MWRA initiated a multi-faceted plan to meet these mandates, most significantly including an upgrade to secondary treatment, elimination of sludge disposal into the harbor, and relocation of wastewater discharge through an offshore diffuser located 9.3 mi off Deer Island in Massachusetts Bay. In 2015, MWRA and its member communities completed a series of 35 projects intended to eliminate or minimize the impacts of Combined Sewer Overflows (CSOs) to Boston Harbor and its tributaries (Kubiak et al. 2016).

MWRA has conducted benthic monitoring in Boston Harbor on an ongoing basis since 1991 to evaluate changes to the ecosystem, in particular the benthic community, as contaminated discharges have been reduced over time. This report provides a summary of the results of the benthic surveys that were conducted in 2019. These include sediment conditions, benthic infauna, and sediment profile imagery. An omission in the 2018 data was noticed during the 2019 benthic survey analyses, Appendix A presents a description of the omission and revised tables and figures for the 2018 Boston Harbor Benthic Monitoring Report.

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. (2019a) for previous monitoring years. Detailed descriptions of the methods are contained in the Quality Assurance Project Plan (QAPP) for Benthic Monitoring (Rutecki et al. 2017). 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 2019 (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 1, 2019.

SPI samples were collected in triplicate at 61 stations from August 4-5, 2019 (Figure 2-1).

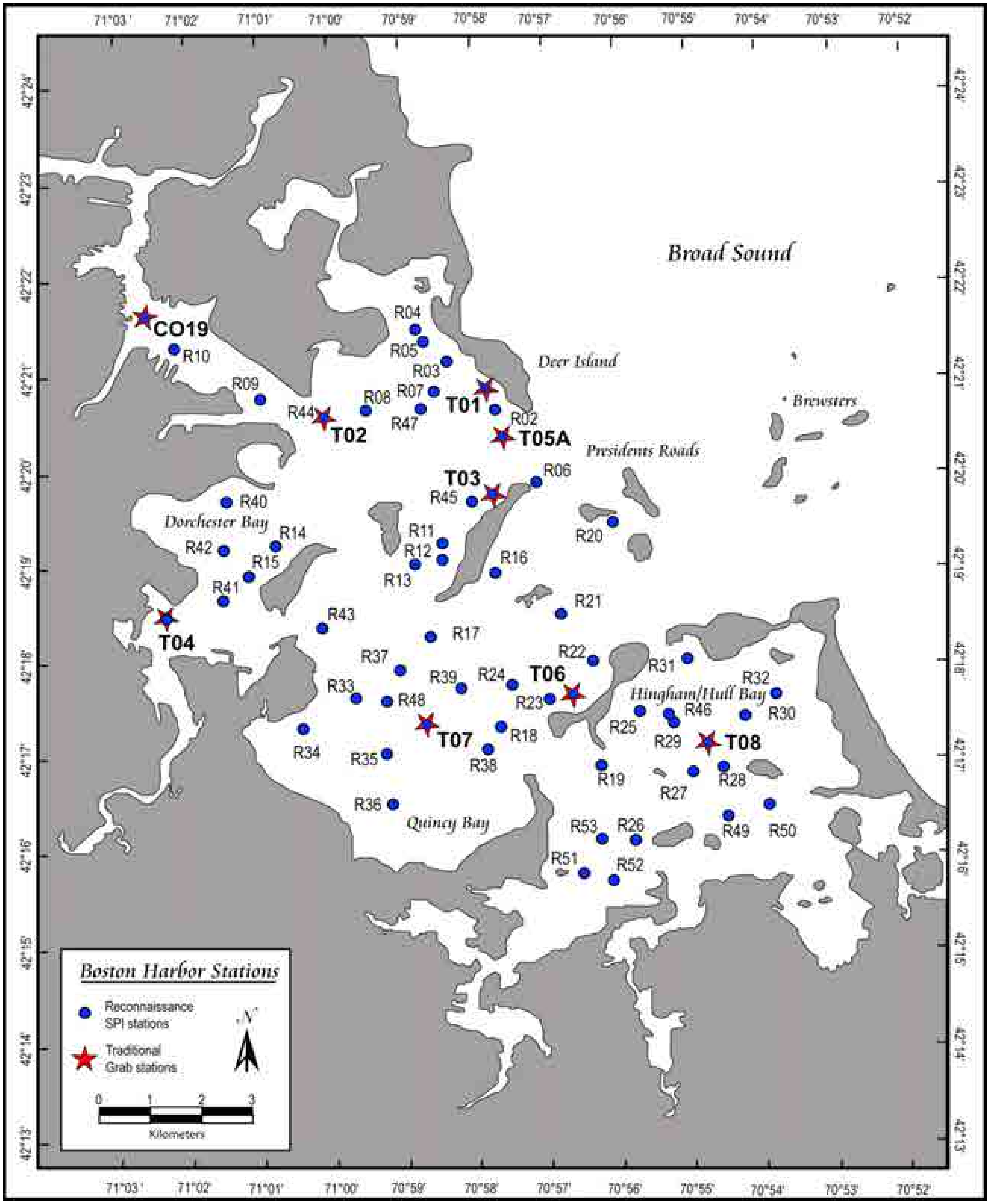


Figure 2-1. Locations of soft-bottom sampling and sediment profile imaging stations for 2019.

2.2 LABORATORY METHODS

Laboratory methods for benthic infauna and SPI image analyses were consistent with the QAPP (Rutecki et al. 2017). Two of the infauna samples were randomly selected for processing, while the third was archived. Analytical methods for grain size, TOC, and *Clostridium perfringens* are described in (Constantino et al. 2014).

2.3 DATA HANDLING, REDUCTION, AND ANALYSIS

All benthic data were extracted directly from the HOM database and imported into Excel. Data handling, reduction, and graphical presentations were performed in Excel or SAS (version 9.3), as described in the QAPP (Rutecki et al. 2017) or in Maciolek et al. (2008). Data are presented graphically as means (averages per station) unless otherwise noted. Shannon-Weiner (H') was calculated using log base 2. Multivariate analyses were performed using PRIMER v6 (Plymouth Routines in Multivariate Ecological Research) software to examine spatial patterns in the overall similarity of benthic assemblages in the survey area (Clarke 1993, Warwick 1993, Clarke and Green 1988). These analyses included classification (cluster analysis) by hierarchical agglomerative clustering with group average linking and ordination by non-metric multidimensional scaling (MDS). Bray-Curtis similarity was used as the basis for both classification and ordination. Prior to analyses, infaunal abundance data were fourth-root transformed to ensure that all taxa, not just the numerical dominants, would contribute to similarity measures.

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

Temporal patterns in the infaunal community and sediment chemistry were evaluated in the context of the four discharge periods described by Taylor (2006). 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 grab samples. 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) (The R Foundation for Statistical Computing at: https://www.r-project.org/foundation/).

3. RESULTS AND DISCUSSION

3.1 SEDIMENT CONDITIONS

Sediment conditions in Boston Harbor were characterized in 2019 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 2019 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 (T01, T05A, T06, and T08) generally had more than 50% sand with varying fractions of silt-clay. Outer harbor stations T02 and T07 had nearly equal proportions of sand and silt-clay. Grain size has been variable at Station T03, in the lee of Long Island, having more fines than sand from 2017 through 2019 but more sand in 2016. The grain size composition at each station in 2019 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 2019 were generally similar to 2018, remaining within the ranges reported in prior years (Figure 3-3). Higher TOC values were generally associated with higher percent fine sediments (silt + clay; Figures 3-2 and 3-3). During 2019, 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 2019 are consistent with this trend. The lowest TOC concentrations for 2019 were reported at Stations T01, T05A, and T08 which have predominantly sand sediments.

***Clostridium perfringens*.** Spores of *Clostridium perfringens*, an anaerobic bacterium found in the intestinal tract of mammals, provide a sensitive tracer of effluent solids. Abundances of *C. perfringens* (normalized to percent fines) during 2019 (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, have exhibited the highest variability among years. After a period of decline from 2008-2012, followed by an increase in 2013 and 2014, *C. perfringens* counts at T04 decreased again in 2015-2017, then increased in 2018, and remained steady in 2019 (Figure 3-4). Normalized *C. perfringens* counts at Station T08 were considerably higher in 2016 than in 2017-2019; this was largely an artifact of the atypically low percent fines at T08 in 2016. Except at Inner Harbor station C019, *C. perfringens* counts at other Harbor stations have remained consistently below historical averages since around 1999 (Figure 3-4).

Table 3-1. Monitoring results for sediment condition parameters in 2019.

Parameter		C019	T01	T02	T03	T04	T05A	T06	T07	T08
Grain Size	Gravel (%)	0	9.1	0	0	0	0	0	0	1.2
	Sand (%)	3.8	73.6	48.8	38.6	6.8	85.2	72.7	48.6	95.6
	Silt (%)	62.7	13.3	33.3	41.4	72.5	9.7	18.2	31.9	1.8
	Clay (%)	33.5	4.0	17.8	20.0	20.8	5.1	9.1	19.4	1.5
	Percent Fines (Silt + Clay)	96.2	17.3	51.2	61.4	93.3	14.8	27.3	51.4	3.3
Total Organic Carbon	TOC (%)	2.2	0.4	1.1	2.1	3.9	0.3	1.1	2.0	0.2
Clostridium perfringens	Not Normalized	2730.0	238.0	449.0	1390.0	4410.0	519.0	0.0	776.0	93.1
	Normalized (cfu/g dry/%fines)	28.4	13.8	8.8	22.7	47.3	35.0	0.0	15.1	28.7

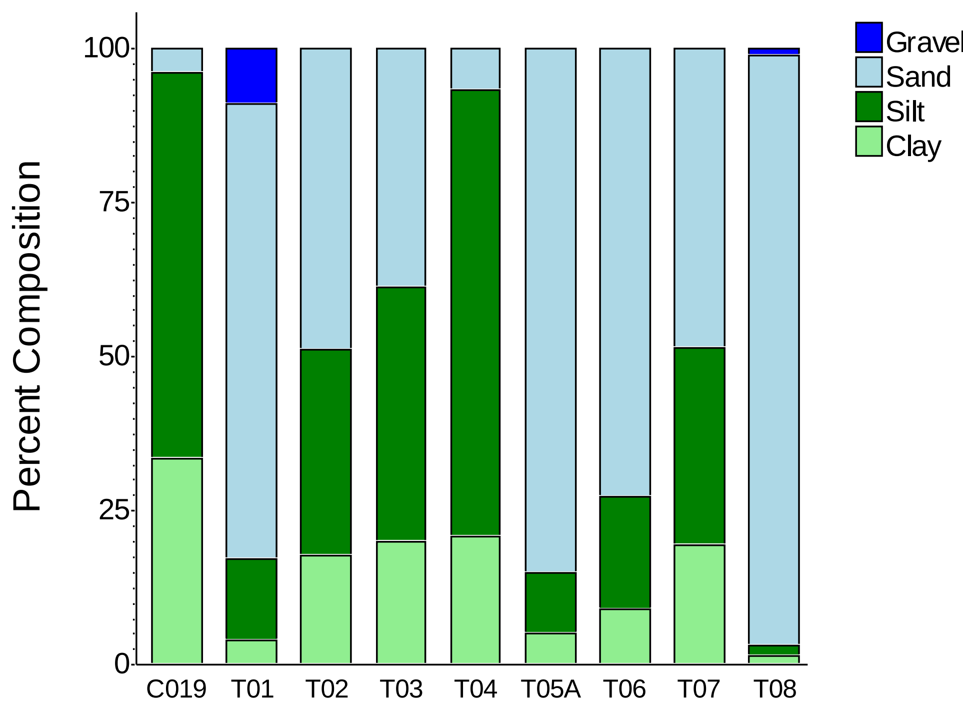


Figure 3-1. Monitoring results for 2019 sediment grain size in Boston Harbor.

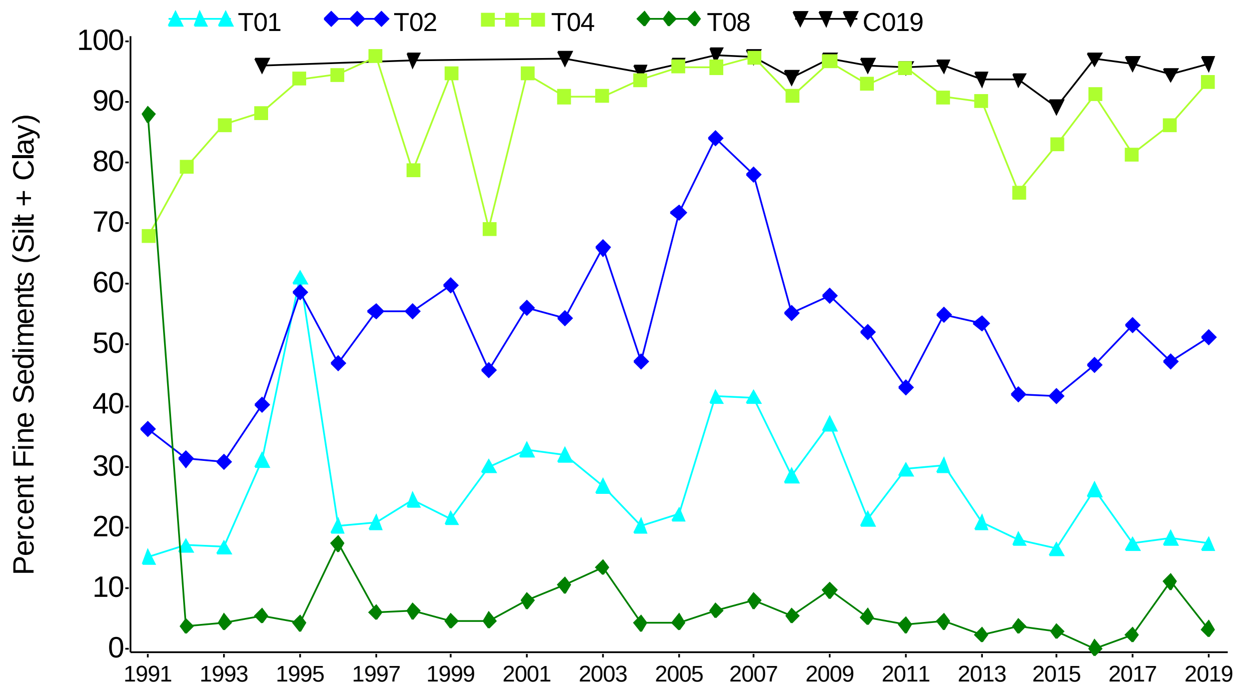


Figure 3-2. Mean percent fine sediments at five stations in Boston Harbor, 1991 to 2019.

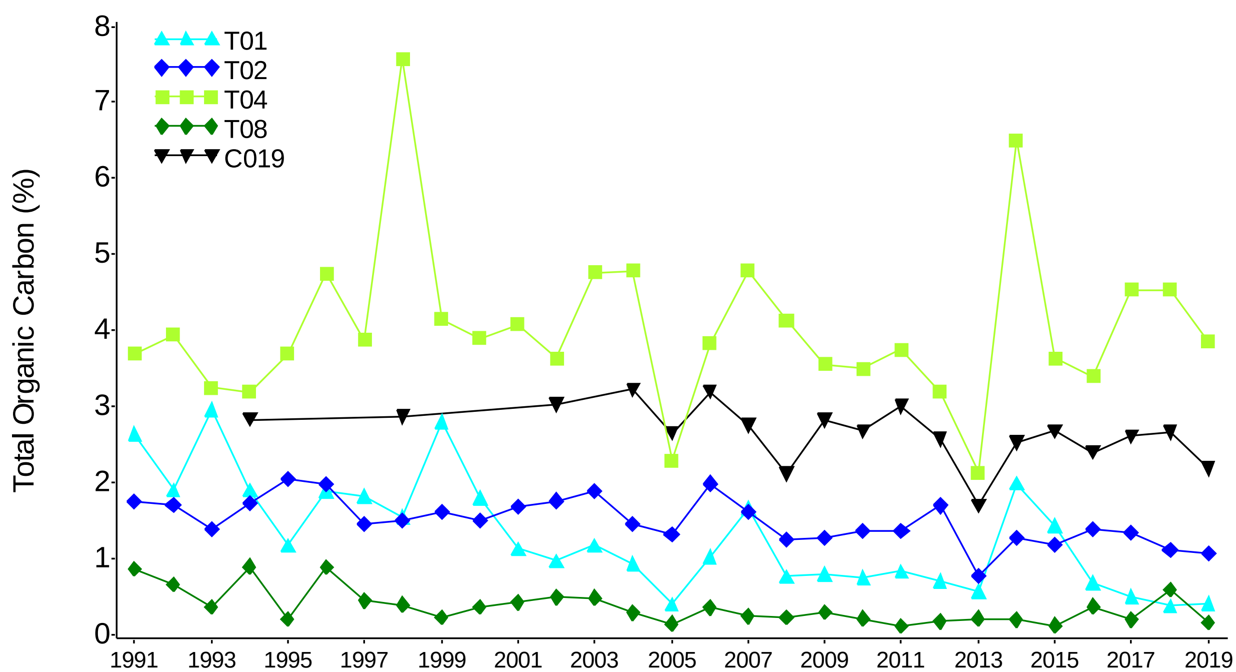


Figure 3-3. Mean concentrations of TOC at five stations in Boston Harbor, 1991 to 2019.

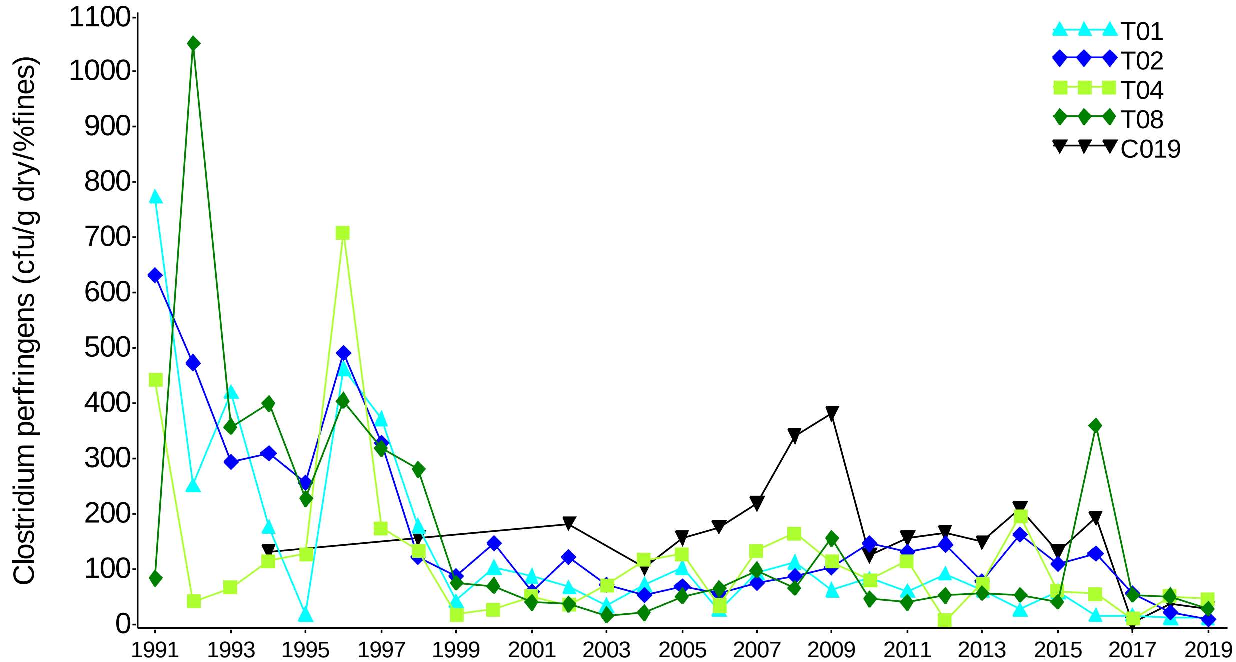


Figure 3-4. Mean normalized concentrations of *Clostridium perfringens* at five stations in Boston Harbor, 1991 to 2019.

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

Results during 2019 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. 2019a). 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 five-year segments and the 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).

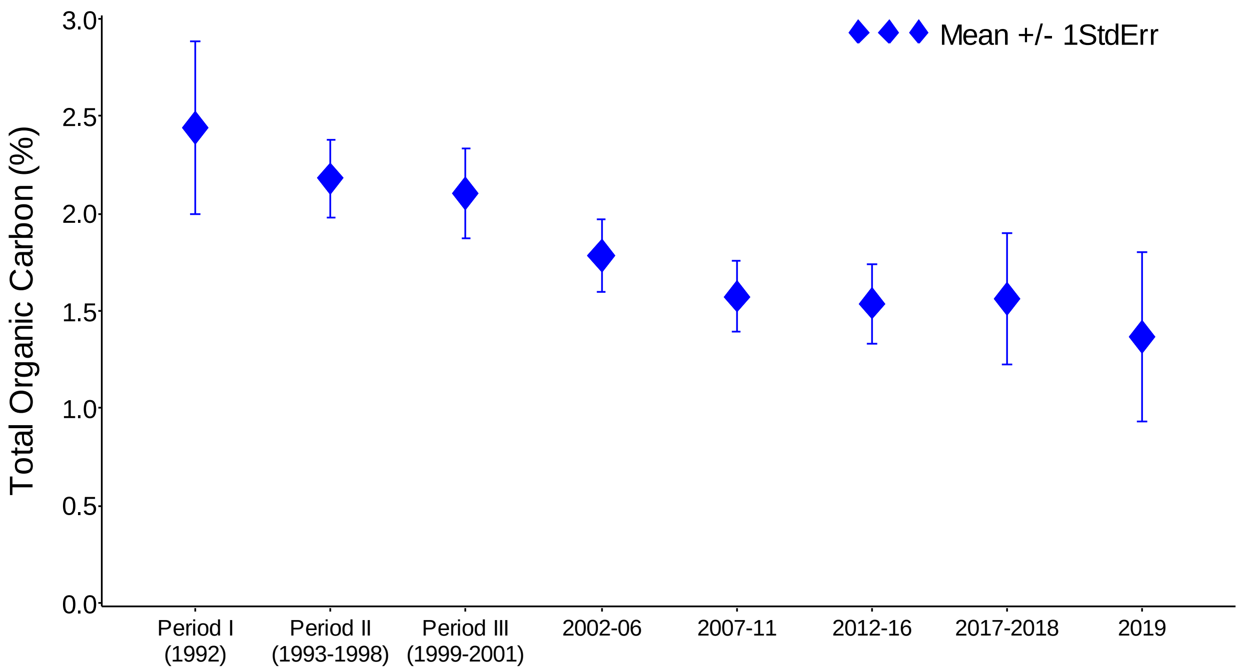


Figure 3-5. Comparison of TOC across time periods (offset by one year) at Boston Harbor stations (T01-T08) from 1992 to 2019 (1991 excluded).

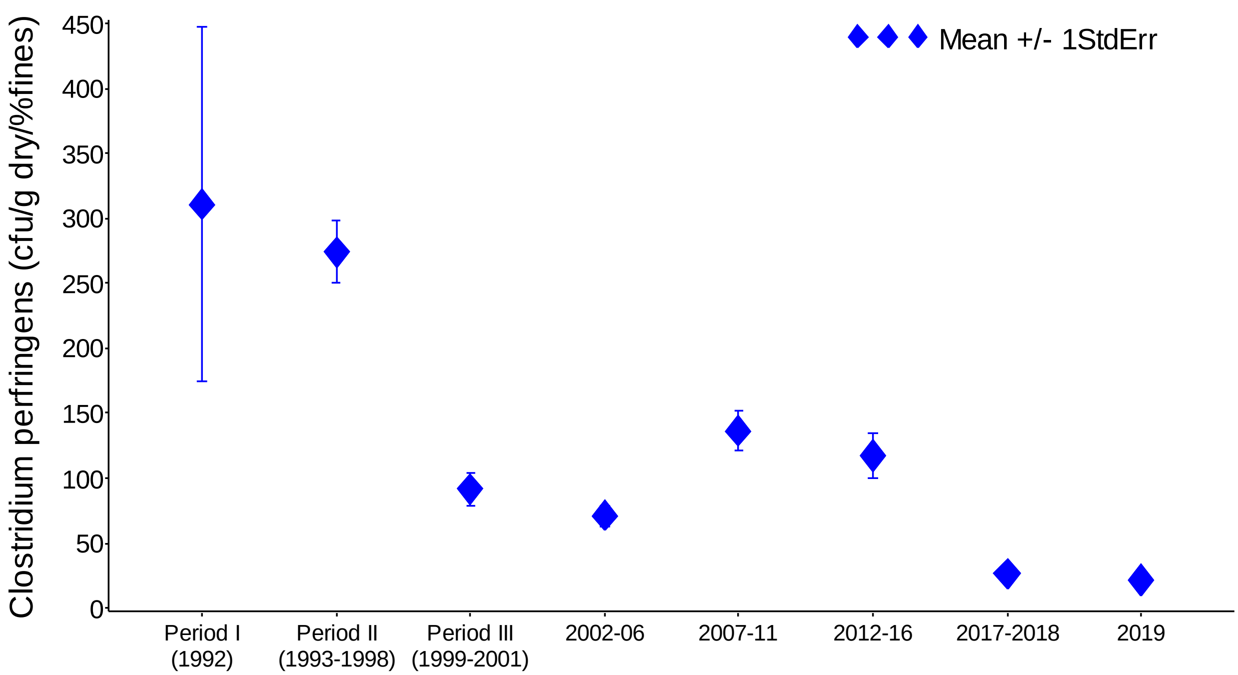


Figure 3-6. Comparison of *Clostridium perfringens* across time periods (offset by one year) at Boston Harbor stations (T01-T08) from 1992 to 2019 (1991 excluded).

3.2 BENTHIC INFAUNA

3.2.1 Community Parameters

A total of 34,252 infaunal organisms were counted from the 18 samples processed in 2019. Organisms were classified into 160 discrete taxa, 143 of which were species-level identifications. More than 98% 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 2019 infaunal community parameters by station.

Station	Total Abundance	Number of Species	Pielou's Evenness (J')	Shannon-Wiener Diversity (H')	Log-series alpha
C019	552.5	18.0	0.56	2.33	3.58
T01	2,146.5	50.0	0.61	3.44	9.17
T02	1,797.0	47.0	0.56	3.12	8.86
T03	2,755.5	51.0	0.59	3.32	8.92
T04	1,954.0	15.5	0.23	0.88	2.30
T05A	1,825.5	56.0	0.67	3.91	10.97
T06	3,871.0	51.5	0.53	3.03	8.48
T07	774.0	23.0	0.47	2.12	4.46
T08	1,450.0	52.0	0.47	2.67	10.80

At most stations mean total abundance values reported for 2019 were lower than values in 2018. Decreases in mean abundance were observed at five stations (C019, T01, T02, T03, and T05A) and ranged from 13 to 58% (Appendix A). Station T06 exhibited an increase in mean abundance of 16% and Station T07 an increase of 88%. Station T07 typically has low infaunal abundance. Station T08 increased by more than 2 times the mean abundance observed in 2018 (Appendix A). Abundances in 2019 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 2019 each contributed 4.0% or more of the animals counted, and together they provided 75% 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 2019 (Table 3-3) although the rank order changed. The tube-dwelling amphipod *Ampelisca* spp. continued to decline in 2019 compared to 2017 and 2018, and was not in the eight most abundant species in 2019. Six species of polychaetes were among the most abundant taxa in 2019. The five most abundant taxa in 2019 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

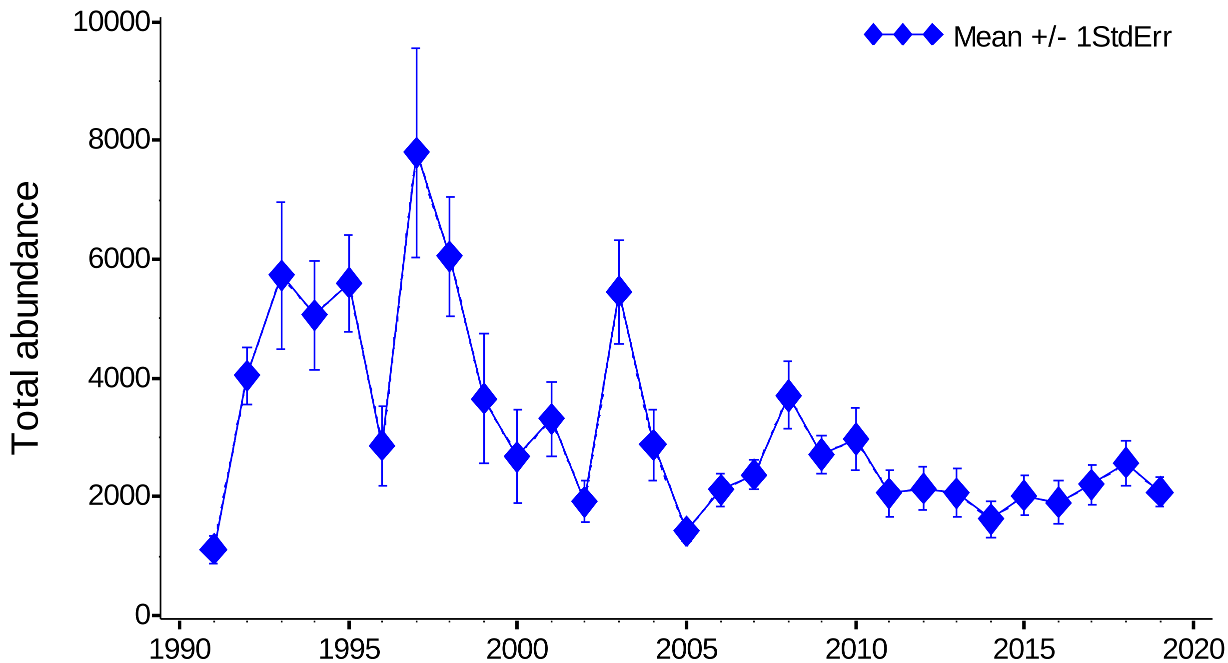


Figure 3-7. Mean abundance of benthic infauna at eight Boston Harbor stations (T01-T08), 1991-2019.

Table 3-3. Dominant taxa at eight grab stations (T01-T08) in Boston Harbor in August 2019.

Taxon	**Total 2019 Abundance (compared with 2018)[a]**
Aricidea catherinae	5,997 (similar)
Polydora cornuta	3,879 (decrease)
Streblospio benedicti	3,471 (similar)
Limnodriloides medioporus	3,260 (similar)
Tubificoides intermedius	2,710 (similar)
Tharyx acutus	2,103 (increase)
Scoletoma hebes	1,985 (similar)
Bipalponephtys neotena	1,415 (increase)

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

consistent with previous years; T07 and C019 continued to support low infaunal abundances (Table 3-2). As previously observed, Station T03 supported among the highest abundances among the harbor stations, although Station T06 had the highest abundance in 2019.

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. *Aricidea catherinae* and *Limnodriloides medioporus* have exhibited little interannual variation in abundance whereas both *Polydora cornuta* and *Ampelisca* spp. have exhibited fluctuations of one to two orders of magnitude, and abundances of both species are currently low. Both of these species reside in the upper substrate layer so variability could be related to many factors, including changes in organic enrichment, physical forces such as storm events, and reproductive success in a given year as was described in previous reports (Maciolek et al. 2006, 2011). It is noteworthy that abundances of the oligochaete *Tubificoides intermedius* (not shown) have steadily increased.

Table 3-4. Mean abundance per sample of dominant taxa during four discharge periods at eight Boston Harbor stations (T01-T08), 1992-2019.

Phylum	Higher taxon	Family	Species[a]	Period I	Period II	Period III	Period IV	2019
Annelida	Polychaeta	Capitellidae	*Capitella capitata* complex	65.2	88.8	3.4	6.2	7.5
		Cirratulidae	*Tharyx acutus*	50.6	111.8	52.4	57.1	131.4
		Lumbrineridae	*Scoletoma hebes*	3.4	10.5	4.2	78.0	124.1
		Nephtyidae	*Bipalponephtys neotena*[b]	-	11.4	10.3	170.5	88.4
		Paraonidae	*Aricidea catherinae*	325.0	237.4	204.3	247.7	374.8
		Spionidae	*Polydora cornuta*	525.8	1053.0	269.6	271.3	242.4
			Streblospio benedicti	236.0	298.6	27.7	93.0	216.9
	Oligochaeta	Tubificidae	*Limnodriloides medioporus*	484.7	297.9	315.2	235.3	203.8
			Tubificoides intermedius	42.6	101.4	231.2	239.4	169.4
Arthropoda	Amphipoda	Ampeliscidae	*Ampelisca* spp.	354.3	1698.3	1205.9	508.0	59.1
		Corophiidae	*Corophiidae* spp.	16.1	336.2	23.0	1.4	-
			Crassicorophium bonellii	7.9	217.3	37.3	6.8	0.3
			Leptocheirus pinguis	29.0	117.4	66.0	71.5	9.4
		Photidae	*Photis pollex*	11.4	77.0	86.8	27.9	0.9
		Phoxocephalidae	*Phoxocephalus holbolli*	28.0	116.9	125.9	6.0	3.9

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

[b]previously identified as *Nepthys cornuta.*

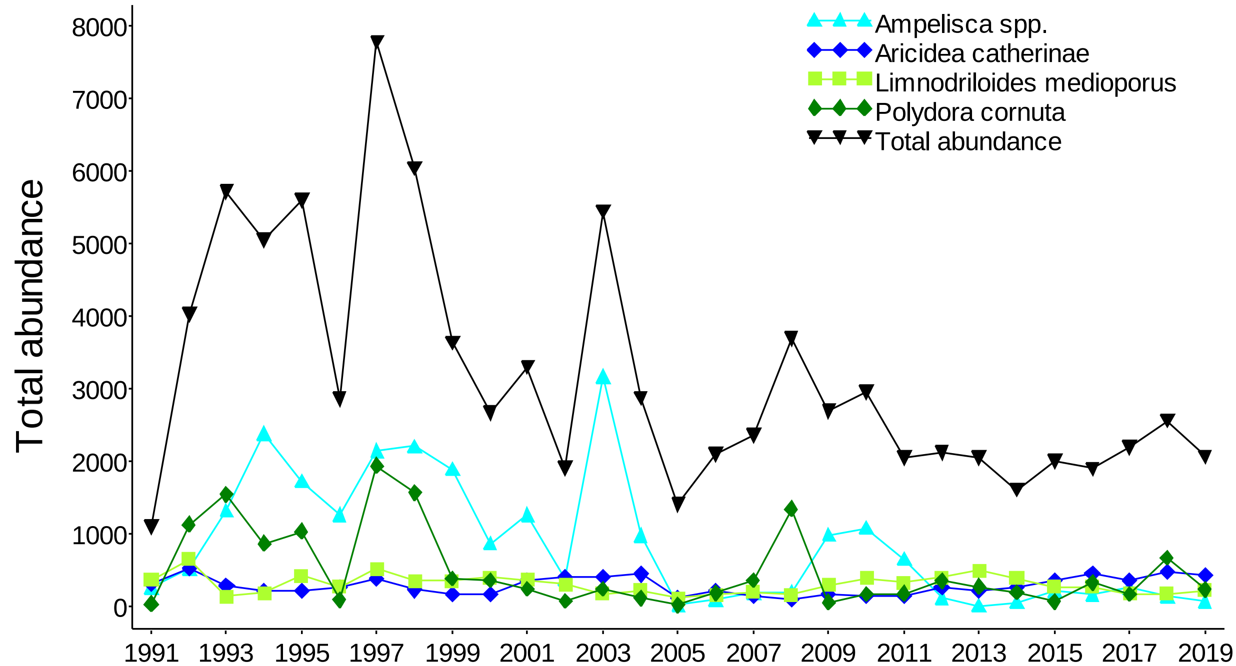


Figure 3-8. Total abundance of four dominant taxa at eight Boston Harbor stations (T01-T08), 1991-2019.

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. 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, declining in 2012-2014 to levels comparable to those seen in 2005-2008, and increased slightly in 2015 and 2017 (Figure 3-9). *Ampelisca* was more widespread in 2015 (seven stations) compared to 2014 (five stations) although in both years more than 90% of the population was found at Station T03 in the vicinity of the Main Ship Channel (Figure 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 could also have resulted in disturbances (sedimentation or substrate contact from anchored vessels) to stations T03 and T05A. Abundances at Station T06 increased in 2019 compared to 2018, but declined at Station T03. As observed in the past five years, Station T03 supported the largest population of this species.

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 predominate 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 has remained low through 2019 ranging from 0 to 20%. *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 2019 (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 are further discussed in Section 3.3.5 of this report.

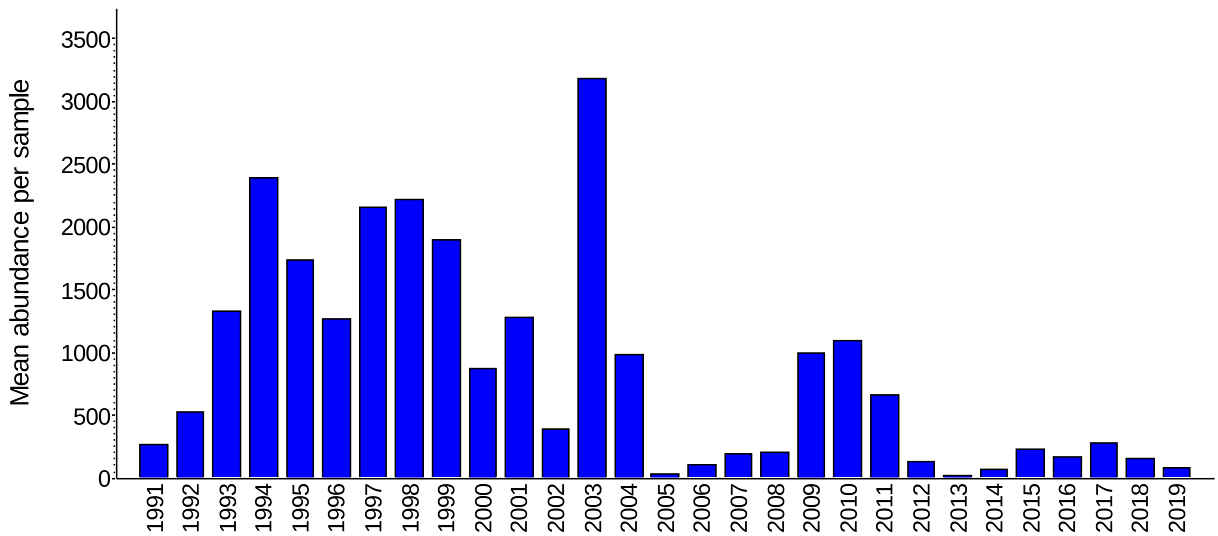


Figure 3-9. Mean annual abundance of *Ampelisca* spp. averaged over eight Boston Harbor stations (T01-T08), 1991-2019.

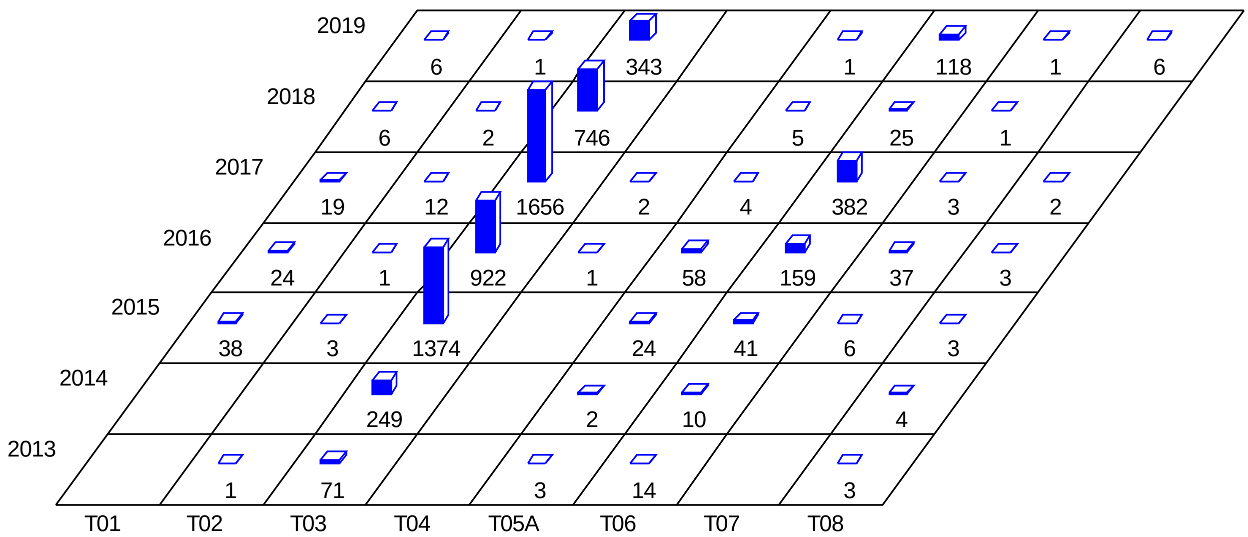


Figure 3-10. Spatial distribution of *Ampelisca* spp. at eight Boston Harbor stations (T01-T08), 2013-2019.

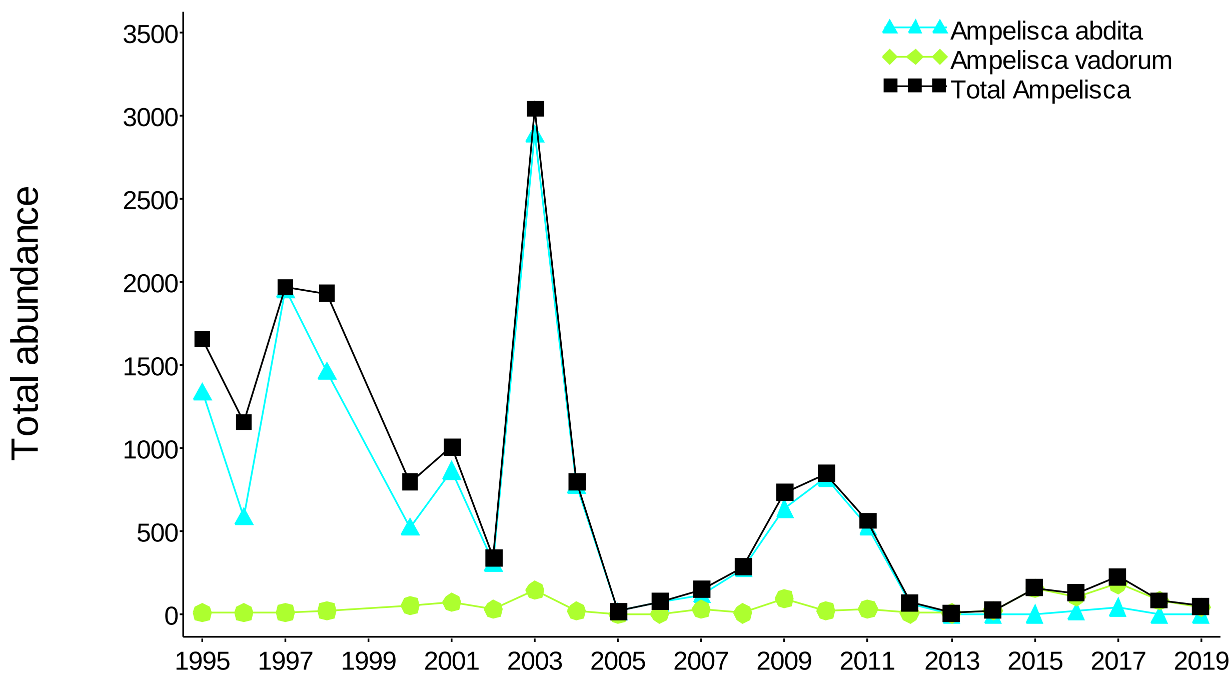


Figure 3-11. Mean total abundance of the two dominant *Ampelisca* taxa at eight Boston Harbor stations (T01-T08), 1995-2019.

The numbers of species reported for 2019 ranged from 15.5 to 56.0 per station and averaged 43 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 higher in 2019 than in 2018 (Figure 3-12). Stations T02, T03, and T08 were among the most species-rich stations from 2011 through 2018 (Appendix A); in 2019 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. Station T07 in Quincy Bay, showed unusual peaks in species richness in 2013 and 2016 (Pembroke et al. 2014, 2017), but exhibited more typical species richness in 2019.

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 2018, the 2019 value was the same as 2018. Average Shannon-Weiner diversity declined from 3.11 in 2015 to 2.76 in 2018; diversity increased slightly in 2019 to 2.81 (Figures 3-13 and 3-14, Table 3-2). Within each station, differences in these metrics between 2018 and 2019 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, increased in 2019 (8.0) compared to 2018 (7.5; Appendix A), and was well above pre-diversion values (1991-2000; Figure 3-15). The highest log-series alpha diversity occurred at T05A in 2019. Typically Stations T01 or T08 have the highest log-series alpha diversity in the Harbor. Consistent with recent patterns, log-series alpha diversity was lowest at T04 in 2019 (Table 3-2; Pembroke et al. 2017, Rutecki et al. 2019a, Appendix A). The largest change in log-series alpha compared to 2018 was the increase at T05A.

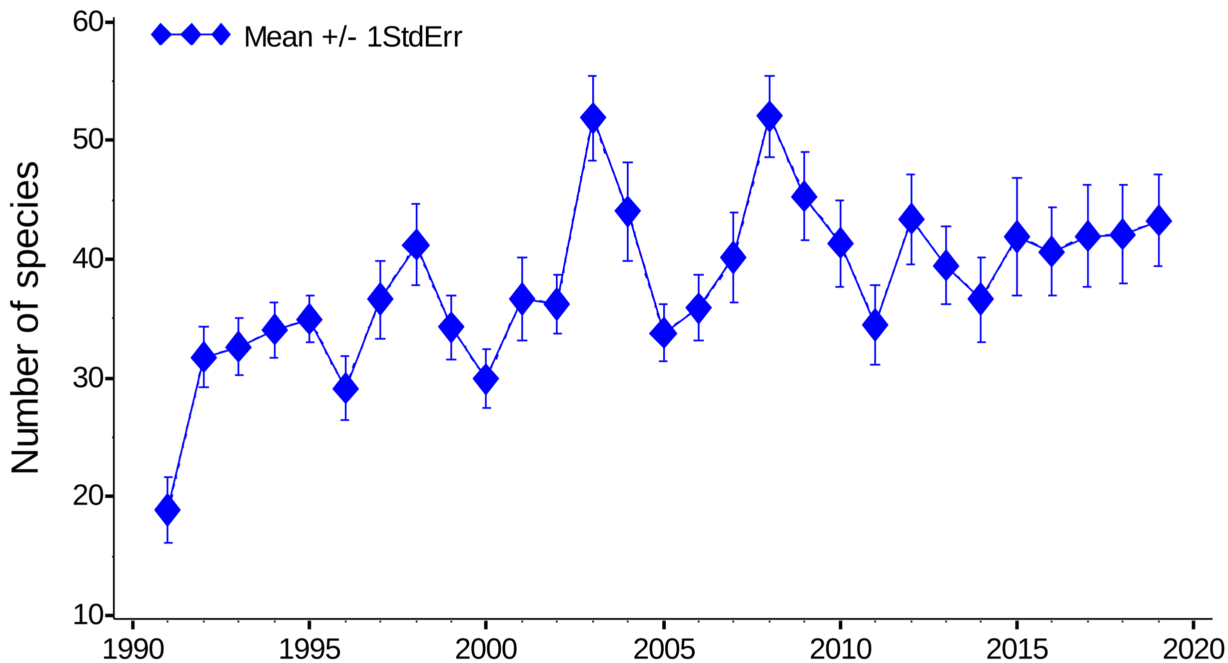


Figure 3-12. Mean species richness at eight Boston harbor stations (T01-T08), 1991-2019.

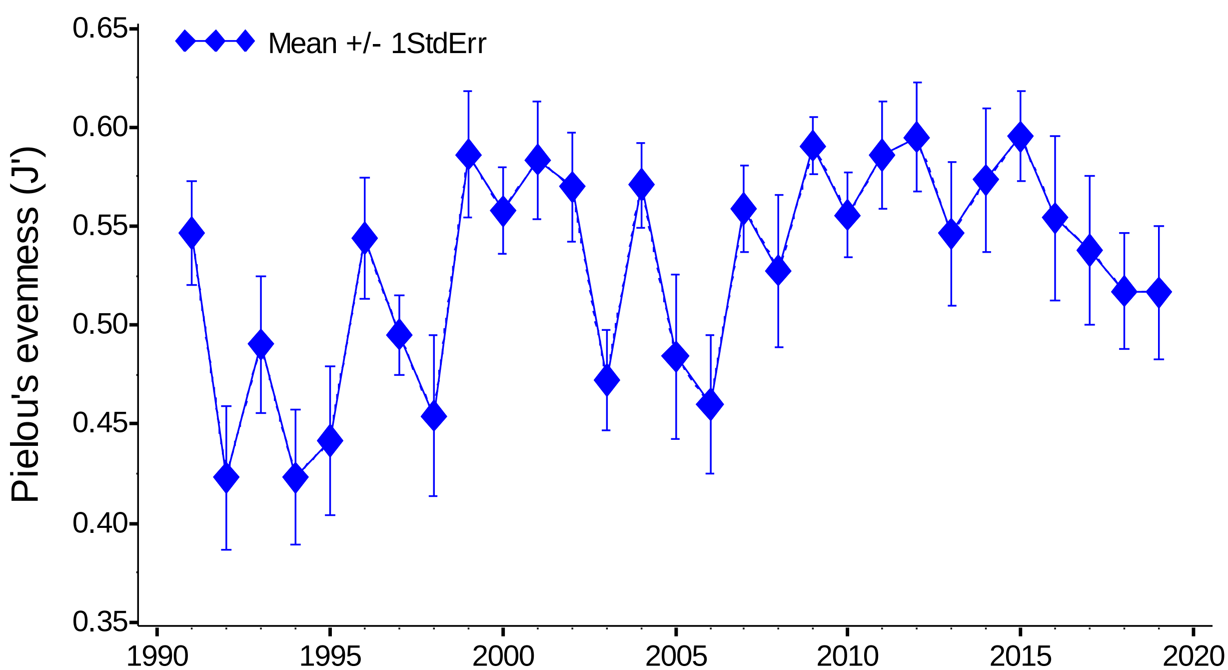


Figure 3-13. Mean community evenness at eight Boston Harbor stations (T01-T08), 1991-2019.

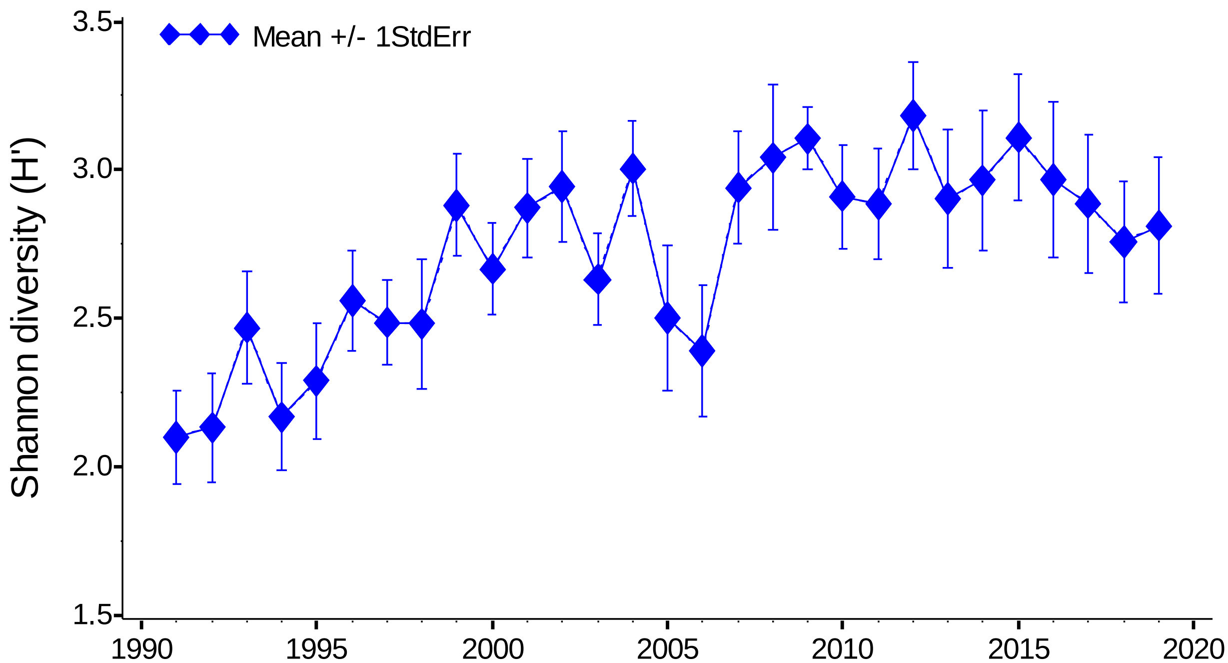


Figure 3-14. Mean Shannon-Weiner diversity at eight Boston harbor stations (T01-T08), 1991-2019.

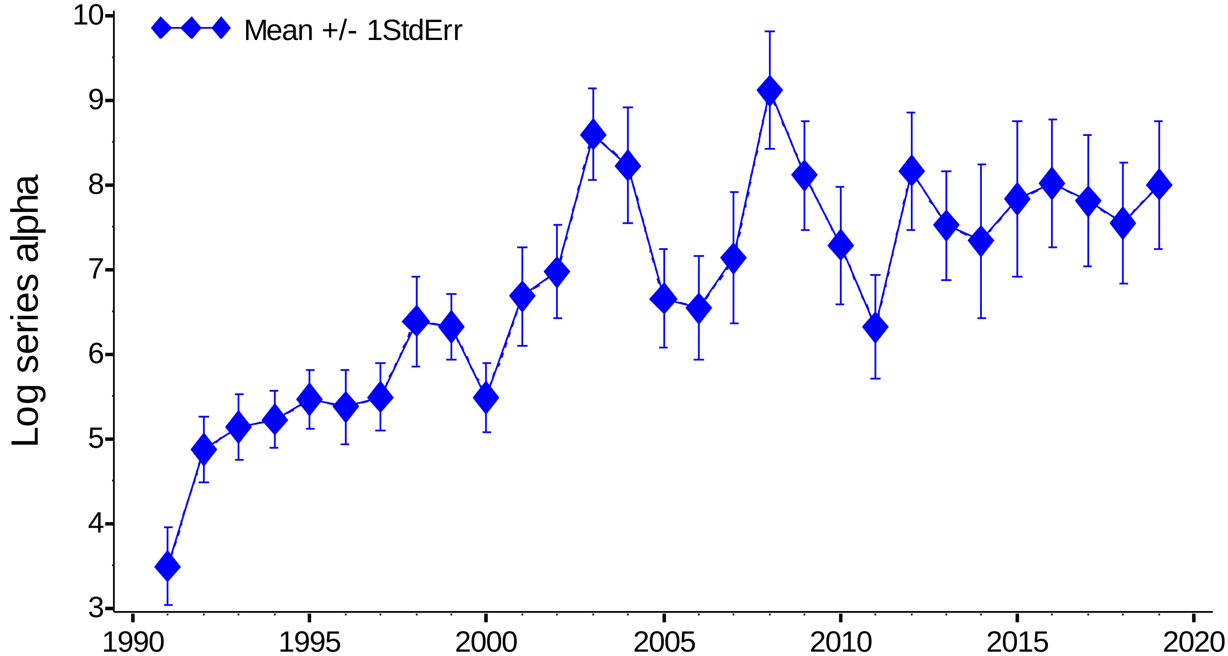


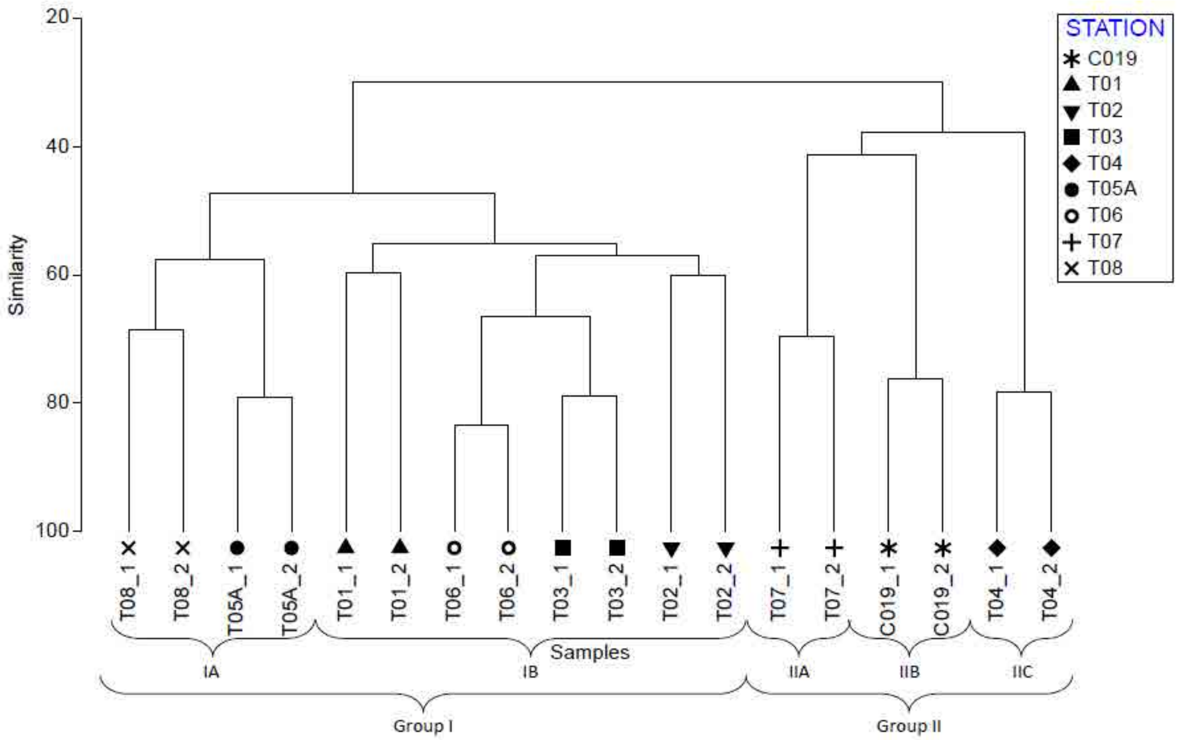
Figure 3-15. Mean log-series alpha diversity at eight Boston Harbor stations (T01-T08), 1991-2019.

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 2019 (Figure 3-16). Patterns identified through cluster analysis were confirmed in the MDS ordination plot for the 2019 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 2,308 individuals) and species richness (averaging 51 species per collection). Six species of polychaetes and oligocheates (*Aricidea catherinae*, *Polydora cornuta*, *Limnodriloides medioporus*, *Tubificoides intermedius*, *Tharyx acutus*, and *Scoletoma hebes*) had relatively high abundances (Table 3-5). Within Group I, Stations T05A and T08 were distinct enough to form Subgroup IA dominated by *T. acutus*, *P. cornuta, Ameritella agilis, and Polygordius jouinae* and were characterized by high species richness (averaging 54 species per collection). Subgroup IB was comprised of Stations T01, T02, T03, and T06 characterized by high abundance and species richness (averaging 50 species per collection). Dominants included *A. catherinae*, *L. medioporus*, *P. cornuta*, *T. intermedius*, and *S. hebes.* The main Group II consisted of Stations C019, T04, and T07 and were dominated by five species, *Streblospio benedicti*, *Bipalponephtys neotena*, *T. intermedius*, *Cossura* sp. 1 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 *B. neotena* and *T. intermedius*. This subgroup was characterized by low abundance and species richness (averaging 23 species per collection). Station C019 formed Subgroup IIB dominated by *Cossura* sp. 1 and *P. cornuta*; total abundance and species richness were low. Station T04 formed Subgroup IIC dominated by *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. Subgroup IA (T05A and T08) was predominantly sand and very low TOC. Sediments at stations in Subgroup IB ranged from approximately 39 to 74% sand and moderate to low TOC (0.4 to 2.1%). Sediments at Station T07 (Subgroup IIA) were approximately 51% fines with a moderate TOC (2.0%). Sediments at C019 (Subgroup IIB) were predominantly fines (96%) with a moderate TOC (2.2) and sediments at Station T04 (Subgroup IIC) were predominantly fines and TOC was higher than at other locations (Table 3-1).

a.



b.

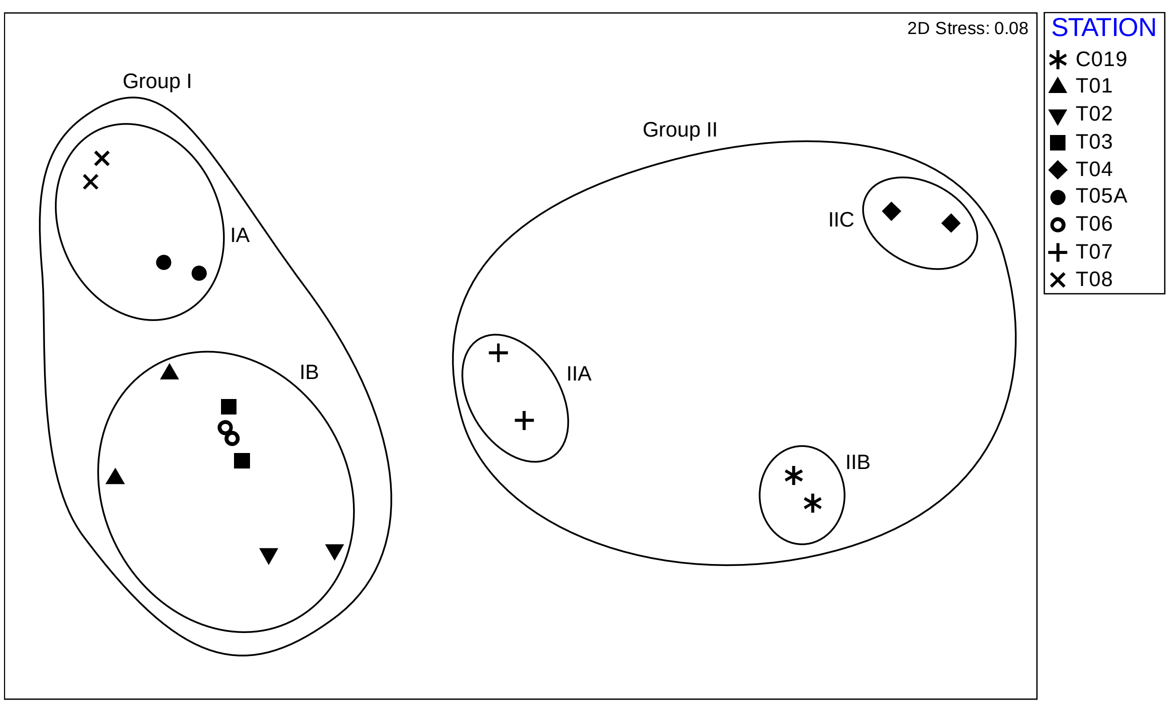


Figure 3-16. Results of (a) cluster analysis and (b) multidimensional scaling analysis of the 2019 infauna samples.

Table 3-5. Mean abundance of dominant taxa in 2019 Boston Harbor station groups defined by cluster analysis.

Major Taxon	Family	Species	I	IA[a]	IB[a]	II	IIA[b]	IIB[b]	IIC[b]
Bivalvia	Mactridae	*Mulinia lateralis*	**-**	0.5	-	**-**	-	1.5	6.5
	Tellinidae	*Ameritella agilis*	**76.5**	189.8	19.9	**5.5**	10.0	2.5	4.0
Polychaeta	Capitellidae	*Mediomastus californiensis*	**-**	3.8	7.9	**-**	0.5	3.0	-
	Cirratulidae	*Tharyx acutus*	**169.4**	466.3	21.0	**11.7**	31.5	-	3.5
	Cossuridae	*Cossura* sp. 1	**0.2**	-	0.3	**79.3**	-	238.0	-
	Hesionidae	*Microphthalmus pettiboneae*	**-**	8.8	4.3	**-**	0.5	4.5	1.0
	Lumbrineridae	*Scoletoma hebes*	**164.4**	3.8	244.8	**2.0**	6.0	-	-
	Maldanidae	*Clymenella torquata*	**70.8**	62.3	75.0	**-**	-	-	-
	Nephtyidae	*Bipalponephtys neotena*	**41.9**	1.8	62.0	**167.3**	394.0	46.0	62.0
		Nephtys incisa	**6.3**	3.5	7.8	**6.3**	-	12.5	6.5
	Orbiniidae	*Leitoscoloplos robustus*	**-**	3.3	5.0	**-**	6.5	0.5	-
	Paraonidae	*Aricidea catherinae*	**498.8**	10.3	743.0	**2.3**	6.0	1.0	-
	Polygordiidae	*Polygordius jouinae*	**-**	183.0	0.5	**-**	0.5	-	0.5
	Spionidae	*Dipolydora quadrilobata*	**-**	-	53.6	**-**	-	-	-
		Polydora cornuta	**308.7**	284.0	321.0	**78.8**	33.5	149.0	54.0
		Spiophanes bombyx	**-**	36.3	2.6	**-**	-	-	-
		Streblospio benedicti	**6.5**	1.8	8.9	**576.2**	12.5	32.0	1684.0
	Terebellidae	*Polycirrus phosphoreus*	**-**	0.8	1.0	**-**	-	7.0	-
Oligochaeta	Tubificidae	*Limnodriloides medioporus*	**267.1**	7.8	396.8	**9.2**	27.5	-	-
		Naidinae sp. 1	**67.8**	86.5	58.5	**2.5**	6.5	-	1.0
		Tubificoides benedeni	**-**	17.8	-	**-**	-	-	-
		Tubificoides intermedius	**190.5**	57.3	257.1	**84.3**	212.0	41.0	-
		Tubificoides sp. 2	**-**	-	-	**39.3**	-	-	118.0
Amphipoda	Ampeliscidae	*Ampelisca* spp.	**78.8**	3.0	116.6	**0.2**	0.5	-	-
	Aoridae	*Grandidierella japonica*	**-**	-	-	**-**	-	-	4.5
		Microdeutopus anomalus	**-**	0.5	7.0	**-**	6.5	-	-
	Corophiidae	*Monocorophium insidiosum*		-	0.1		0.5	-	1.5
Isopoda	Idoteidae	*Edotia triloba*	**-**	32.3	1.1	**-**	-	-	-

[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 2019, species richness, Shannon-Weiner diversity, evenness, and log-series alpha were high at T01. All of these community parameters increased slightly compared to 2018 but remained within the ranges of values recorded in recent years (Appendix A). Mean abundance in 2019 decreased compared to 2018 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 2019, 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 (868) levels in 2018 (1,165), and then declined in 2019 to 552.5 (Figure 3-17, Table 3-2). Species richness also peaked in 2013, decreased in both 2014 and 2015, and has fluctuated near average levels (17.6) since 2016 with a slight decrease in 2019 compared to the previous year (Figure 3-18). Log series alpha reached its peak value in 2014, declined from 2015 through 2017, and increased in 2018 and 2019 (Figure 3-19). Shannon-Weiner diversity also peaked in 2014, declined from 2015 through 2017, increased slightly in 2018 and then declined in 2019 but remained above the average value (1.8; Figure 3-20). Pielou's evenness reached its peak value in 2014, declined in 2015 and 2016, increased in 2017, and then declined in 2018 and 2019 but remained above the average value (0.42; Figure 3-21). Despite decreasing values in some recent years, the diversity measures remained among the highest levels observed to date. The polychaete *Bipalponephtys neotena* (formerly called *Nepthys cornuta*) 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 2019. *P. cornuta* and *B. neotena*, respectively, were the next two dominant taxa in the infaunal community in 2019 (Figure 3-22, Table 3-5).

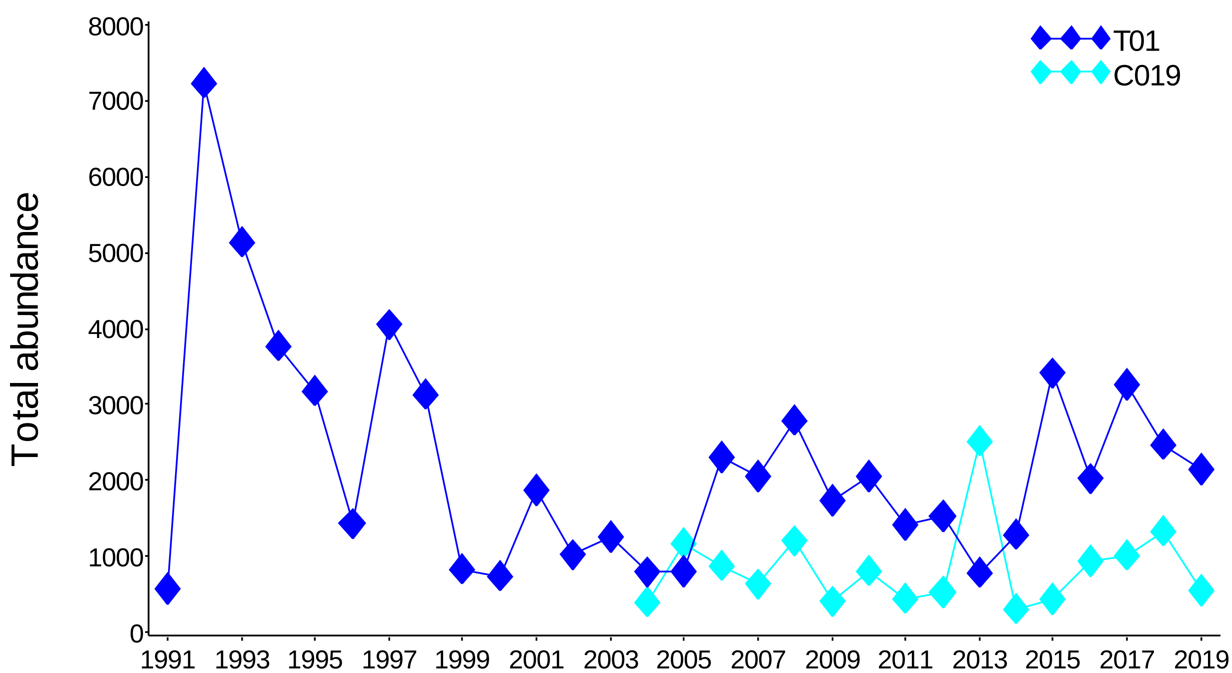


Figure 3-17. Mean total abundance at Boston Harbor Stations T01 and C019, 1991-2019.

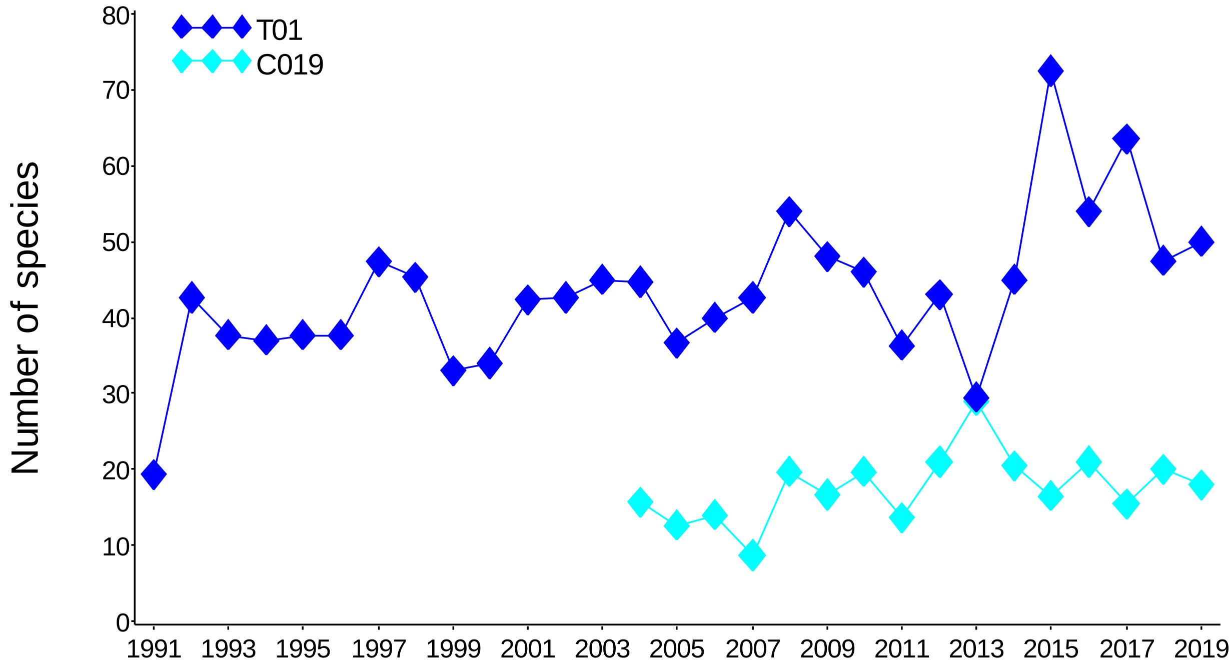


Figure 3-18. Mean species richness at Boston Harbor Stations T01 and C019, 1991-2019.

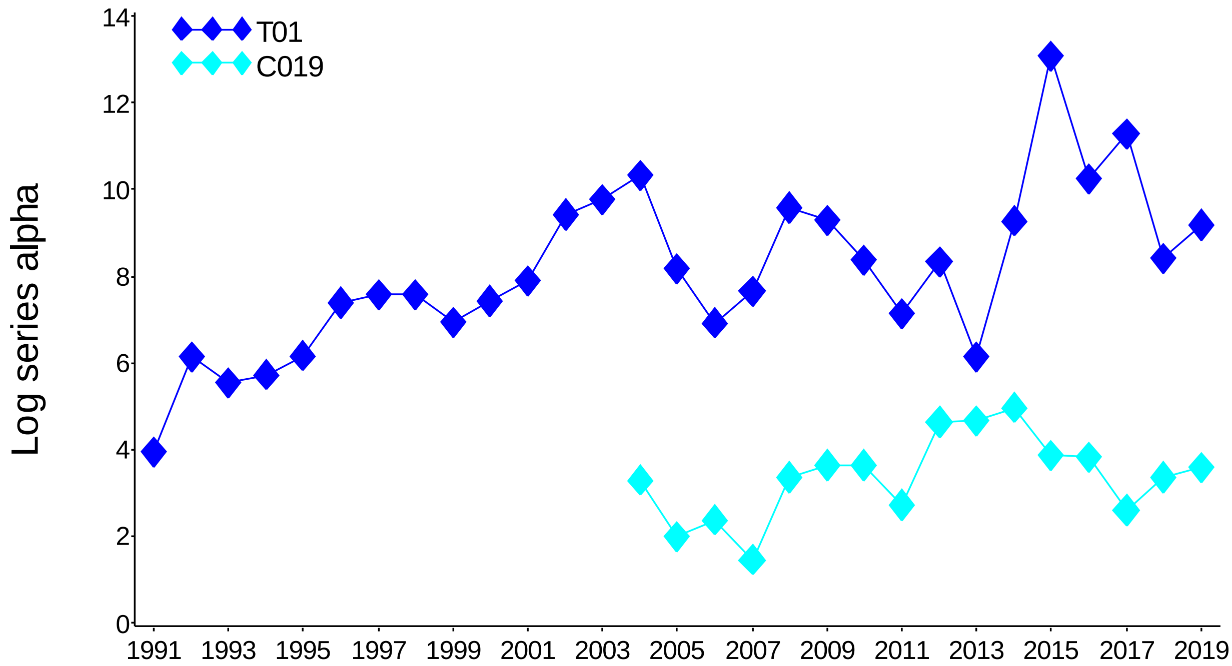


Figure 3-19. Mean log-series alpha diversity at Boston Harbor Stations T01 and C019, 1991-2019.

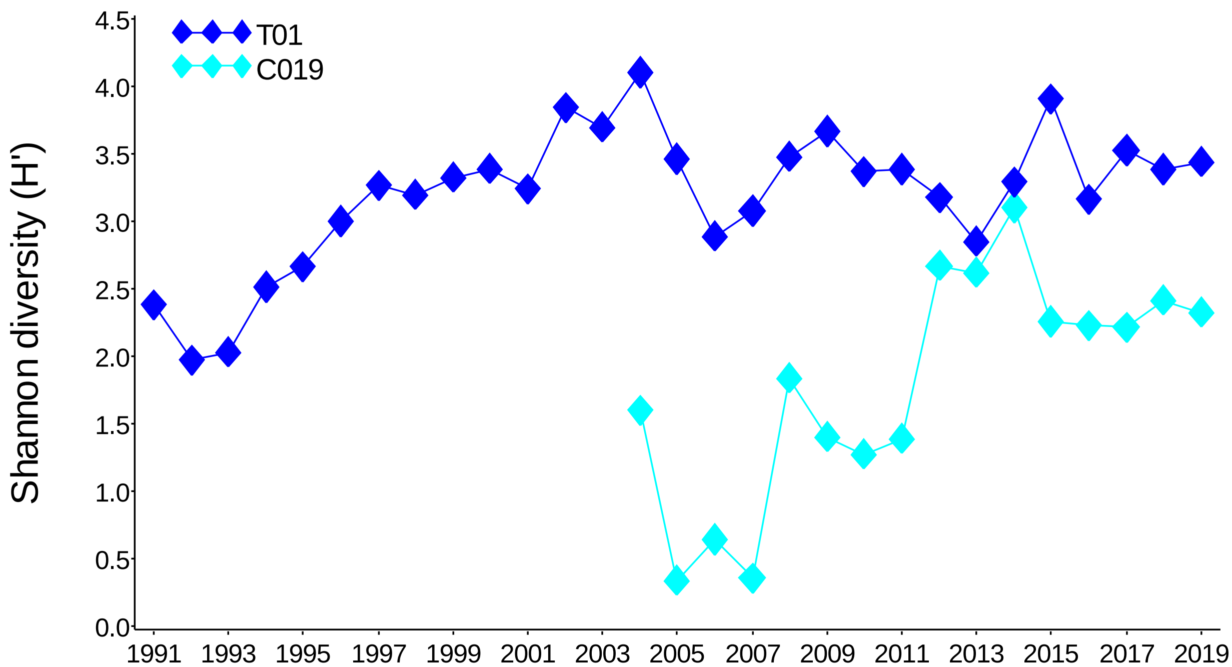


Figure 3-20. Mean Shannon-Weiner diversity at Boston Harbor Stations T01 and C019, 1991-2019.

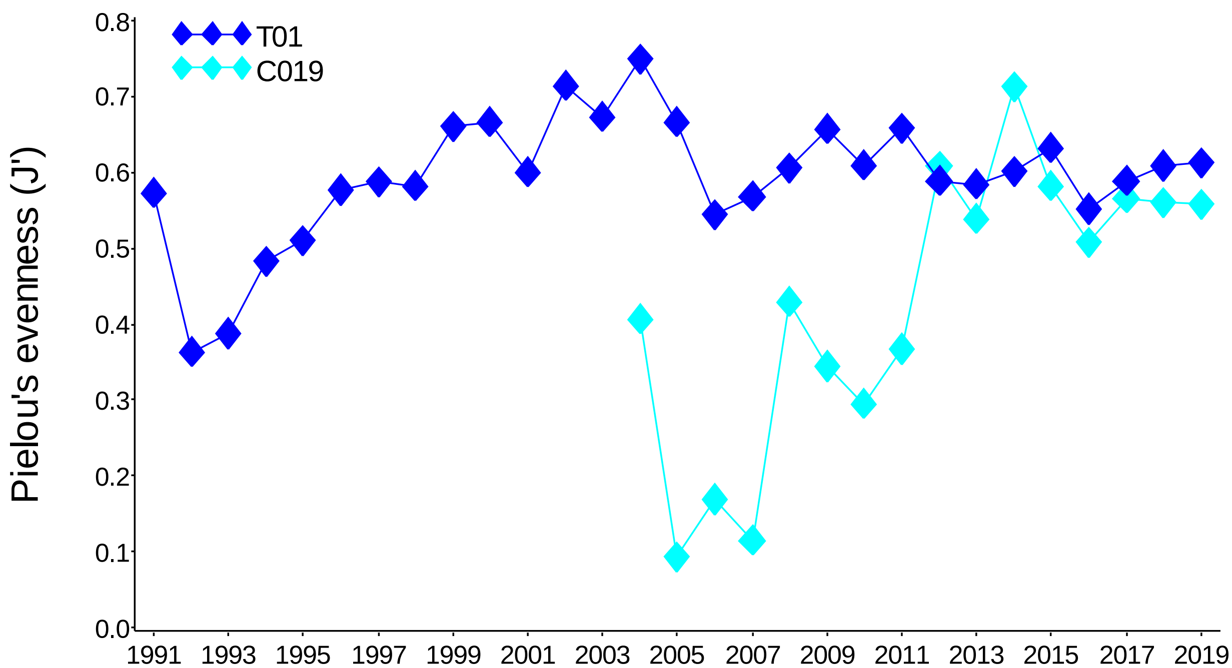


Figure 3-21. Mean evenness at Boston Harbor stations T01 and C019, 1991-2019.

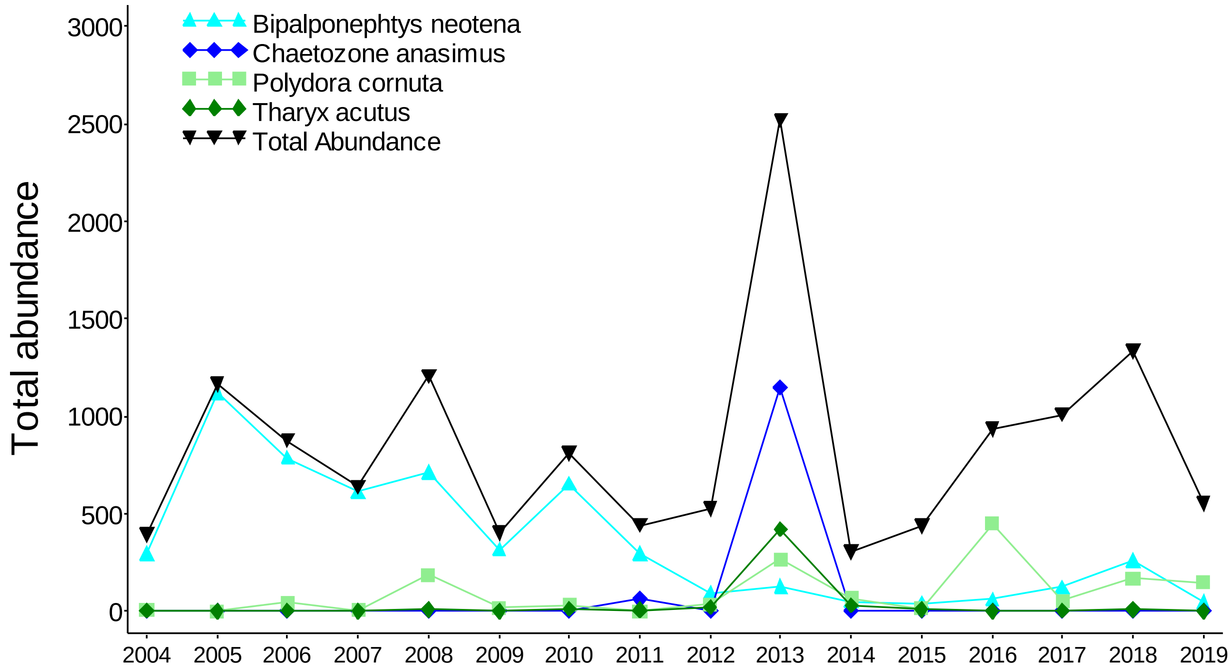


Figure 3-22. Mean abundance of *Bipalponephtys neotena* and other dominants and total community abundance at Station C019, 2004-2019.

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 2002-2019 were virtually the same as for 2002-2018 (Appendix A) 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).

	Period I (prior to Dec. 1991)		Period II (Dec. 1991-mid 1998)		Period III (mid-1998-Sept. 2000)		Period IV (after Sept. 2000)	
Parameter	**Mean**	**Std Err**	**Mean**	**Std Err**	**Mean**	**Std Err**	**Mean**	**Std Err**
Total Abundance	2,606	344	5,513	469	3,213	493	2,518	116
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	0.54	0.01
Number of Species	25.4	2.1	34.7	1.1	33.6	1.7	41.4	0.9
Years included (with one year offset)	1991-1992		1993-1998		1999-2001		2002-2019	

3.3 SEDIMENT PROFILE IMAGING

3.3.1 General Benthic Habitat Conditions

Benthic habitat quality in Boston Harbor for 2019 trended higher relative to 2018 (Figure 3-23), as measured by the Organism Sediment Index (OSI, Rhoads and Germano 1986). 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 and was associated with the biggest reductions in loadings (Blake et al. 1998, Taylor et al. 2019). 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. 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 $F = 56.2$, $p = <0.001$, year as covariate $F = 83.7$, $p = <0.001$) (Figure 3-24). The significant interaction between harbor regions and year ($F = 2.7$, $p = 0.012$) also indicated that all regions did not respond the same through time.

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 effected by wastewater and sludge disposal due to the nearby Deer Island outfalls (Taylor 2010). Habitat quality was consistently highest at the 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 (Figure 3-25).

Prior to the completion of the wastewater-improvement project, Boston Harbor ecosystems were dominated by wastewater discharge (freshwater), and organic and nutrient loadings (Figure 3-26a). Between 1991 and 2000, there was a 80-90% decrease in loadings of total nitrogen, total phosphorus and particulate organic carbon (POC; Taylor 2010, Taylor et al. 2011, 2019) and about a 50% decrease in freshwater input (Signell et al. 2000). This led to a new phase for the Harbor where internal cycling and other broad-scale external factors became more prominent in determining benthic habitat quality (Figure 3-26b).

From 2003 on, regional variation in habitat quality occurred but was no longer related to improvements in wastewater treatment and diversion to the offshore outfall. Inner to outer harbor gradients were less obvious and primarily maintained by the Harbor's complex geomorphology and hydrodynamics, and secondarily to sediment grain-size. Changes in habitat quality now appear to be driven by either broader harbor-wide forcing factors such as storms and climate variability, or other local-scale factors such as dredging. Climate change has already altered sea level, storminess, wind and wave energy, temperature, and salinity in the Boston region (USGCRP 2017, Talke et al. 2018, Voorhies et al. 2018, Reguero et al. 2019, Codiga et al. 2019, Werme et al. 2019).

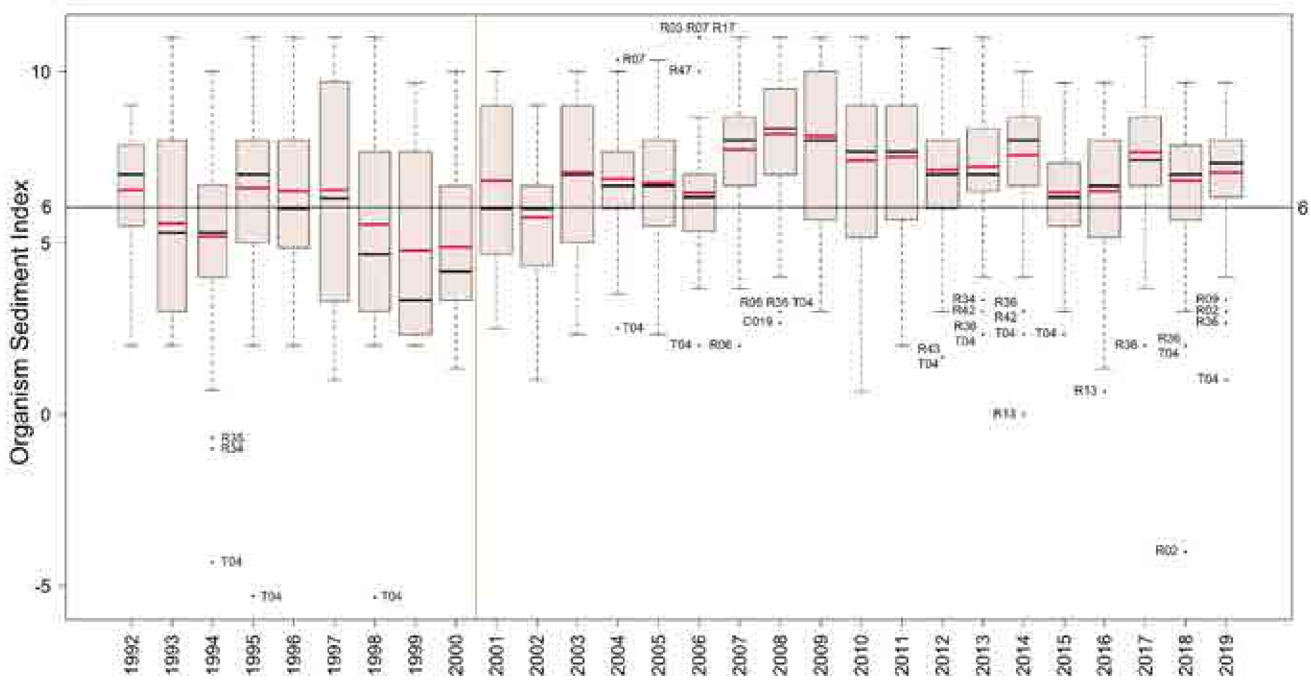


Figure 3-23. Box plot of OSI for all 61 Harbor stations by year. Boxes are interquartile range (IR), whiskers are 2IR, and outliers are labeled. The black bar in the box is the annual median and the red bar is the mean. The horizontal line at 6 is the breakpoint between stress and non-stress benthos (>6 represents good benthic habitat). The vertical line shows the diversion to the offshore outfall.

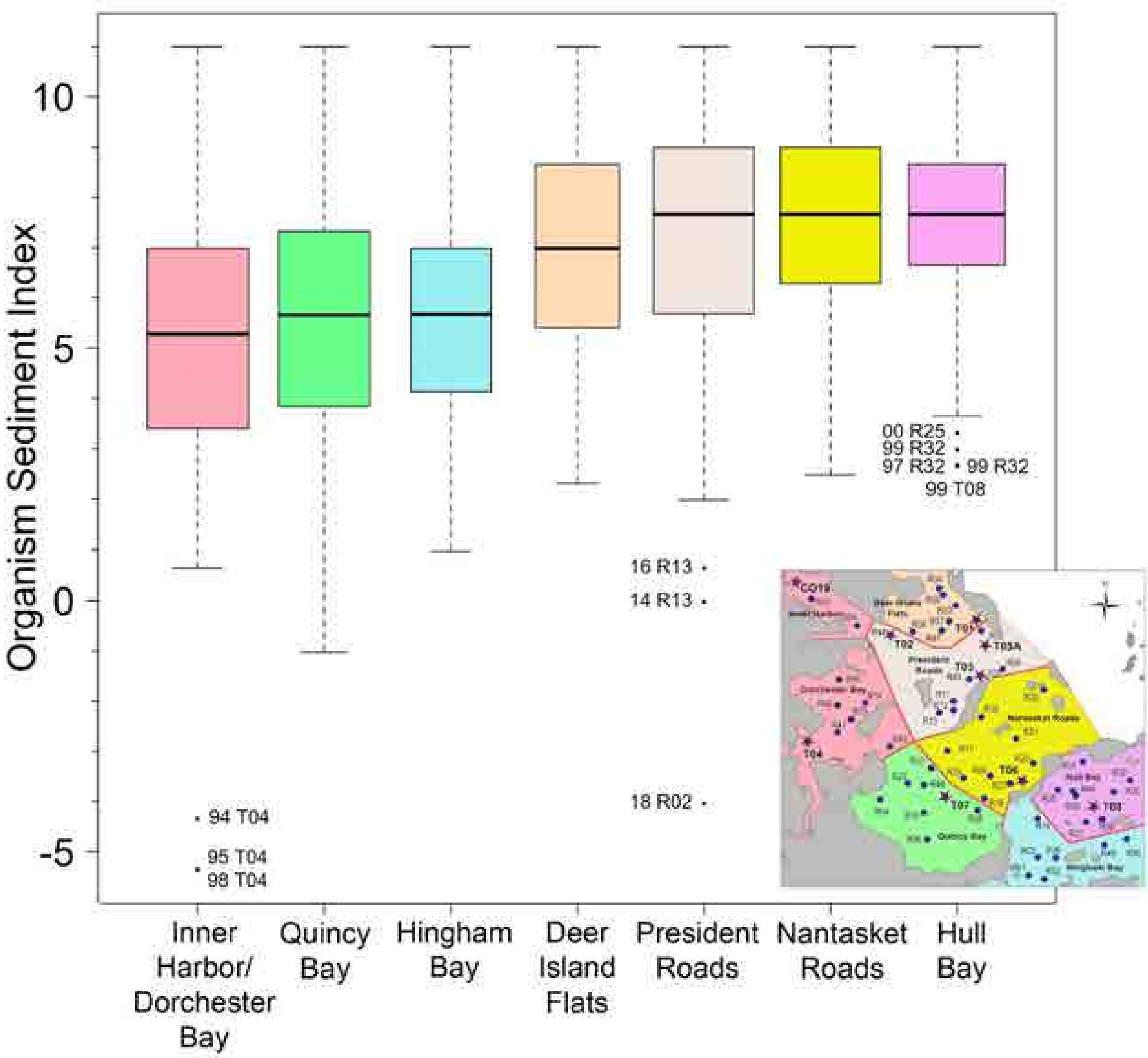


Figure 3-24. Box plot of OSI for Harbor regions summarized for all years. Boxes are interquartile range (IR), whiskers are 2IR, and outliers are labeled. The black bar in the box is the region median.

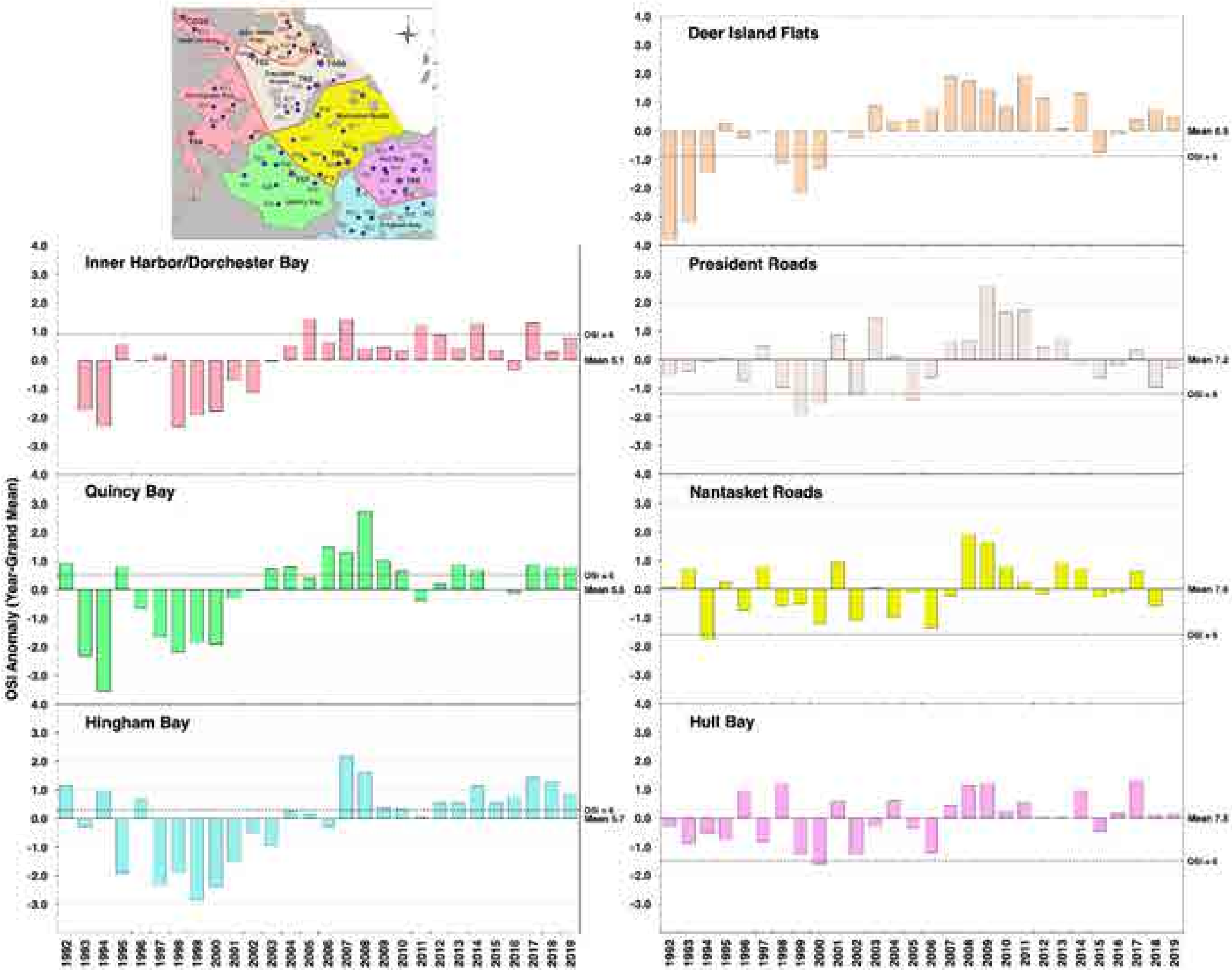


Figure 3-25. OSI anomaly (year mean - grand mean) for Boston Harbor regions. Higher than grand mean OSI years are positive and lower are negative values. The horizontal dotted line at 6 is the breakpoint between stress and non-stress benthos (>6 represents good benthic habitat).

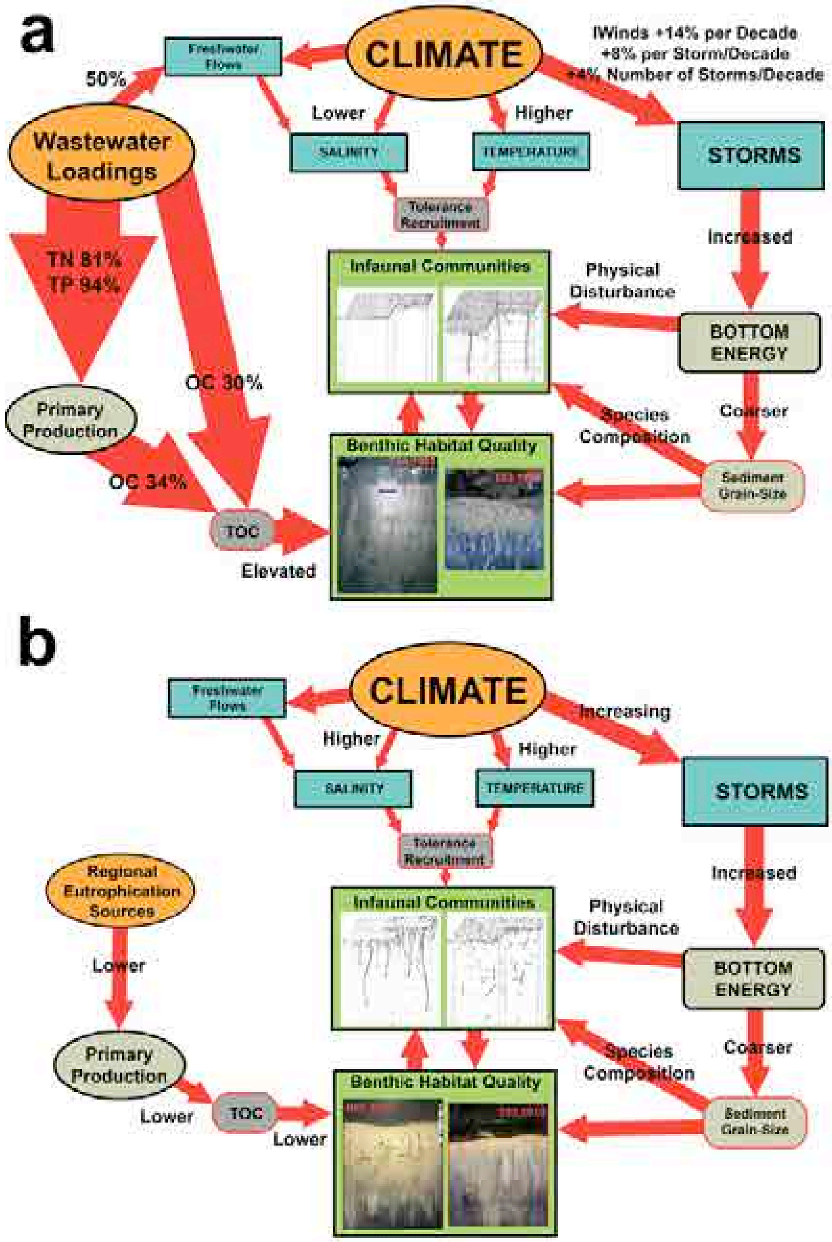


Figure 3-26 Conceptual model of major driving factors effecting benthic and pelagic ecosystems in Boston Harbor. (a) Between 1991 and 2000, external inputs of total Nitrogen (TN), and total Phosphorus (TP), and organic carbon (OC) were dominated by wastewater. (b) From 2001 on, river and non-point sources returned to being dominant. Over the entire period (1991-2019), climatic factors exerted increasing pressure through increasing storminess measured as winter-period integrated surface wind stress at 10m (IWindS). Wastewater percent contributions are from Taylor (2013), storm data from Rutecki et al. (2019), and primary production from Olviatt (2007).

3.3.2 Local-Scale Factors

An example of a local-scale disturbance factor would be recent dredging operations in President Roads that are part of the deep draft navigation improvement project (Massport and Corps 2013). Station R02 was dredged in August 2018 just prior to SPI sampling. A year later (August 2019) the effect of dredging can still be 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 (Figure 3-27). 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 did 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. Similar light colored clay sediments can be seen at R09 and at R02 in previous years (Figure 3-27).

Another example of a local-scale factor that improved habitat quality in the long-term would be the eelgrass (*Zostera marina*) bed planted around Station R08 on Deer Island Flats as part of a restoration effort by MA Division of Marine Fisheries on Deer Island Flats (Evans et al. 2018). It appeared in SPI images in 2008 (Figure 3-28). Prior to 2008, 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). The area of eelgrass beds declined within Boston Harbor from about 81 ha to 27 ha between 1996 to 2001 and then increased to 47 ha by 2007 (Costello and Kenworthy 2011). The increase in Harbor eelgrass coincided with the startup of the offshore outfall. Costello and Kenworthy (2011) reported a similar decadal scale recovery of eelgrass in a small embayment on Long Island Sound following the removal of a municipal wastewater discharge.

Figure 3-27. Changes at stations within the boundaries of President Roads dredging, part of the Boston Harbor deep draft navigation improvements. Black arrows from the station symbol to the 2018 image indicate the stations and their corresponding SPI images.

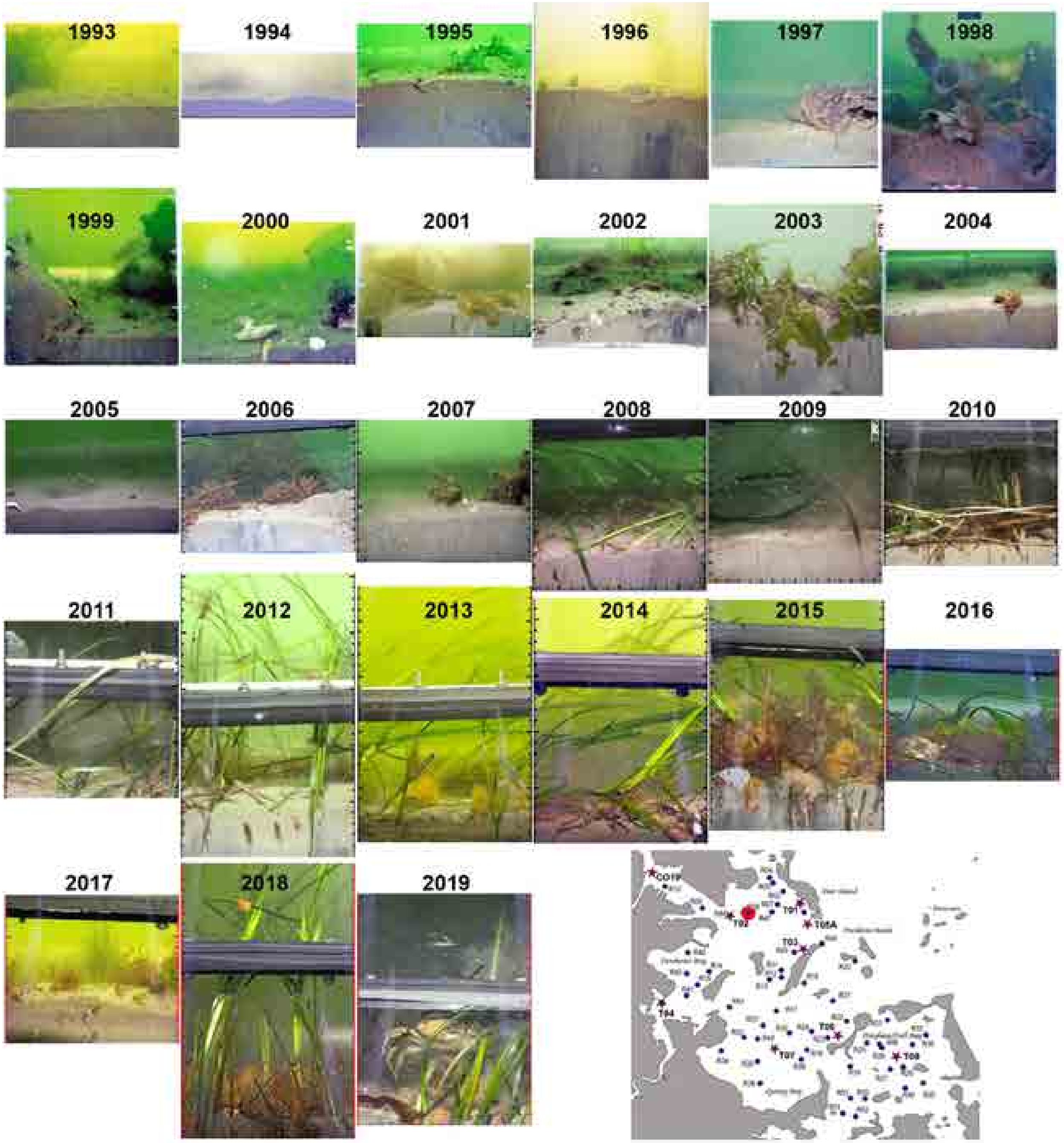


Figure 3-28 Time series of images at Station R08 on Deer Island Flats, showing the persistence of the eelgrass bed after 2008. Scale on side of images is in cm.

3.3.3 Long-Term Patterns

Over the 29-year Harbor monitoring, data on benthic habitat quality and infaunal communities were highly variable, and express continuous and asynchronous change though time (Figures 3-25, Figures 3-2 and 3-7). Most trends reflected complex interactions of harbor-wide driving factors. The three most important being: 1) the October 1991 severe storm (known as the "perfect storm"); 2) the December 1991 cessation of sludge dumping within the Harbor; and 3) subsequent treatment upgrades and final diversion to the offshore outfall in September 2000 (Blake et al. 1998, Taylor et al. 2010). The first two events 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 (Gallagher and Keay 1998). The stepped treatment upgrades fostered a continuation of habitat improvement. Prior to these wastewater treatment improvements, Boston Harbor was one of the most contaminated embayments of those studied in US and the world (Gallagher and Keay 1998, Taylor et al 2019).

The effect of climate change over the monitoring period was less clear within the Harbor than in Massachusetts Bay communities (Rutecki et al. 2019b) because of interactions 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 Sediment Organic Matter

As organic loading declined from 1990 to 2001, along with primary production (Oviatt et al. 2007), sediments shifted from being primarily anaerobic to aerobic as organics in the sediments were metabolized by microbes and benthic infauna (Tucker et al. 2014; Figure 3-29). This transition and recovery to more aerobic sediments was the main factor driving improvements in habitat quality and benthic infauna composition at most stations. Through time the transition point from aerobic to anaerobic metabolism (redox-potential discontinuity (RPD) layer at Eh = 0 volts) became deeper in the sediments. Coincident with the deepening RPD layer was the decline in sedimentary total organic carbon (TOC) through time at all T-Stations except T04 and CO19 (Figure 3-30). Part of the decline in TOC was related to the relationship between TOC and percent fines (silt+clay) with higher percent fine sediments having higher TOC (Hyland et al. 2005). Percent fines at T-Stations was variable from year to year and significantly affected TOC at all stations except T04, T07, and CO19 (Table 3-7, Figure 3-31). At Station T01 the relationship between TOC and percent fines was reversed. TOC declined with increasing percent fines, which was likely due to diversion of Deer Island discharges offshore September 2000. The Deer Island outfall was located within 500 m of Station T01 likely leading to wastewater organic matter being directly incorporated into the sediments.

Bioturbation by the burrowing amphipod *Leptocheirus pinguis* appeared to be responsible for accelerating the transition to aerobic sediments at Station T02, but not so much at Station T03. Its abundance peaked in 2007 and 2008, seven to eight years after diversion, and was coincident with largest increases in the depth of both the measured RPD and SPI image estimated aRPD (Figure 3-32). At Station T02, located in inner President Roads protected from exposure to high currents, the abundance of *Leptocheirus pinguis* was significantly correlated with RPD layer depth ($r = 0.76$, $p = <0.001$, $n = 19$) and with aRPD layer depth (r = 0.74, p = <0.001, n = 27). At Station T03, located in outer President Roads and exposed to strong tidal currents (Signell and Butman 1992), *Leptocheirus pinguis* abundance was correlated only with aRPD layer depth (r = 0.83, p = <0.001, n = 28) and not RPD layer depth. Peak abundance of *Leptocheirus pinguis* at T03 occurred in 1995 and 1996, four to five years before diversion (Figure 3-32). Tube building amphipods in the genus *Ampelisca* were much more abundant than *Leptocheirus pinguis* but were not related to either RPD or aRPD layer depth at either station. While sediments at both T02 and T03 transitioned to a more aerobic biogeochemical state (Tucker et al. 2014), physical processes likely played more of a role in this transition at T03 and biological process at T02.

3.3.5 Salinity

As the Harbor recovered from its historic organic loading, the effects of regional changes have become more obvious. As in Massachusetts Bay, annual averaged salinity of the Harbor increased by 0.47 psu per decade from 1991 to 2019 (linear regression, R^2 = 0.38, n = 29, p = <0.001, Figure 3-33). This change was likely enough to favor the recruitment of a different *Ampelisca* species to the outer Harbor. *Ampelisca vadorum* replaced *Ampelisca abdita* around 2014. *Ampelisca vadorum* is a more coastal species that occurs at higher salinities than the more estuarine *Ampelsica abdita*. This transition in species can be seen in SPI as *A. vadorum* tubes are shorter and wider than those of *A. abdita* (Mills 1967; Figure 3-34).

Table 3-7. Relationship between TOC at T-stations through time (Year) and percent fines (silt+clay) based on multiple linear regression.

	Year		% Fines		
Station	**Coef.**	**p**	**Coef.**	**p**	**R^2**
T01	-0.065	<0.001	-0.020	0.038	0.59
T02	-0.025	<0.001	0.008	0.019	0.54
T03	-0.061	<0.001	0.016	0.004	0.73
T04	-0.002	0.914	-0.044	0.132	0.09
T05A	-0.020	0.001	0.016	0.014	0.45
T06	-0.034	<0.001	0.022	<0.001	0.73
T07	-0.022	0.027	-0.002	0.751	0.17
T08	-0.010	0.016	0.026	0.008	0.45

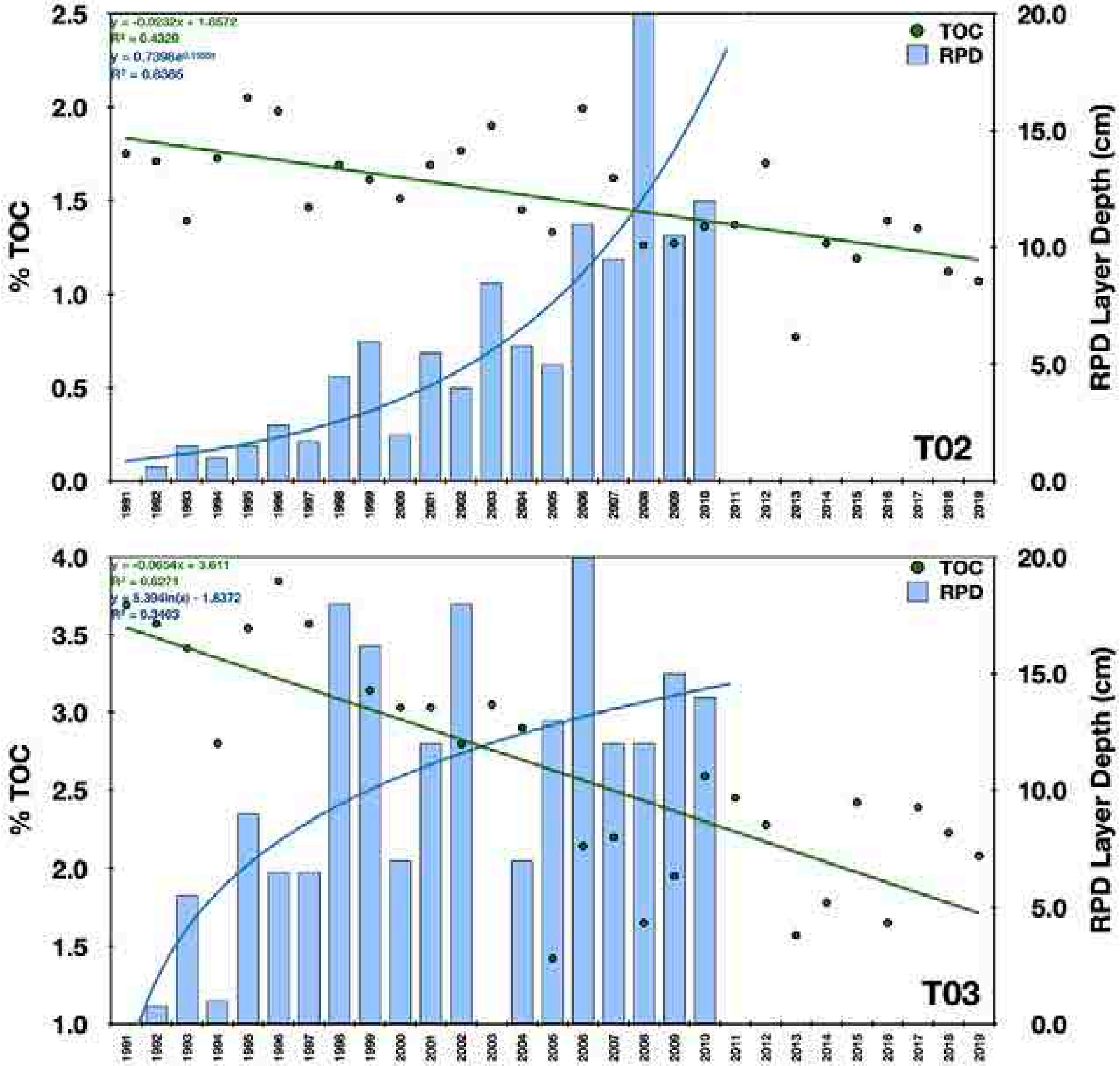


Figure 3-29. Deepening of the measured RPD layer (Eh = 0.0 volts, Tucker et al. 2014) and decline in sedimentary TOC through time at Stations T02 in inner President Roads and T03 in outer President Roads.

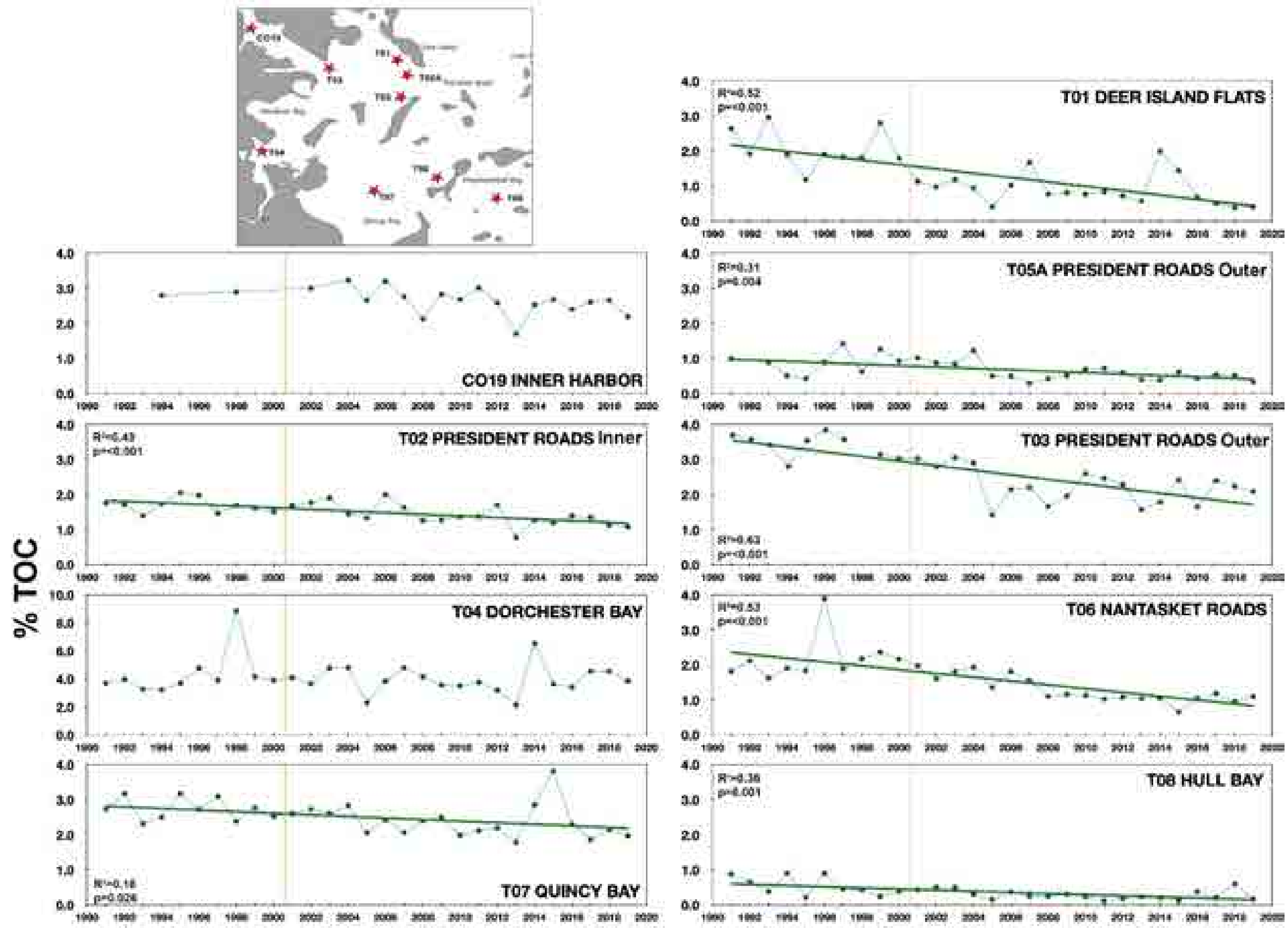


Figure 3-30. Decline in sedimentary TOC through time at infaunal monitoring stations. The vertical line shows the diversion to the offshore outfall.

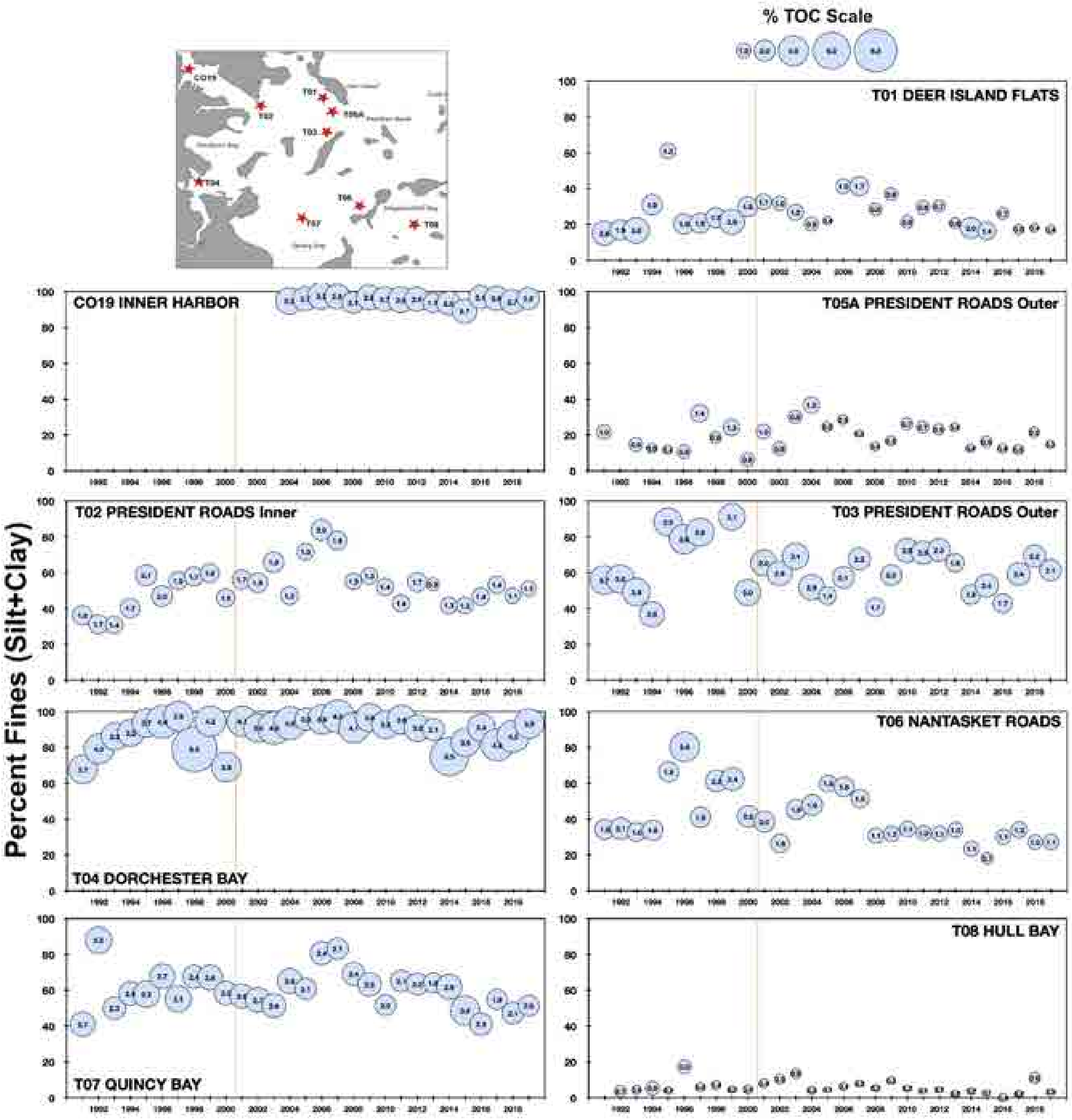


Figure 3-31. Patterns in percent fines (silt+clay) and TOC through time for Harbor regions. The vertical line shows the diversion to the offshore outfall.

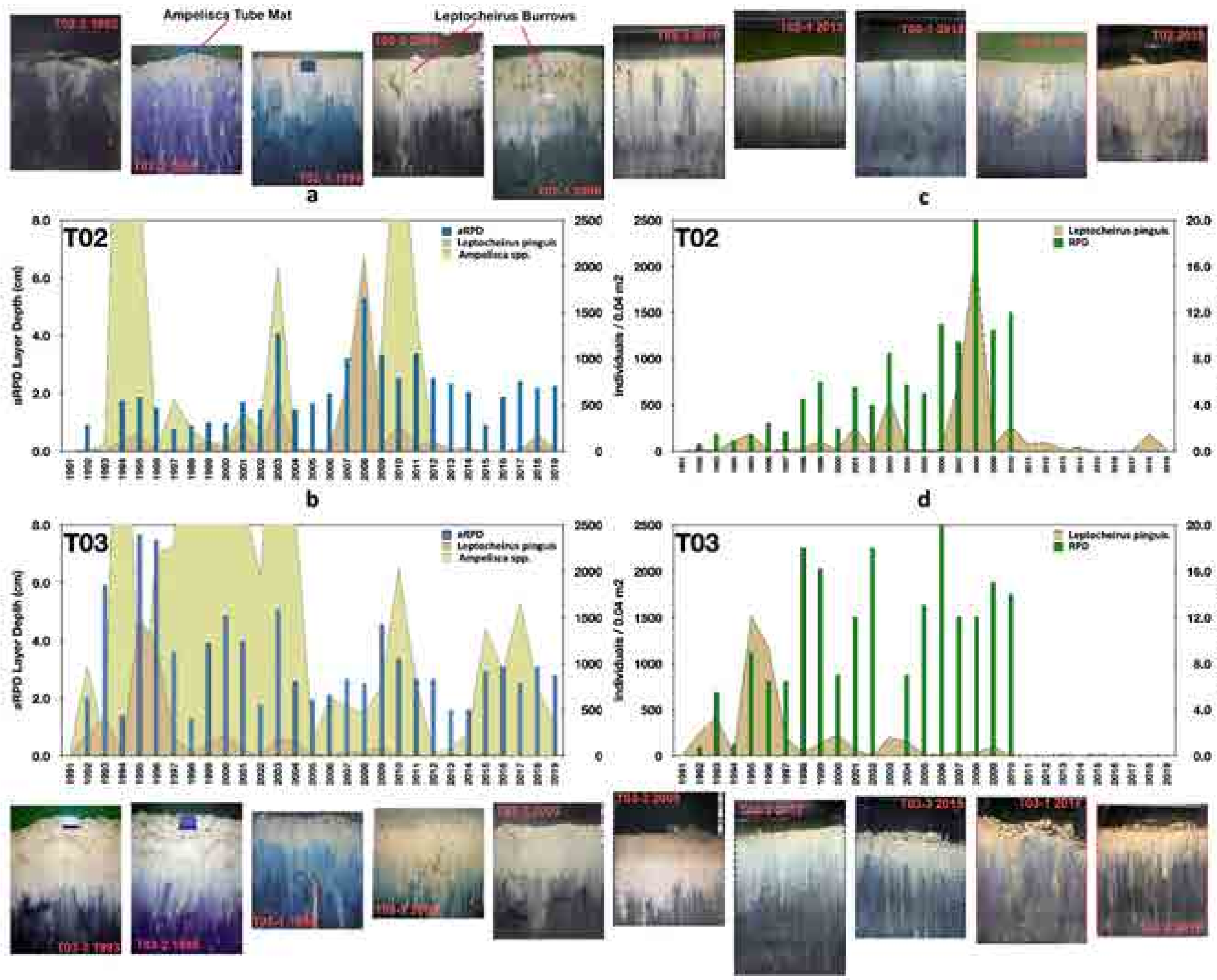


Figure 3-32. Pattern of habitat improvement at Stations T02 and T03, inner and outer President Roads, respectively. Panels (a) and (b) show aRPD measured from SPI images based on color transition from reddish-brown to grayish sediments. Panels (c) and (d) show RPD measured from sediment cores based on depth of Eh = 0 volt (Tucker et al. 2014). Burrows of the amphipod *Leptocheirus pinguis* created voids in the sediment deepening the RPD and aRPD. Tube mats of *Ampelisca* spp. amphipods stabilized the sediment surface but were not related to deepening the RPD layer depth. Images are 15 cm wide.

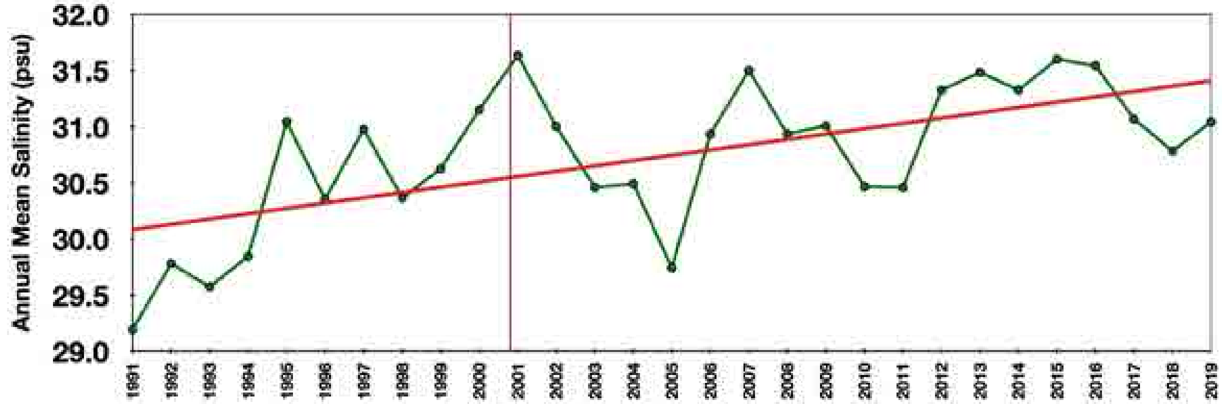


Figure 3-33. Trend in annual mean salinity for Boston Harbor. The vertical line shows the diversion to the offshore outfall. Linear regression $R^2 = 0.38$, $p = 0.039$.

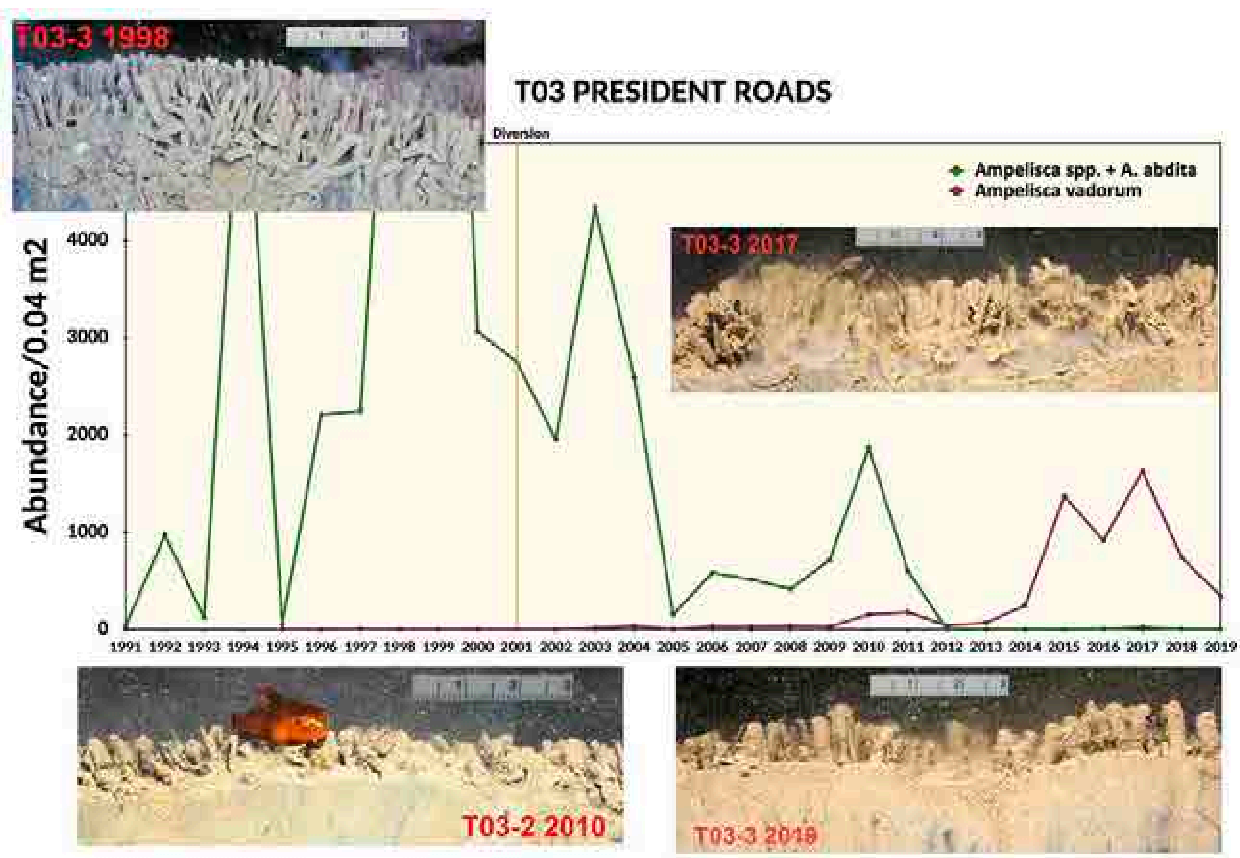


Figure 3-34. Shift in *Ampelisca* species from *A. abdita* to *A. vadorum* at Station T03 starting in 2014. Tubes of *A. abdita* are longer and thinner than *A. vadorum*. The vertical line shows the diversion to the offshore outfall.

3.3.6 Storms

Between 1985 and 2019 there has been a long-term increase in winter-period (October 1 through May 31) storminess over Massachusetts Bay and the Boston region. Both integrated wave stress (IWaveS) and integrated wind stress (IWindS) from storms increased (Codiga et al. 2019). In the nearfield, part of inner Massachusetts Bay, IWaveS calculated for 30 m depth was used to assess effects of storminess on benthos (Rutecki et al. 2019b). Because of its complex geomorphology and shallower depths, cumulative IWindS for winter-period storms was used to assess effects of storminess in Boston Harbor.

Regional winter-period IWindS storms increased in intensity by 22.7% between 1985 and 2019 (Table 3-8, Figure 3-35). This was a result of both increasing storm frequency and increasing storm-average IWindS, the latter mainly due to increasing storm durations (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 3-35). To put the 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). For the 1985 to 2019 period it was the 4th highest ranked IWindS storm and the winter of 1991-1992 (1992 winter-period) was ranked 18th of the 35-years (Codiga et al. 2019). The top ten storm years occurred between 2003 and 2019 (Table 3-9).

Table 3-8. Change in storm integrated wind strength (IWindS) parameters from 1985 to 2019 based on linear regression. Data from Codiga et al. (2019).

Parameter	Sum IWindS (Pa-hr)	Number of Storms	IWindS per Storm (Pa-hr)	Duration per Storm (hr)	% Time Stormy
Slope	4.54	0.26	0.10	0.24	0.21
R^2	0.52	0.27	0.36	0.31	0.49
p	<0.001	0.002	<0.001	<0.001	<0.001
Mean	200.5	27.1	7.3	22.7	10.7
Change/Decade	+45.4	+2.6	+1.0	+2.4	+2.1
% Change/Decade	22.7	9.7	14.1	10.7	19.8

Table 3-9. Ranking of winter-period integrated wind strength (IWindS) storminess from 1985 to 2019. Data from Codiga et al. (2019). Winter-period is October to May prior to August benthic monitoring, for example 1992 would be October 1, 1991 to May 31, 1992.

Year	Rank	Sum IWindS (Pa-hr)	Number of Storms	IWindS per Storm (Pa-hr)	Duration per Storm (hr)	% Time Stormy
1985	33	97	18	5.4	20.6	6.3
1986	34	58	15	3.9	15.0	3.9
1987	31	108	19	5.7	19.8	6.5
1988	28	126	25	5.1	17.8	7.6
1989	32	98	19	5.1	16.1	5.2
1990	26	153	29	5.3	16.1	8.0
1991	21	188	31	6.1	19.7	10.5
1992	18	205	26	7.9	25.6	11.4
1993	22	188	24	7.8	21.1	8.7
1994	17	212	26	8.2	26.5	11.8
1995	25	173	17	10.2	30.4	8.9
1996	14	220	32	6.9	23.7	13.0
1997	24	177	29	6.1	18.0	9.0
1998	19	199	32	6.2	19.8	10.9
1999	30	118	22	5.4	17.0	6.4
2000	12	228	35	6.5	20.0	12.0
2001	11	230	28	8.2	23.6	11.3
2002	29	126	24	5.2	18.7	7.7
2003	9	242	35	6.9	21.3	12.8
2004	13	225	25	9.0	27.3	11.7
2005	15	216	25	8.6	25.2	10.8
2006	8	258	35	7.4	24.1	14.5
2007	7	268	31	8.7	26.1	13.9
2008	27	150	27	5.5	16.3	7.6
2009	16	215	29	7.4	23.9	11.9
2010	2	289	33	8.8	26.4	15.0
2011	3	288	31	9.3	28.2	15.0
2012	Limited Data					
2013	1	319	29	11.0	31.0	15.4
2014	23	187	26	7.2	22.3	9.9
2015	4	285	28	10.2	27.8	13.4
2016	20	190	29	6.5	21.0	10.4
2017	5	277	30	9.2	29.7	15.3
2018	6	274	30	9.1	25.8	13.3
2019	10	230	29	7.9	25.7	12.8

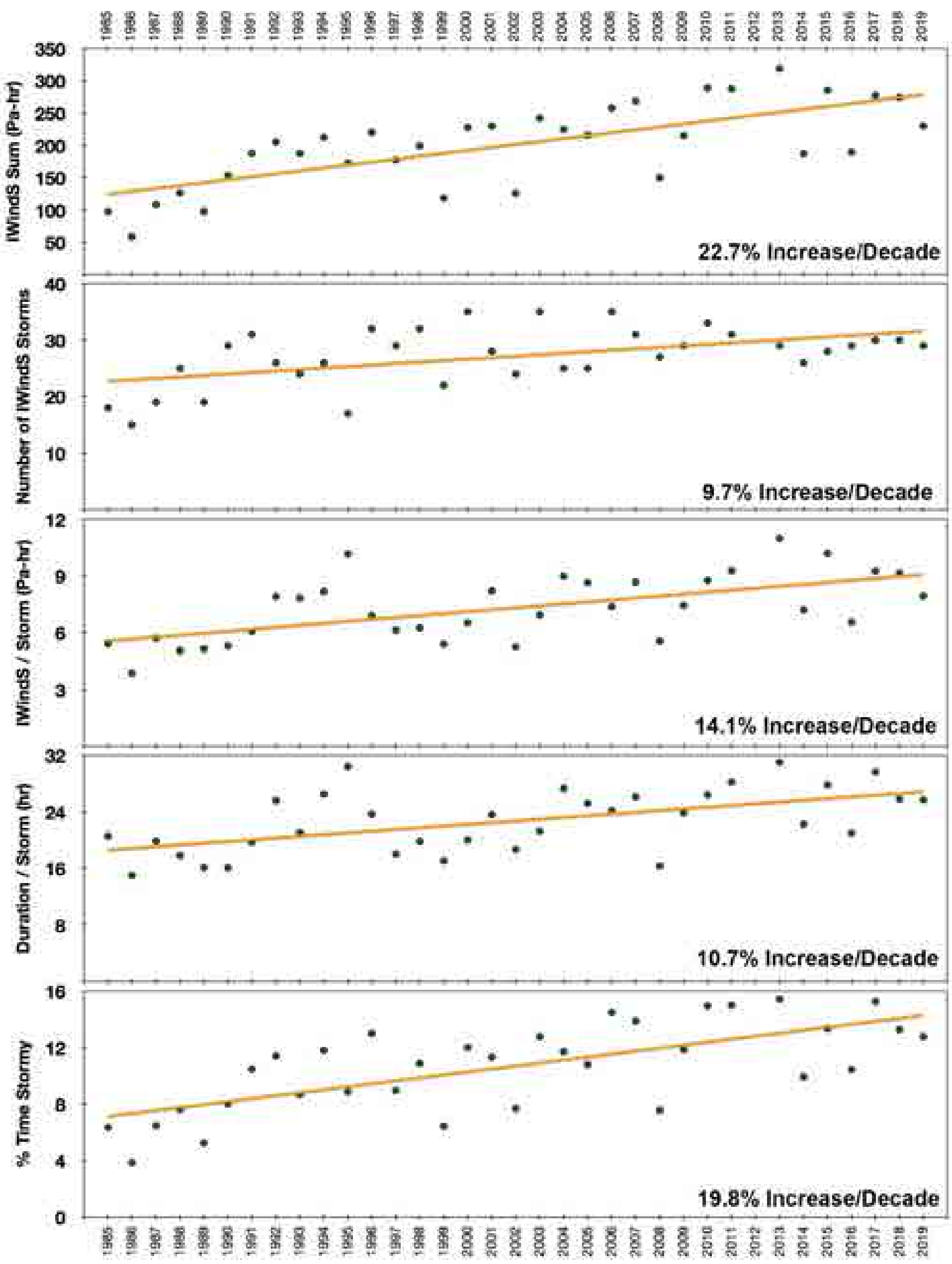


Figure 3-35. Trends in annual winter-period integrated wind strength (IWindS) storm parameters from 1985 to 2019. Data from Codiga et al. (2019).

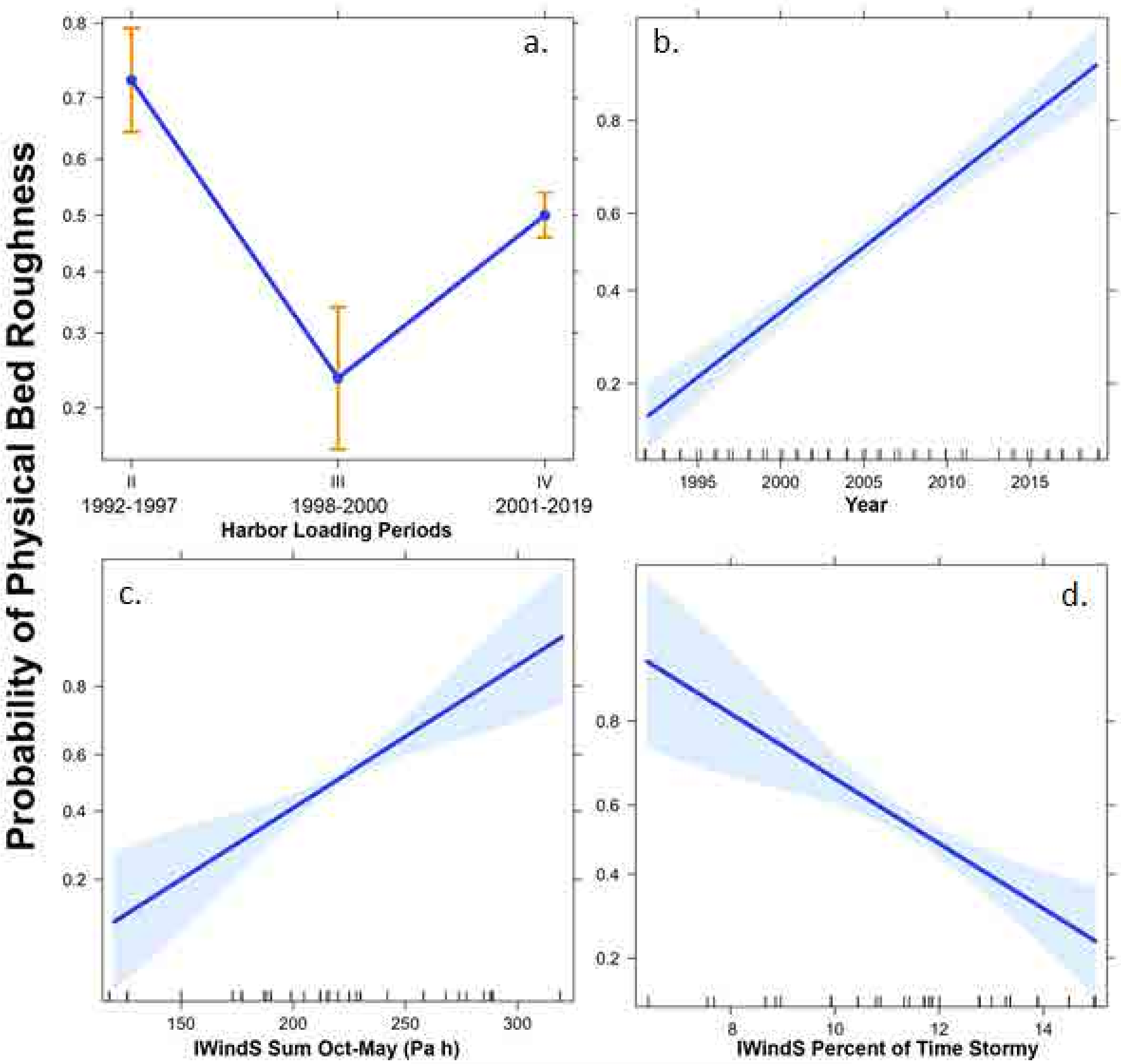
3.3.7 Sediments

There were significant relationships between processes structuring bed roughness and POC loading to the Harbor, winter-period storms, and time (Figure 3-36). For the whole Harbor the probability of bed roughness being dominated by physical processes increased through time and as the sum of winter-period IWindS storms increased. 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 POC loading, time, and storminess. Declining POC loading, through its influence on biology, and increased winter-period storm strength, through its influence on bottom stress, had the strongest influences on bed roughness.

The influence of biological processes was strongest from 1998 to 2000 with implementation of full secondary treatment (Period III). During post sludge disposal and implementation of full primary treatment (II) physical processes dominated as levels of organic and other toxic substances were likely too high for establishment of species that create sediment surface biogenic structures. The dominance of physical processes returned after offshore diversion (IV) and continued through to 2019. In 2019, only Station T03 had biologically dominated surface (Figure 3-37). Another 16 stations had a combination of biological and physical processes dominating bed roughness, and 44 were primarily dominated by physical processes (Figure 3-37).

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 3-38). Through time fewer stations changed modal grain-size. In 2009 and 2012 none of the 61 stations change modal grain-size. When a station did change modal grain-size, storminess was a factor, based on a multinomial model of the proportion of stations that either: 1) remained the same, 2) became finer, or 3) became coarser (Figure 3-39). The proportion of stations becoming finer declined with increasing sum of winter-period IWindS and the number of storms. The proportion becoming finer increased with increasing percent time stormy. The proportion of stations that coarsened declined with increasing months prior to August sampling without a major (top 50) IWindS storm (Figure 3-39).

Changes in median grain-size, calculated from sediment samples, at the eight T-Stations were variable from year to year but tended to become coarser through time. For outer harbor Stations T01, T05A, T06, and T08 the coarsening in median Phi was significant (Figure 3-40). It also coarsened with increasing IWindS at Stations T01 ($r = -0.41$, $p = 0.038$, $n = 26$) and T08 ($r = -0.48$, $p = 0.013$, $n = 26$) (Figure 3-41).



Period II to III	Period II to IV	Year	IWindS Sum Oct-May	IWindS Percent Time Stormy
<0.001	<0.001	<0.001	<0.001	<0.001

Figure 3-36. Predicted probability of physical processes dominating bed roughness for (a) POC loading periods (Taylor 2010), (b) by year, and (c) intensity and (d) duration of winter-period storms (Codiga et al 2019). Based on logistic regression of loading periods and storm parameters with surface roughness type (physical vs. biological). Table insert contains alpha probabilities. Shaded area and whiskers are 95% confidence interval.

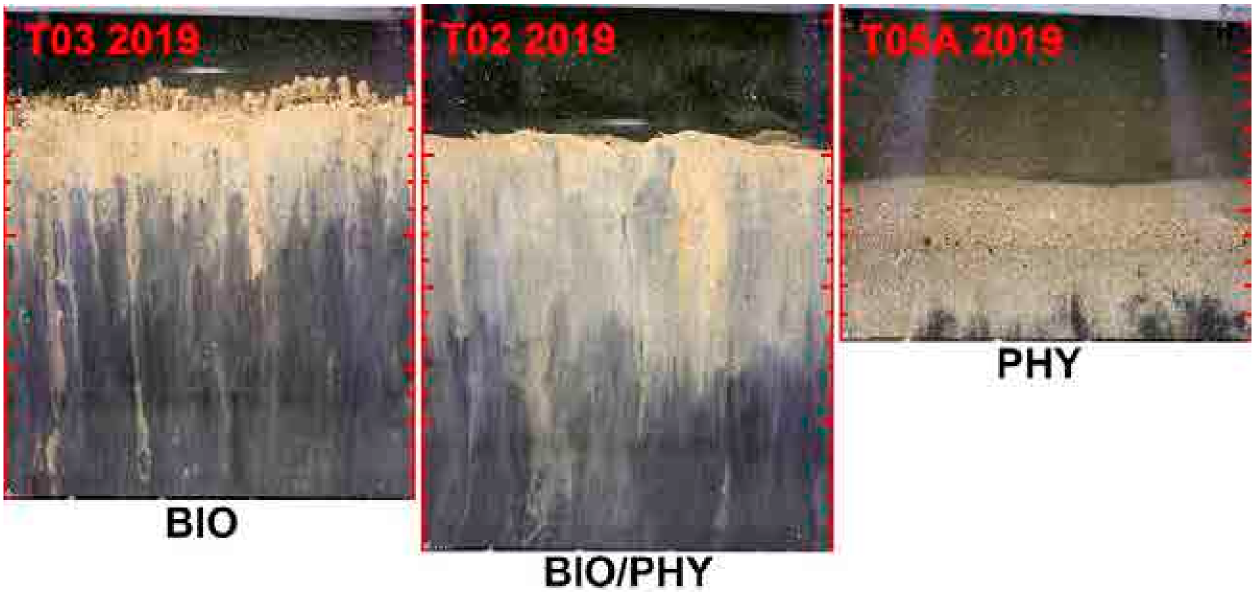


Figure 3-37. Examples of bed roughness being dominated by biological (BIO) and physical (PHY) processes. Scale on side of image is in cm.

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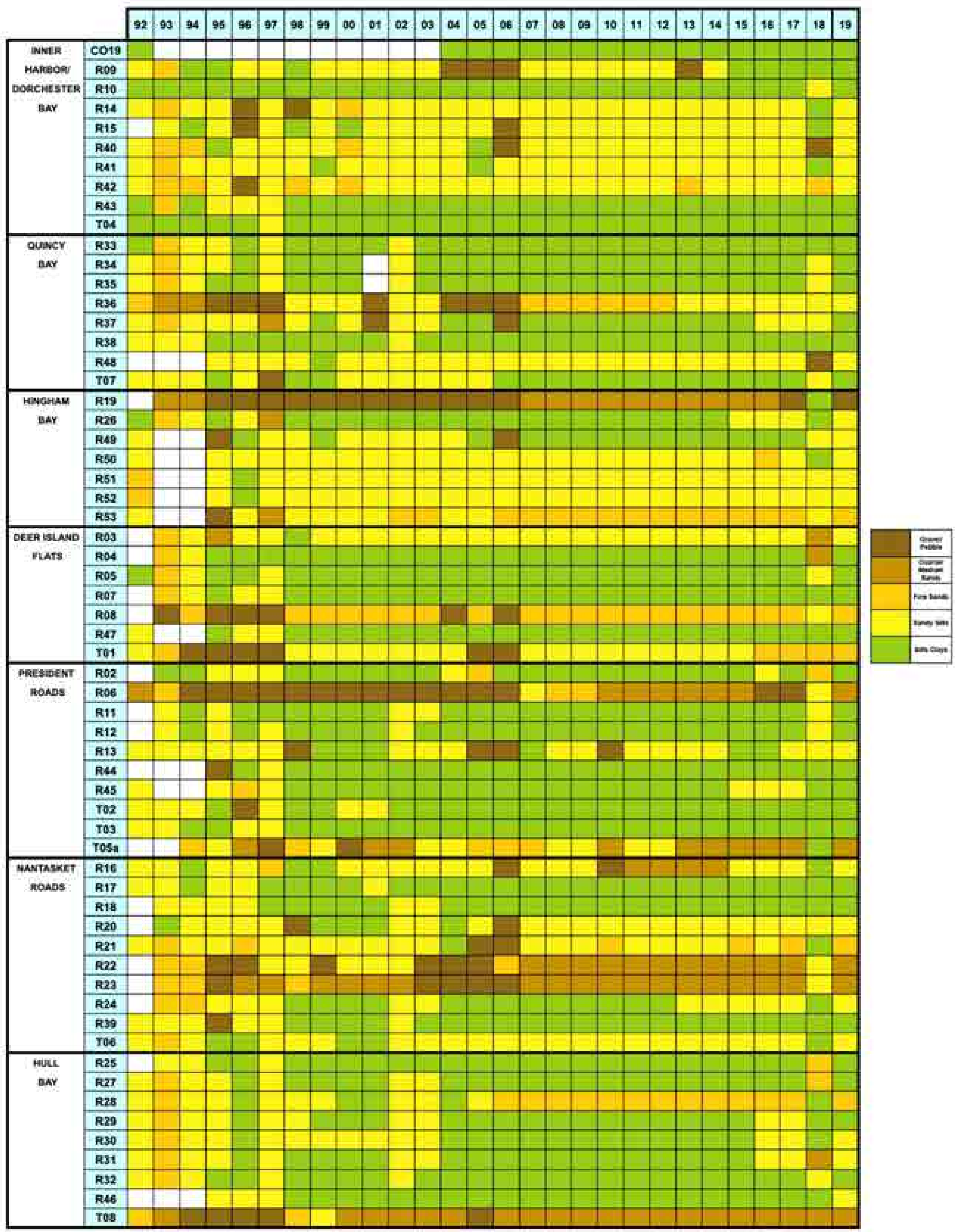
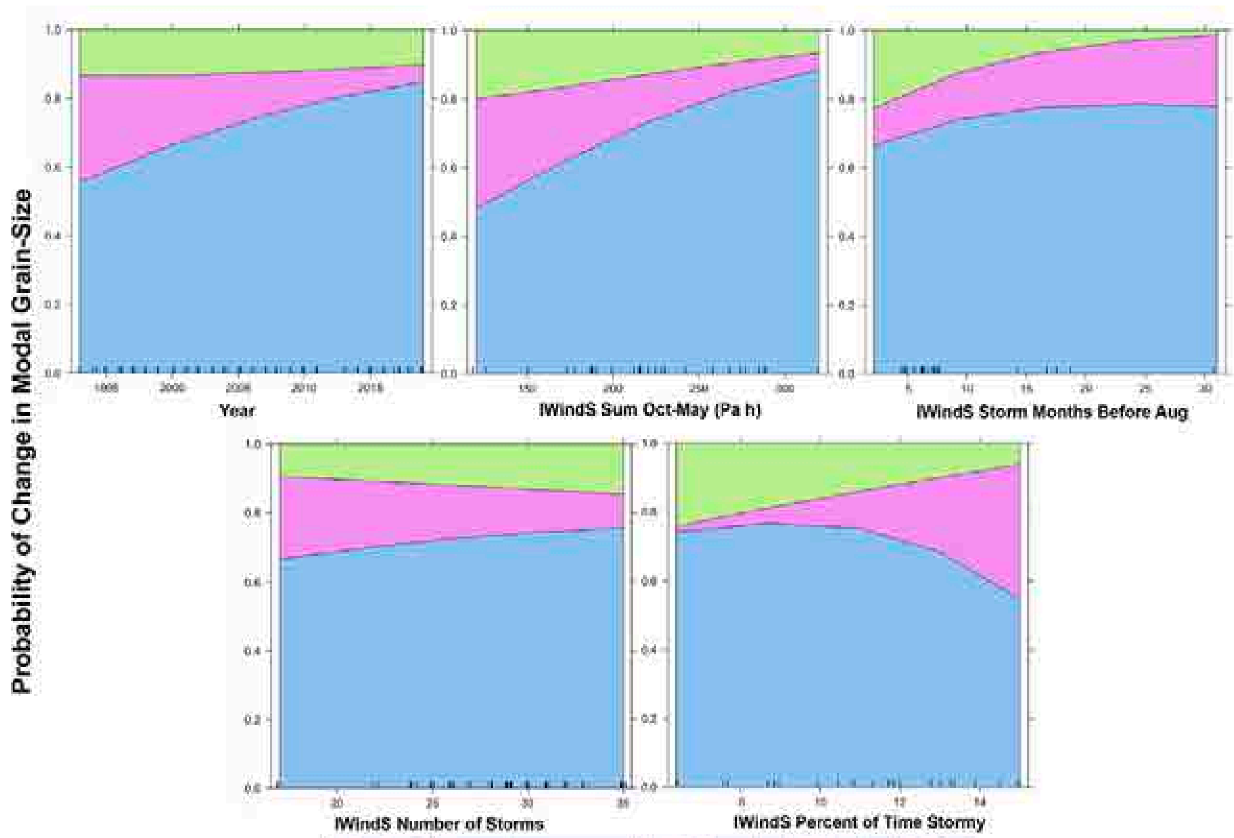


Figure 3-38. Matrix of modal grain-size with stations arranged by Harbor region. Blank cells indicate station was not sampled.



Direction of Sediment Change:	Year	IWindS Sum Oct-May	IWindS Storm Months Before Aug	IWindS Number of Storms	IWindS Percent Time Stormy
Coarser	<0.001	0.174	<0.001	0.473	0.345
Finer	<0.001	0.037	0.270	0.020	0.001

Figure 3-39. Predicted probability of change in modal grain-size for all Harbor stations. Based on multinomial logit model of sediment change from one year to the next (stayed the same vs. got finer vs. got coarser) with time and storm parameters.

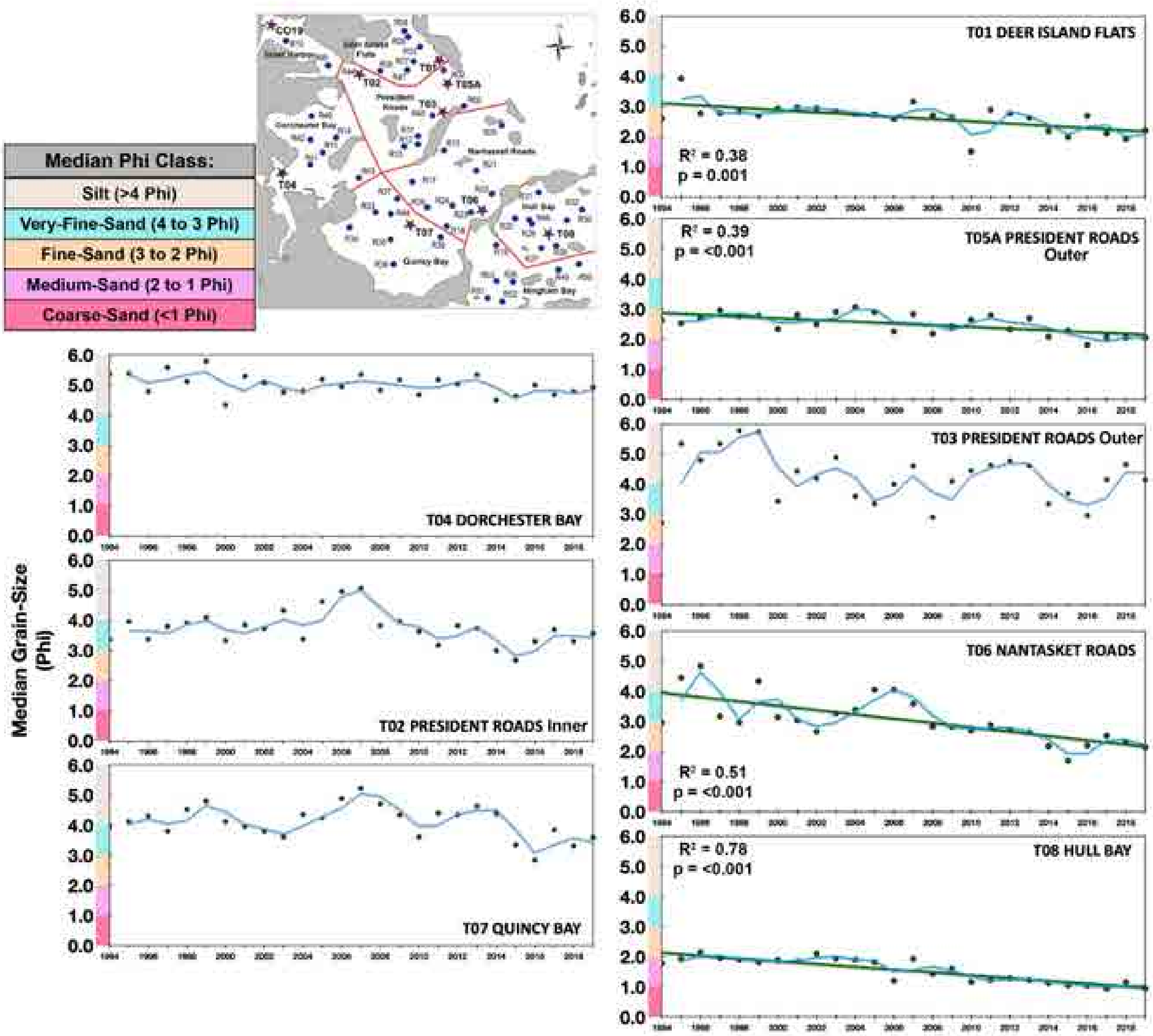


Figure 3-40. Trends in median grain-size by Harbor region through time. Smaller phi sizes are associated with coarser sediments. Only significant regression lines are shown (green). Blue lines are two-year moving average.

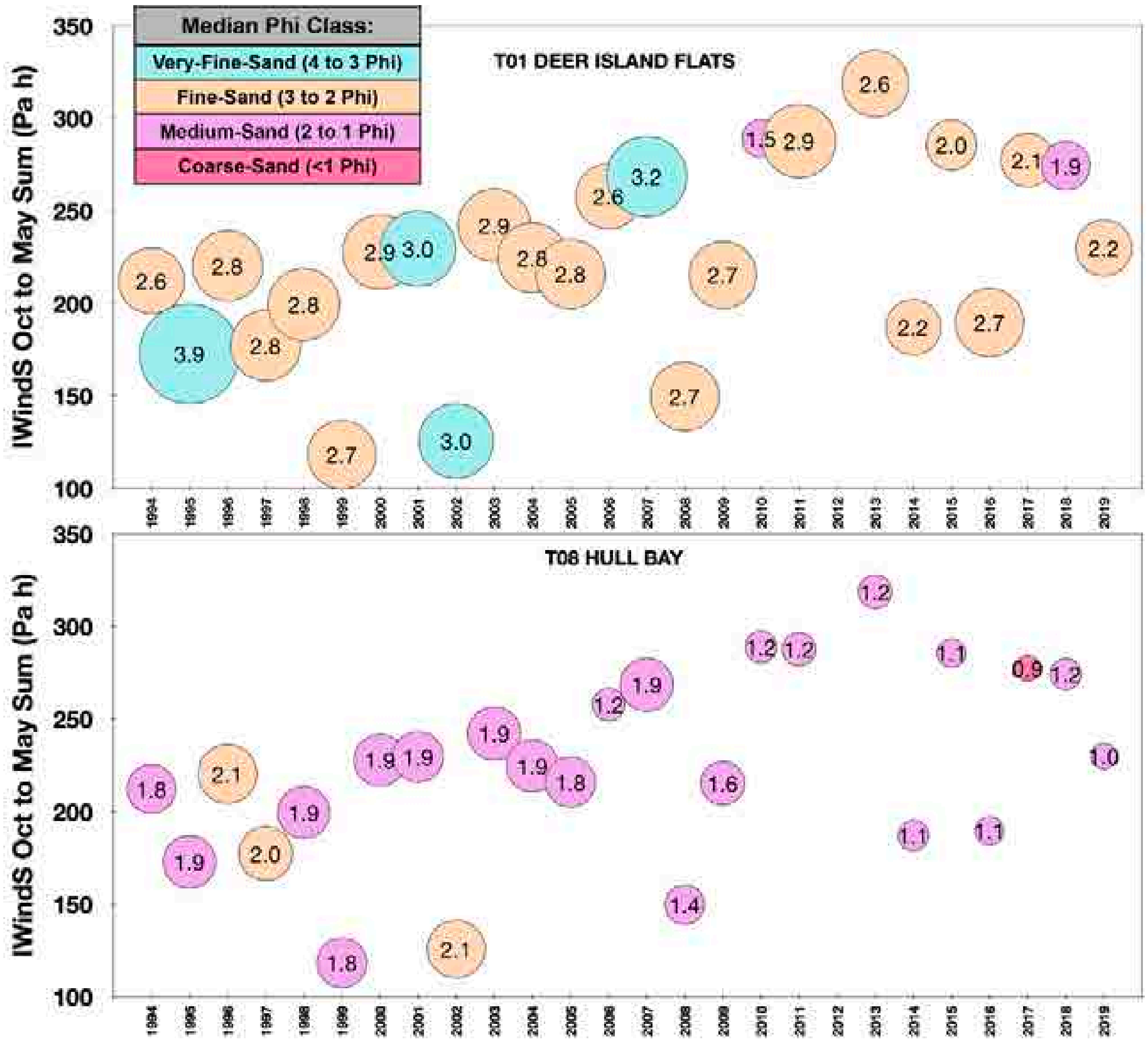


Figure 3-41. Median grain-size (Phi) change relative to sum of winter-period IWindS and year at Stations T01 and T08.

3.3.8 *Ampelisca* spp. Trends

The occurrence of *Ampelisca* spp. tubes was related to both POC loading and intensity of winter period storms as measured by IWindS. 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 3-42). The periods of high, but declining, POC loading (Periods I, II, and III of Taylor 2010) was coincident with six of the ten lowest sum of winter period IWindS storm years (Table 3-9). Between 2006 and 2019 mats peaked again twice, occurring at about 30% of stations. Eight of the top ten IWindS winter period storm years occurred between 2006 and 2019, and all ten stormiest years occurred after the September 2000 diversion (Period IV of Taylor 2010).

Based on a multinomial model, *Ampelisca* spp. tube occurrence (either tube mats present, tubes present at less than mat density, and no tubes observed in SPI) was related to both loading periods and IWindS winter-period storms (Figure 3-43). The probability of *Ampelisca* spp. mats or tubes being present in Period II (1992-1997) and Period III (1998-2000) was the same. The probability of mats declined going from Period II to IV (2001-2019). The presence of tubes increased though time, while mats tended to decline. As the sum of winter period storm strength increased, the probability for tube mats to occur declined (Figure 3-42).

Ampelisca spp. tube mats tended to decline with increasing time (months) with no major storm prior to the August SPI sampling. Mats tended to increase with increasing percent of time stormy. Both of these trends seem counter to what would be expected and likely were related to interactions between *Ampelisca*'s life history (recruitment, sediment preference), harbor geomorphology, and timing of storms. The number of storms per year did not affect *Ampelisca* tube occurrence (Figure 3-43).

Through the monitoring, *Ampelisca* spp. tube mats were consistently more common in the outer harbor regions up to 2004 (Figure 3-44). From 2005 on the combination of lower food availability, from both internal and external 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 2010 it averaged about 300 g C m^{-2} yr^{-1} (Taylor et al. 2019).

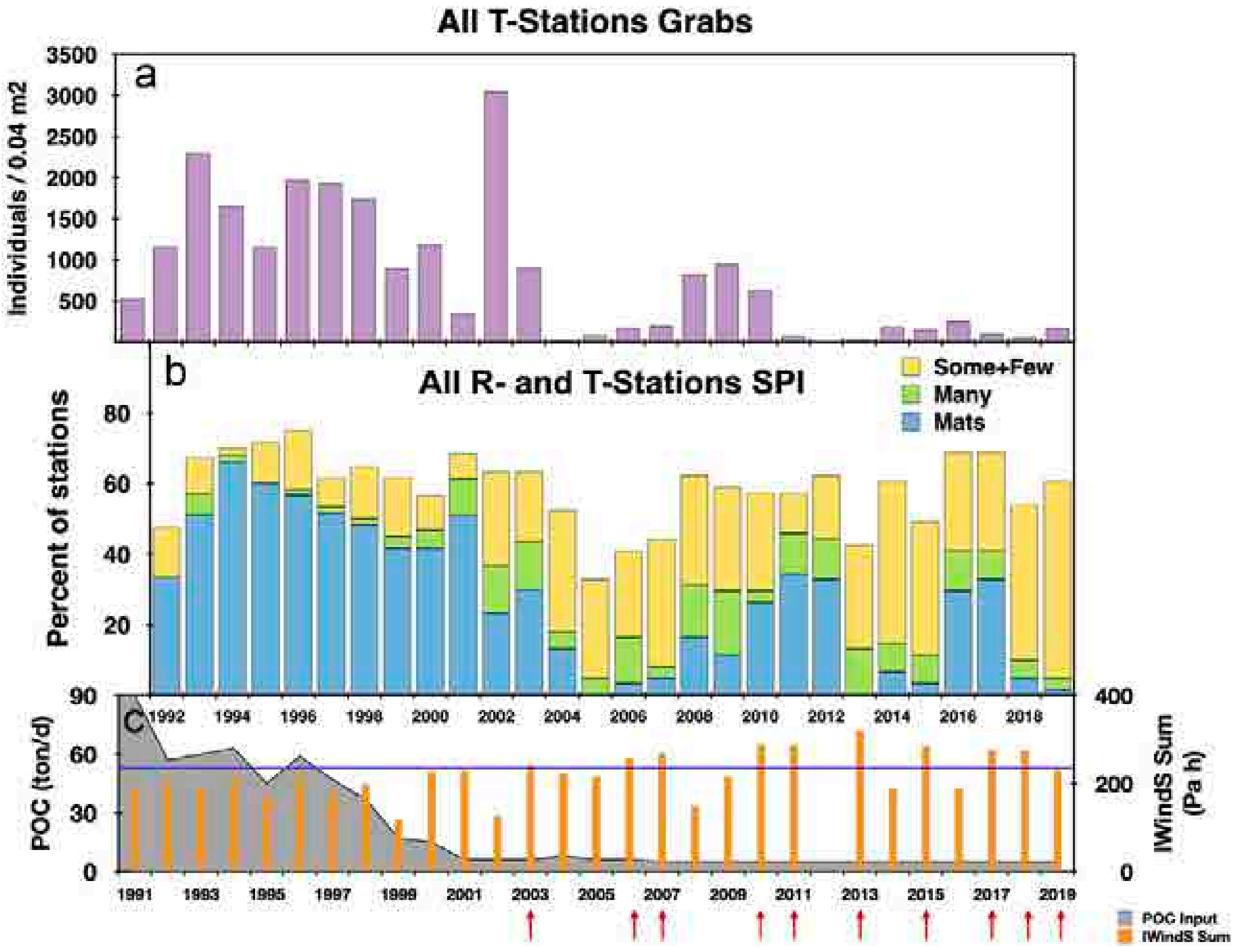
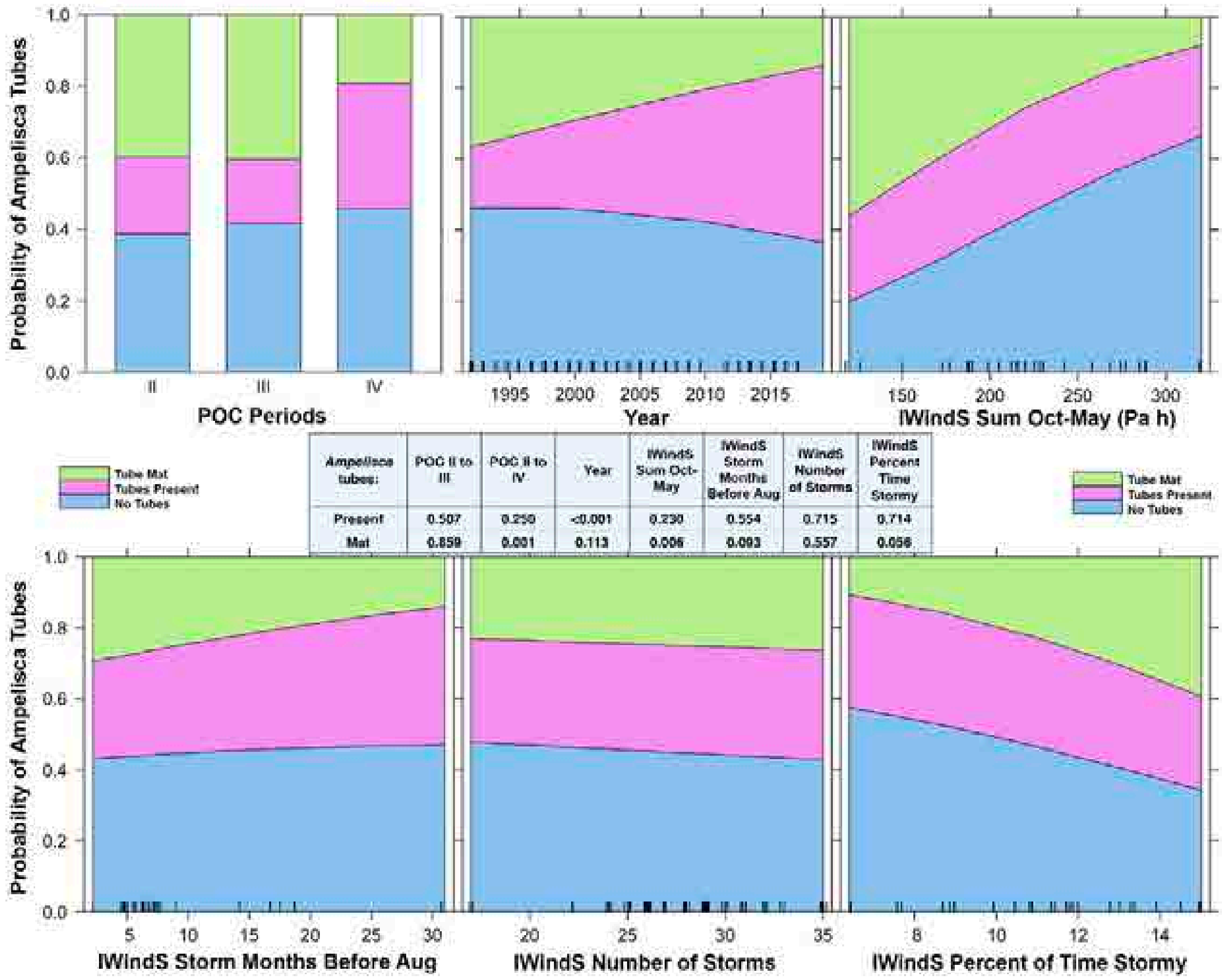


Figure 3-42. Abundance of *Ampelisca* spp. from grab samples at the 8 T-Stations (a) and presence of *Ampelisca* spp. tube mats for all 61 Harbor SPI stations (b). Pattern of POC loading and winter period storm intensity (IWindS) within the Harbor (c). Arrows point to the top ten stormiest years.



Ampelisca tubes:	POC II to III	POC II to IV	Year	IWindS Sum Oct-May	IWindS Storm Months Before Aug	IWindS Number of Storms	IWindS Percent Time Stormy
Present	0.507	0.250	<0.001	0.230	0.554	0.715	0.714
Mat	0.859	0.001	0.113	0.006	0.093	0.557	0.056

Figure 3-43. Multinomial model results for *Ampelisca* spp. tube occurrence (mats present vs. tubes present vs. no tubes) with both POC loading periods of Taylor (2010; Period II from1992-1997, Period III from 1998-2000, and Period IV from 2001-2019) and winter storm parameters (Codiga et al. 2019). Table contains alpha probabilities for model coefficients.

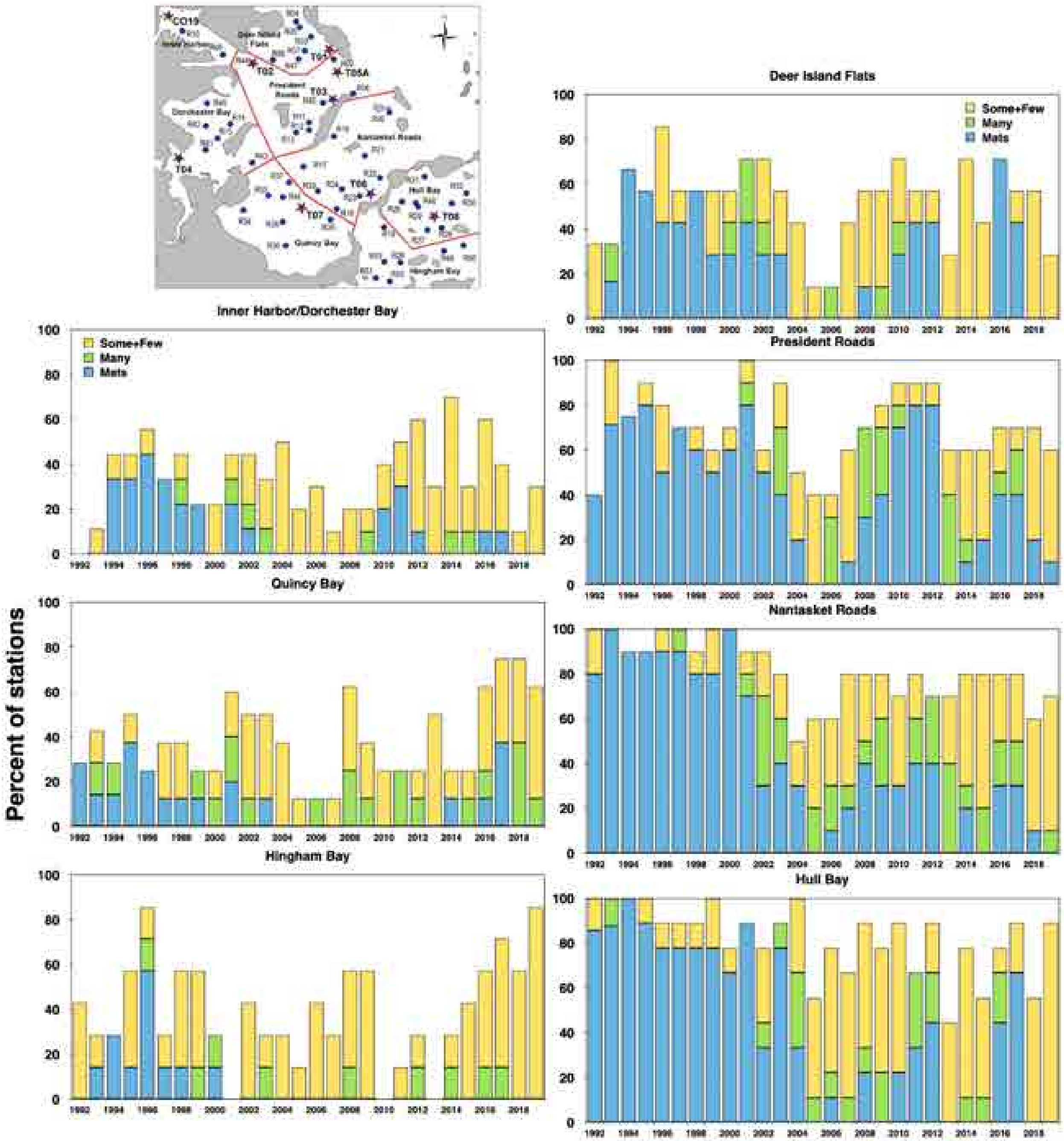


Figure 3-44. Histogram of *Ampelisca* spp. tubes and tube mats by Harbor regions.

3.3.9 Long-term infaunal trends

Through time, total abundance of infauna at the eight T-stations was variable from year to year (Figure 3-7). At the start of monitoring in 1991 total abundance was at its lowest point of 1,070 individuals/0.04 m^2 (SE = 360 individuals/0.04 m^2). This was coincident with the last year of sludge discharge (Taylor et al 2019). By 1992 with POC loading reduced by 60%, infaunal abundance had more than tripled and remained high to 1997 (Figure 3-45). After peaking in 1997 at 7,790 individuals/0.04 m^2 (SE = 3,120 individuals/0.04 m^2) total abundance declined by about 1,040 individuals/0.04 m^2/decade through to 2019 (linear regression, $R^2 = 0.34$, $p = 0.005$, $n = 22$). Most of the annual variation and declining abundance was due to patterns of *Ampelisca* spp. occurrence, which were 23% of all infauna collected over the 29 years of monitoring. With *Ampelisca* spp. removed abundance still peaked in 1997 but there was no significant decline between 1998 and 2019 (Figure 3-45). All other community structure measures (species richness, evenness, and diversity) significantly increased through time with lowest values occurring prior to 1997.

With the wide range of benthic habitats represented at T-stations, no single species was dominant at all stations. Cluster and multidimensional scaling analyses for 2019 grouped stations into an outer Harbor Group I and inner Harbor Group II (Figure 3-15) primarily based on species richness and diversity (log-series alpha), and secondarily on total abundance (Figure 3-46). Patterns in occurrence for the top nine dominant species for 2019 (Table 3-3) point to a high degree of station fidelity through time (Figure 3-47). For example in 2019, *Aricidea catherinae* was present at all stations except T04 but was dominant in cluster group IB (stations T01, T02, T03 and T06) with 99% of its abundance occurring there. *Streblospio benedicti* occurred at all stations in 2019 but was dominant at only group IIC (station T04) with 95% of its abundance there.

The main driving factor for much of the long-term change in community structure was the changes in wastewater loadings and treatment upgrades. Declining total abundance was positively correlated with declining POC loading, while all other community structure parameters increased with declining POC loading (Table 3-10). Because of differing species life-histories and tolerances, other factors such as sediment grain-size, aRPD layer depth, and storminess were important for individual species. On a harbor-wide basis including all years, nine of the top dominant species were correlated with at least one habitat, sediment, or storm parameter (Table 3-11). Most of the significant correlation was a positive relationship with habitat parameters. The exception was *Streblospio benedicti*, which was negatively correlated with habitat parameters. It was the only species correlated with sediment parameters reflecting its key opportunistic life-history traits of being associated with fine-grained, higher organic content sediments (positive correlations with percent fines, median Phi and TOC) and among the first species to colonize disturbed habitats (negative correlations with aRPD and OSI). *Scoletoma hebes* was the only dominant to show a relationship with the intensity of winter-period storms (Table 3-11), which may have been related to it not being dominant prior to 2004-2005 (Figure 3-47) when winter-period IWindS were lower. Its overall station abundance tended to increase as IWindS increased. If the correlations are calculated by stations at which *Scoletoma hebes* dominated (cluster Group IB), patterns in its abundance were related primarily by sediment grain-size and TOC (Table 3-12). It declined in abundance as sediments coarsened or as TOC increased reflecting its preference for mixed sediments (Chang et al.

1992). Storminess was a factor at inner President Roads station T02 where *S. hebes* increased in abundance after 2007 coincident with increasing winter-period IWindS.

Table 3-10. Correlation of community structure parameters with POC loading (Taylor 2013) from 1991 to 2019. Sample size was 29 for all parameters.

Parameter:	r	p
Total Abundance	0.42	0.023
Species Richness	-0.69	<0.001
Pielou's Evenness	-0.48	0.008
Fisher Diversity	-0.85	<0.001
Shannon-Weiner Diversity	-0.81	<0.001

Table 3-11. Correlation of 2019 dominant species with habitat, sediment, and storm parameters. Sample size ranged from 177 for biogenic structures to 230 for fines and TOC. Significant correlations are highlighted (based on adjusted p-values using Holm's method). P-values are indicated by the following notations: * <0.05, ** <0.01, * <0.001.**

	Habitat			Sediment			Storm
Pearson correlations:	**aRPD**	**OSI**	**Total Biogenic Structures**	**% Fines**	**Median Phi**	**% TOC**	**IWindS Sum**
Polydora cornuta	0.14	0.10	0.15	-0.01	0.09	-0.02	-0.16
Aricidea catherinae	0.23	0.35***	0.44***	-0.06	0.01	-0.06	-0.00
Streblospio benedicti	-0.27***	-0.46***	-0.13	0.33***	0.26**	0.35***	-0.06
Scoletoma hebes	0.14	0.34***	0.29**	-0.07	-0.09	-0.17	0.28**
Tharyx acutus	0.25*	0.17	0.23	-0.03	0.06	0.03	-0.08
Limnodriloides medioporus	0.10	0.30***	0.50***	0.03	0.11	-0.00	-0.02
Tubificoides intermedius	0.21	0.32***	0.46***	0.04	0.14	-0.02	0.10
Bipalponephtys neotena	-0.08	0.11	0.07	0.20	0.22	-0.03	0.13
Total *Ampelisca* spp.	0.12	0.18	0.19	0.04	0.13	0.01	-0.12
Corophiidae Juveniles	0.33***	0.22*	0.06	0.10	0.13	0.12	-0.12
Crassicorophium bonellii	0.27**	0.19	0.15	0.07	0.11	0.09	-0.09
Leptocheirus pinguis	0.47***	0.30***	0.29**	0.11	0.15	0.03	-0.12

Table 3-12. Correlation of *Scoletoma hebes* with habitat, sediment, and storm parameters at cluster Group IB stations where it was a dominant. Sample size ranged from 22 for biogenic structures to 29 for fines and TOC. Significant correlations are highlighted (based on adjusted p-values using Holm's method). P-values are indicated by the following notations: * <0.05, ** <0.01, * <0.001.**

	Habitat			Sediment			Storm
Pearson correlations:	**aRPD**	**OSI**	**Total Biogenic Structures**	**% Fines**	**Median Phi**	**% TOC**	**IWindS Sum**
T01	0.44	0.14	-0.40	-0.28	-0.66**	-0.47	0.54
T02	0.22	0.42	0.33	-0.15	-0.33	-0.64**	0.57*
T03	-0.30	-0.01	-0.11	-0.18	-0.22	-0.67**	0.36
T06	0.11	0.44	-0.12	-0.52	-0.82***	-0.57*	0.38

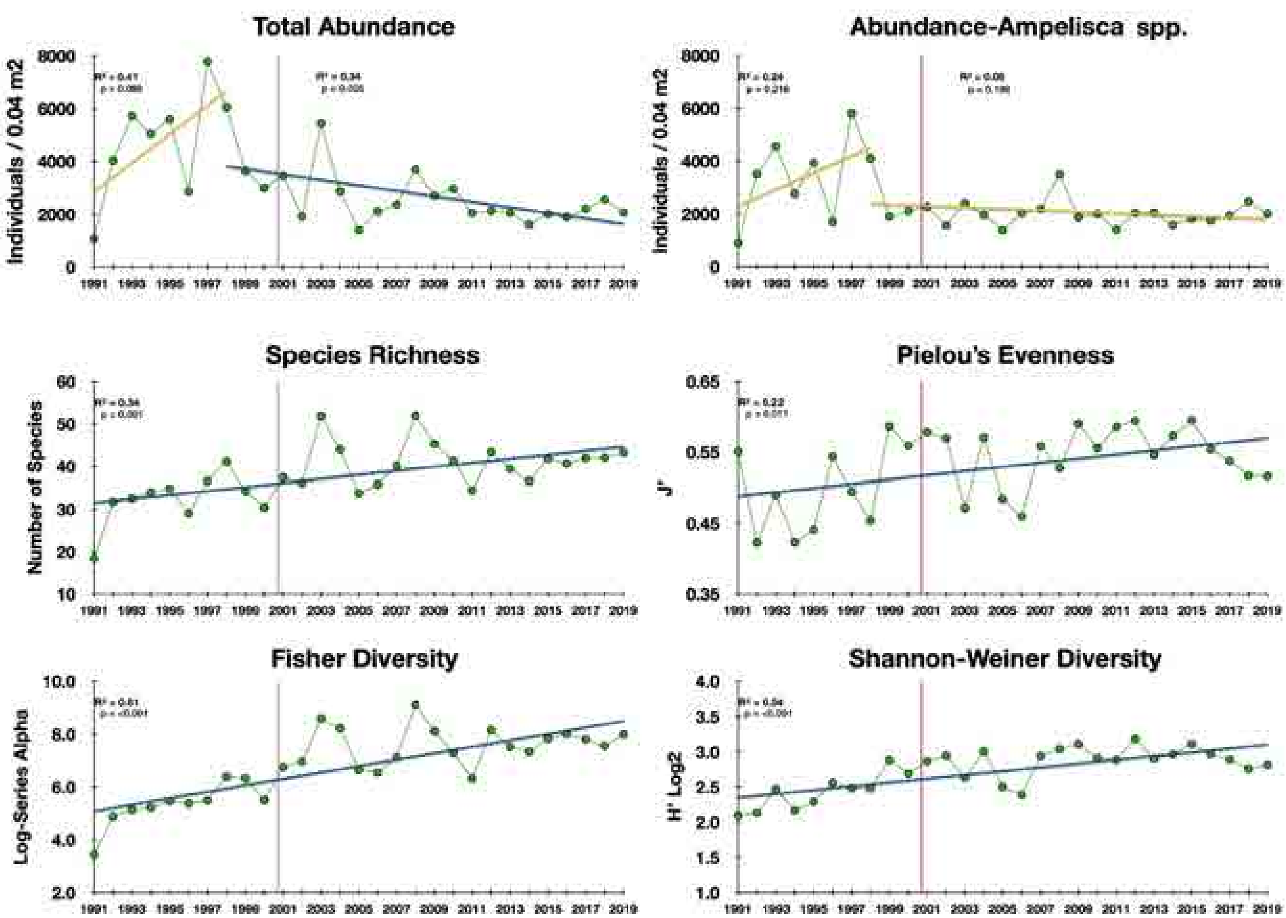


Figure 3-45. Trends in community structure parameters thought time. Significant linear regression lines are green. Yellow lines are not significant but likely indicate trend in abundance. The vertical line shows the diversion to the offshore outfall.

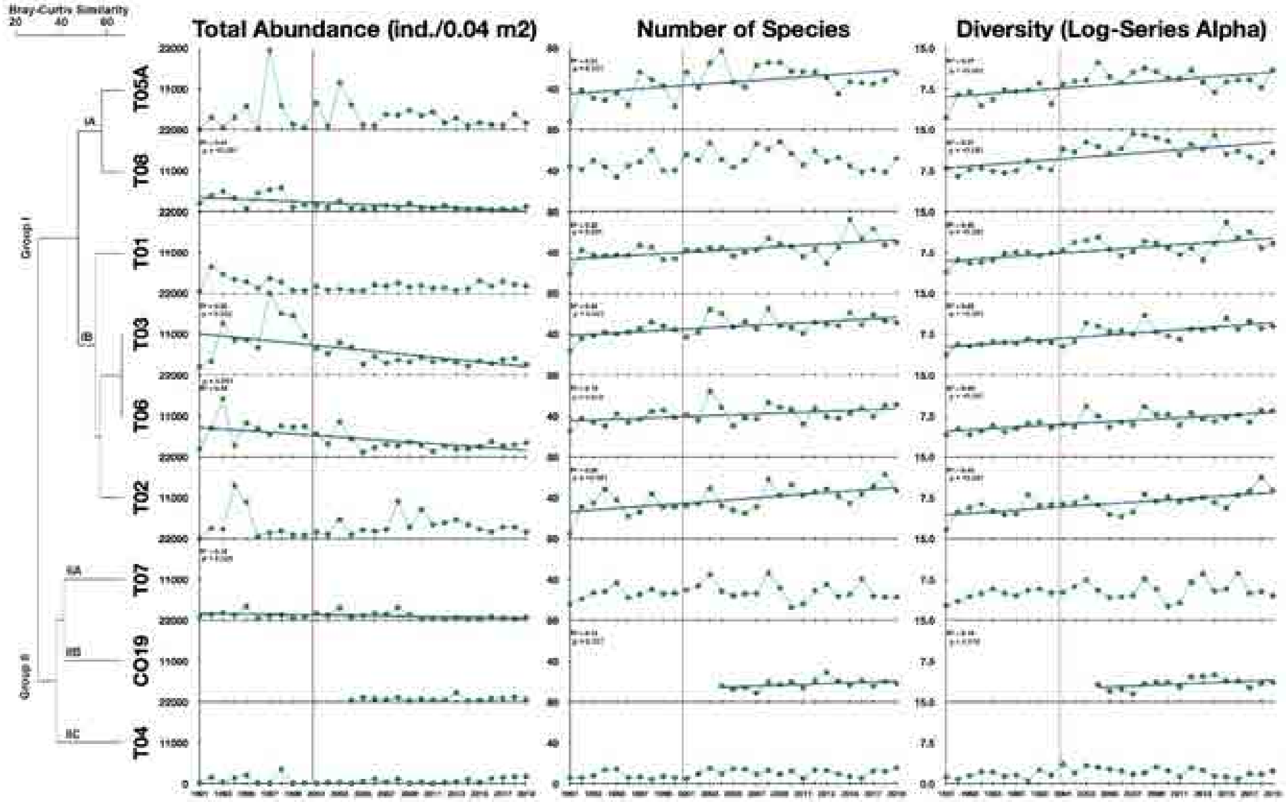


Figure 3-46. Trends in community structure parameters by station arranged by cluster analysis grouping. Significant linear regression lines are green. The vertical line shows the diversion to the offshore outfall.

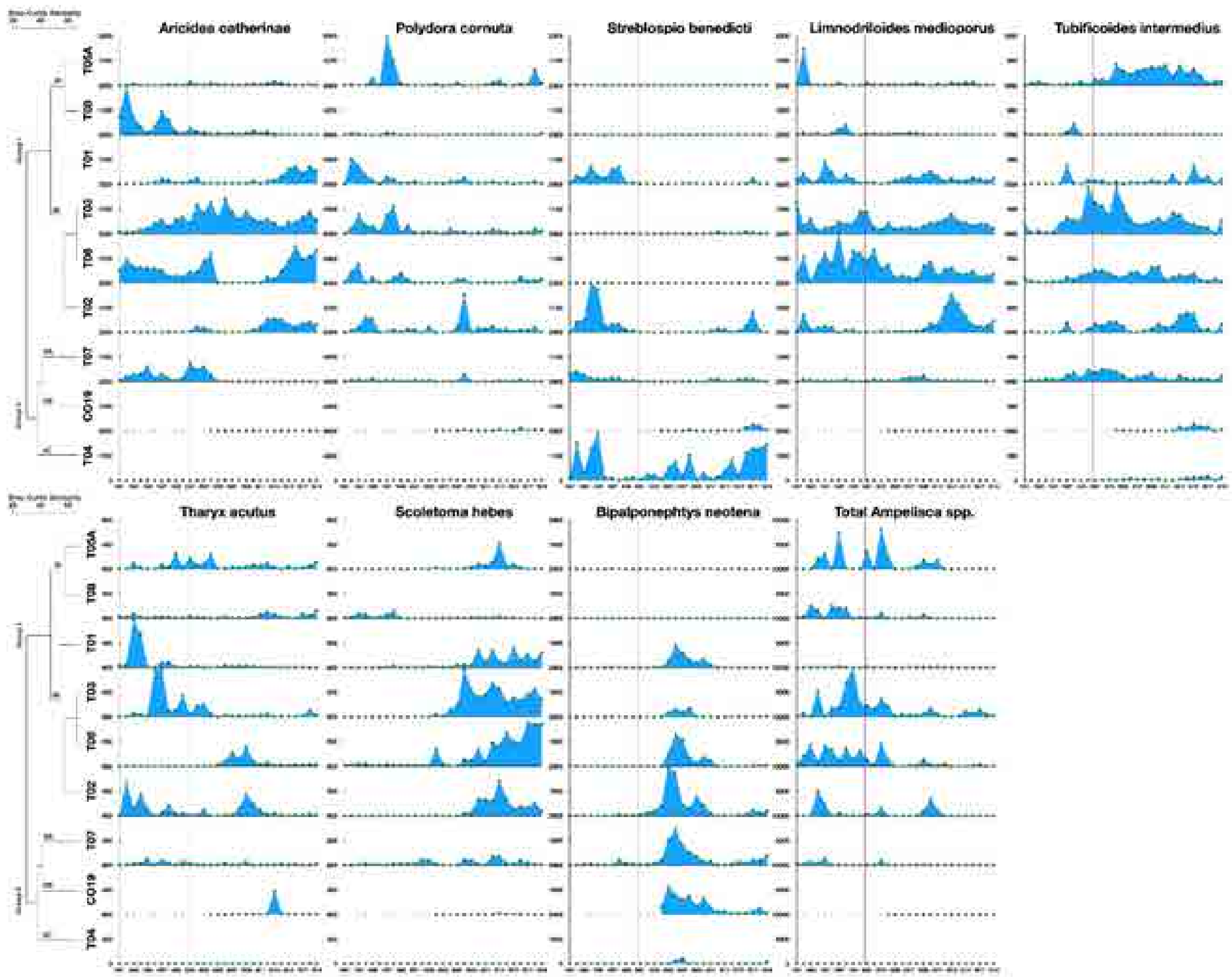


Figure 3-47. Abundance of top nine dominant species for 2019 arranged by cluster analysis grouping. The vertical line shows the diversion to the offshore outfall.

Summary

Improvements in wastewater treatment and moving the outfall offshore did result in improved benthic habitat quality within Boston Harbor by favoring processes that enhance bioturbation or the mixing of sediment by organisms, which has led to more aerobic sediment conditions, particularly for outer Harbor regions.

From 2003 on, regional variation in habitat quality occurred but was no longer related to improvements in wastewater treatment and diversion to the offshore outfall. Inner to outer harbor gradients were less obvious and primarily maintained by the Harbor's complex geomorphology and hydrodynamics, and secondarily to sediment grain-size.

Changes in habitat quality now appear to be driven by either broader harbor-wide forcing factors such as storms and climate variability, or other local-scale factors such as dredging. Climate change has already altered sea level, storminess, wind and wave energy, temperature, and salinity in the Boston region.

4. CONCLUSION

Overall, the improvements in wastewater treatment and moving the outfall offshore have led to improvements in water quality and benthic habitat quality within Boston Harbor by reducing organic and nutrient loading and favoring processes that enhance bioturbation or the mixing of sediment by organisms. From 1990 to the present, the predominant origin of sediment organic matter in Boston Harbor has shifted from sewage to marine derived. Recovery of benthic communities has enhanced bioturbation rates by infaunal and epibenthic species and has led to more aerobic and 'healthier' sediment conditions by enhancing remineralization of legacy organics and nutrients stored in the sediments from years of sewage disposal. Physical and biological properties of the soft substrate in Boston Harbor in 2019 exhibited minor changes from recent years but were consistent with longer-term trends (Rutecki et al. 2019a, Appendix A). Concentrations of both TOC and *Clostridium perfringens*, indicators of organic enrichment and deposition from municipal wastewater discharge, have remained low at most stations compared to the levels occurring prior to the offshore diversion.

Community structure measures also continue to point to improving benthic conditions. Since municipal wastewater and sludge discharges have been eliminated from the Harbor, total abundance has trended downward, particularly for opportunistic species such as *Capitella capitata*. Species richness, while variable, has trended upward as did evenness (J'), Shannon diversity (H'), and log series alpha diversity with all measures appearing to reach static levels in recent years. Although abundances of individual taxa, such as the dominants *Ampelisca* spp., *Aricidea catherinae*, and *Polydora cornuta* have varied over time, the infaunal community structure and evidence from sediment profile imaging suggest that these changes relate more to normal physical disturbances than organic stress in the years since wastewater impacts to the Harbor have been reduced. The trends observed in previous years, including reduction of indicators of organic enrichment and increases in species diversity, that persisted in the 2019 survey are consistent with the recovery of benthic habitats from decades of inadequately treated sewage discharges.

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Appendix A Revised Tables and Figures for the 2018 Boston Harbor Benthic Monitoring Report

Introduction

After the completion of the 2018 Boston Harbor Benthic Monitoring Report, an omission in reporting oligochaetes (e.g., *Limnodriloides medioporous* and *Tubificoides intermedius*) in the 2018 Harbor infaunal data was discovered during the review of the 2019 Harbor Infaunal Data Report. The oligochaete counts from five Harbor stations, C019, T01, T02, T03, and T04, were missing and not entered into the Statistical Analysis System (SAS) software when data sets were compiled. Upon investigation, these data were found to have been lost during data processing of the 2018 Harbor infaunal data as a result of a corrupted Excel file. This issue was confirmed to be isolated to a single corrupt file affecting only oligochaete data in the replicates from these stations. The 2018 Harbor Infauna data were corrected to include the missing oligochaete counts and resubmitted to the project database. The missing data affected the 2018 community parameters at the five stations, dominant taxa, analysis for the eight Boston Harbor stations (T01-T08), analysis of the selected stations, and the classification by hierarchical agglomerative clustering and ordination by non-metric multidimensional scaling (MDS) analyses. This Appendix presents the revised tables and figures for the 2018 Boston Harbor Benthic Monitoring Report corrected to include the missing data.

A review of the 2018 harbor benthic monitoring report indicated that the while individual analyses and figures would be changed by including the oligochaete results, the findings and conclusions of the report would not be affected.

Revised 2018 Tables and Figures

The following tables and figures, organized by subsection, present the revised benthic infauna results for the 2018 Boston Harbor benthic surveys.

Community Parameters

A total of 43,738 infaunal organisms were counted from the 18 samples processed in 2018. Organisms were classified into 148 discrete taxa, 136 of which were species-level identifications. More than 98% of the individuals were identified to species; all remaining individuals were identified to genus or family. 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 (Revised Table 3-2). Data are presented in Revised Figures 3-7 through 3-14 as means (averages per station) unless otherwise noted.

Revised Table 3-2. Mean 2018 infaunal community parameters by station.

Station	Total Abundance	Number of Species	Pielou's Evenness (J')	Shannon-Wiener Diversity (H')	Log-series alpha
C019	1333.0	20.0	0.56	2.41	3.35
T01	2475.5	47.5	0.61	3.38	8.41
T02	3075.0	63.0	0.59	3.51	11.25
T03	4466.5	53.0	0.57	3.25	8.50
T04	1922.0	12.0	0.30	1.05	1.72
T05A	4192.0	48.5	0.40	2.22	7.72
T06	3337.5	51.0	0.54	3.07	8.55
T07	412.5	23.0	0.56	2.54	5.26
T08	655.0	38.5	0.58	3.04	8.96

The eight most abundant species in 2018 each contributed 3.0% or more of the animals counted, and together they provided 75% 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 2018 (Revised Table 3-3) although the rank order changed.

Revised Table 3-3. Dominant taxa at eight grab stations (T01-T08) in Boston Harbor in August 2018.

Taxon	Total 2018 Abundance (compared with 2017)[a]
Polydora cornuta	10,750 (increase)
Aricidea catherinae	6,844 (increase)
Streblospio benedicti	3,295 (decrease)
Limnodriloides medioporus	2,803 (similar)
Scoletoma hebes	2,209 (similar)
Tubificoides intermedius	2,189 (increase)
Ampelisca spp.	1,566 (decrease)
Polygordius jouinae	1,193 (increase)

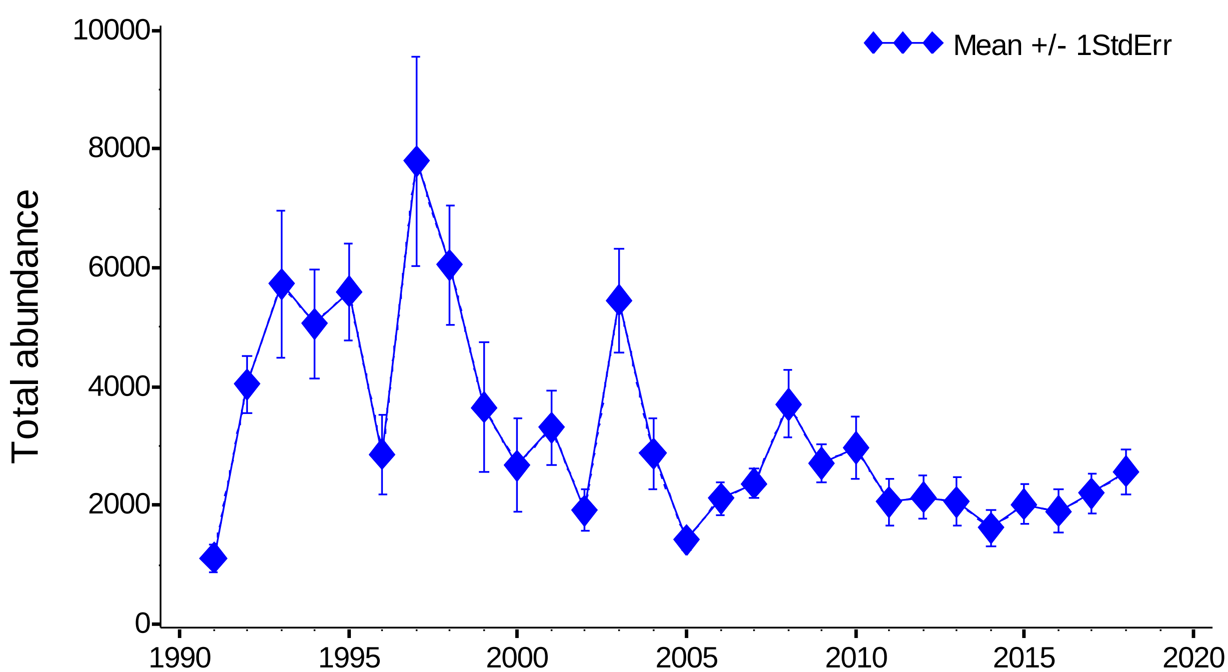
[a] increase or decrease indicates $\geq$25% change from previous year

The five most abundant taxa in 2018 have frequently been among the most abundant in the harbor during previous years (Revised Table 3-4).

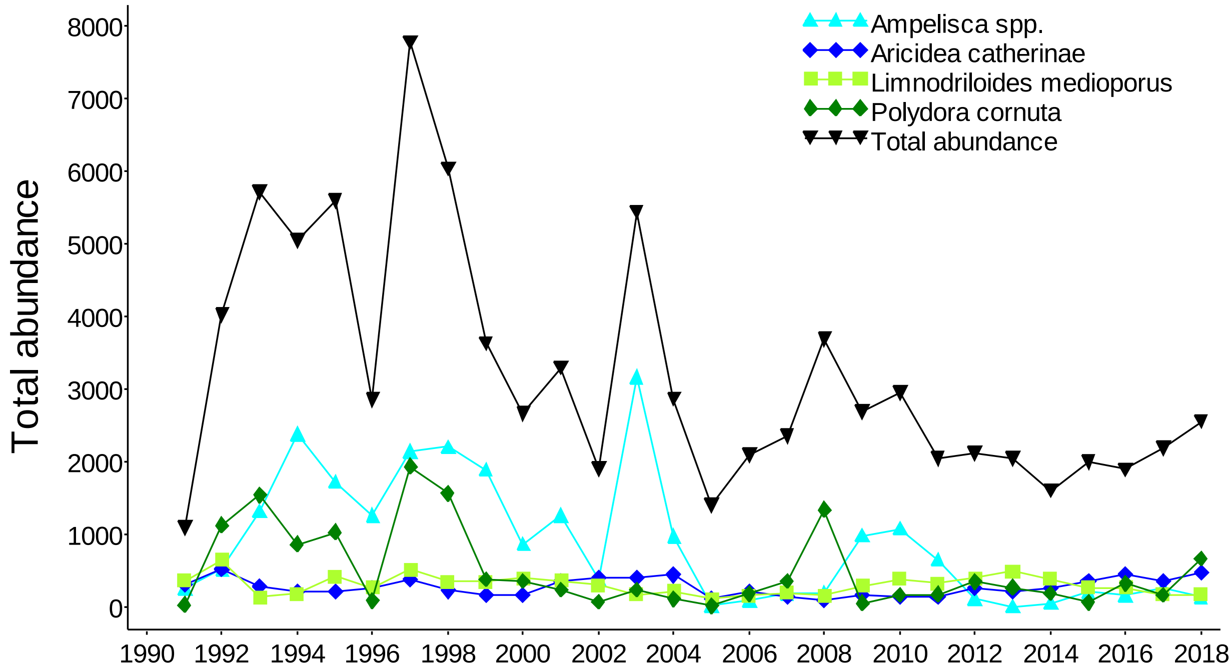
Revised Table 3-4. Mean abundance per sample of dominant taxa during four discharge periods at eight Boston Harbor stations (T01-T08), 1992-2018.

Phylum	Higher taxon	Family	Species[a]	Period I	Period II	Period III	Period IV	2018
Annelida	Polychaeta	Capitellidae	*Capitella capitata* complex	65.2	88.8	3.4	6.1	7.8
		Lumbrineridae	*Scoletoma hebes*	3.4	10.5	4.2	75.9	138.1
		Nephtyidae	*Bipalponephtys neotena*[b]	-	11.4	10.3	174.2	45.9
		Paraonidae	*Aricidea catherinae*	325.0	237.4	204.3	241.9	427.8
		Polygordiidae	*Polygordius jouinae*	19.2	22.4	44.0	18.1	74.6
		Spionidae	*Polydora cornuta*	525.8	1053.0	269.6	272.7	671.9
			Streblospio benedicti	236.0	298.6	27.7	87.4	205.9
	Oligochaeta	Tubificidae	*Limnodriloides medioporus*	484.7	297.9	315.2	236.7	175.2
			Tubificoides intermedius	42.6	101.4	231.2	242.6	136.8
Arthropoda	Amphipoda	Ampeliscidae	*Ampelisca* spp.	354.3	1698.3	1205.9	528.5	97.9
		Corophiidae	*Corophiidae* spp.	16.1	336.2	23.0	1.5	4.1
			Crassicorophium bonellii	7.9	217.3	37.3	7.1	2.2
			Leptocheirus pinguis	29.0	117.4	66.0	74.3	43.3
		Photidae	*Photis pollex*	11.4	77.0	86.8	29.1	1.4
		Phoxocephalidae	*Phoxocephalus holbolli*	28.0	116.9	125.9	6.1	4.7

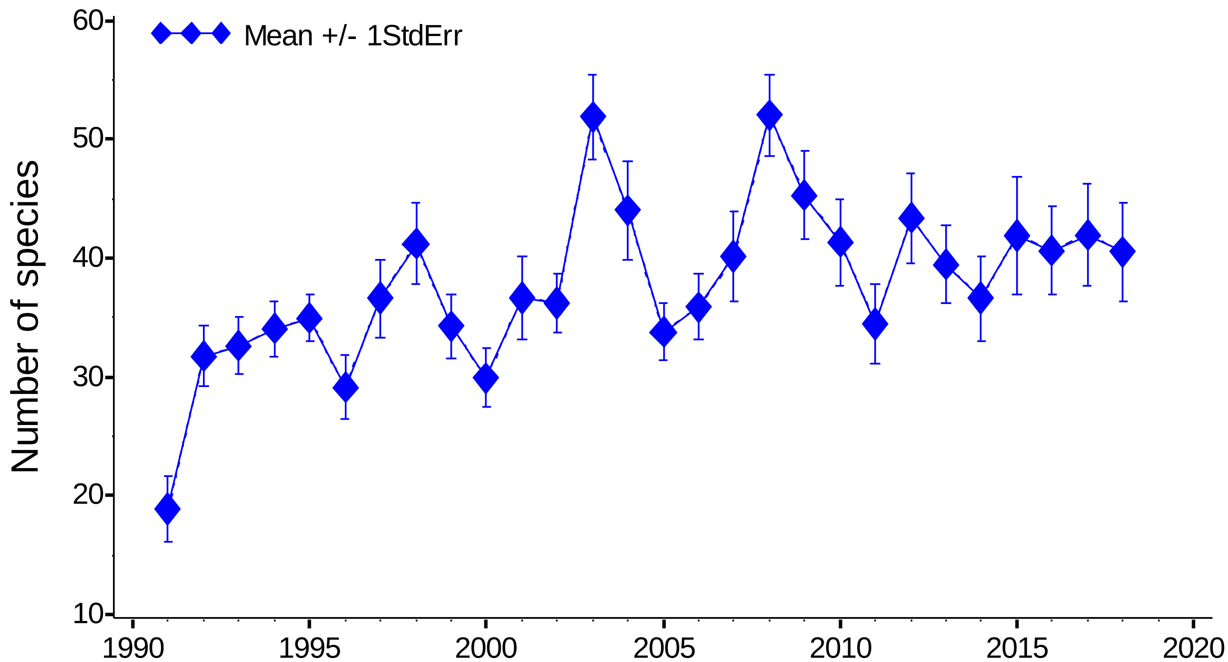
[a]Dominants identified as taxa cumulatively composing 75% of total abundance in each period.
[b]previously identified as *Nepthys cornuta.*



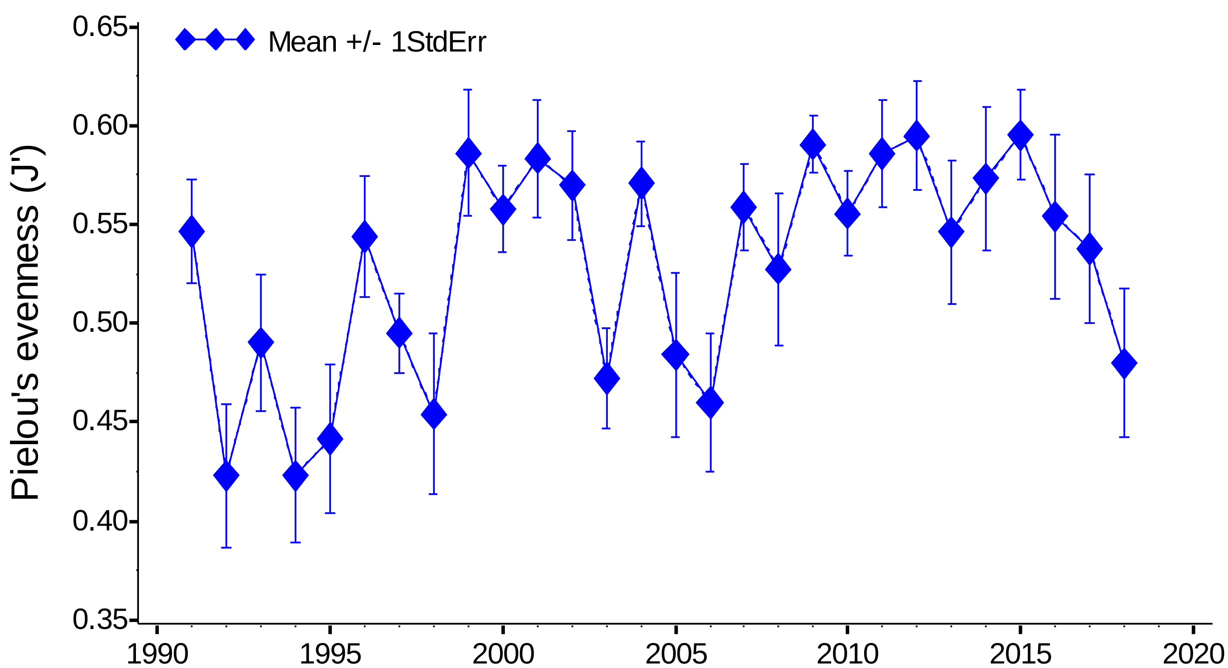
Revised Figure 3-7. Mean abundance of benthic infauna at eight Boston Harbor stations (T01-T08), 1991-2018.



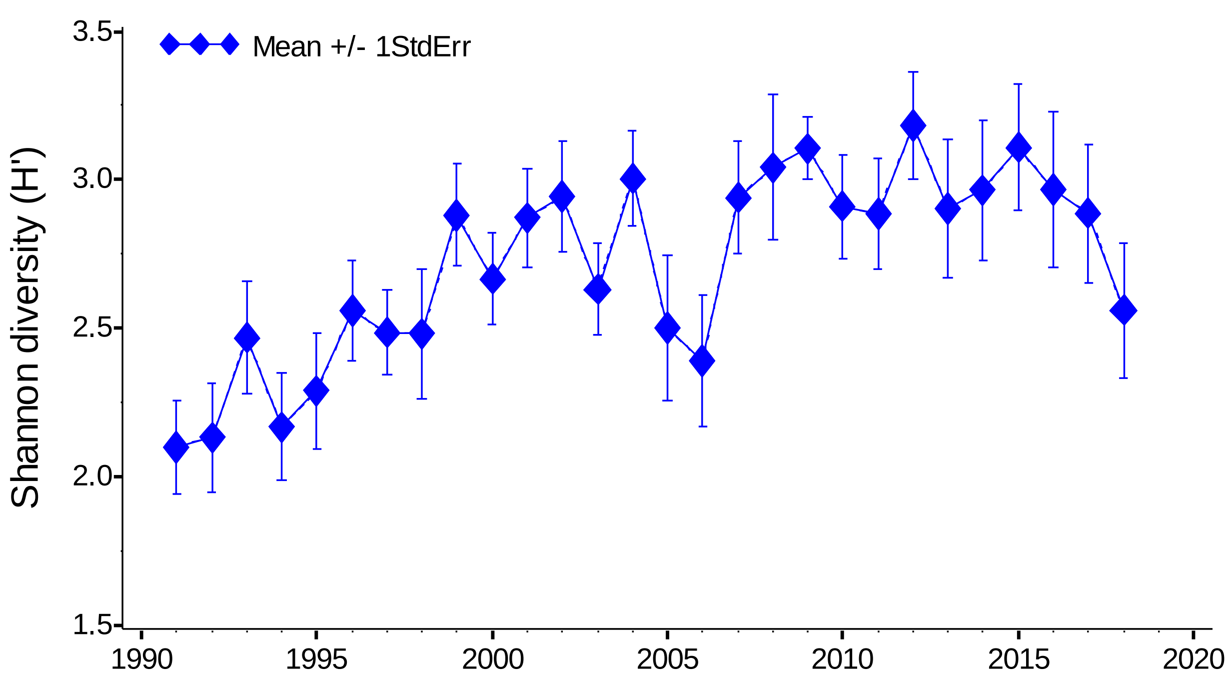
Revised Figure 3-8. Total abundance of four dominant taxa at eight Boston Harbor stations (T01-T08), 1991-2018.



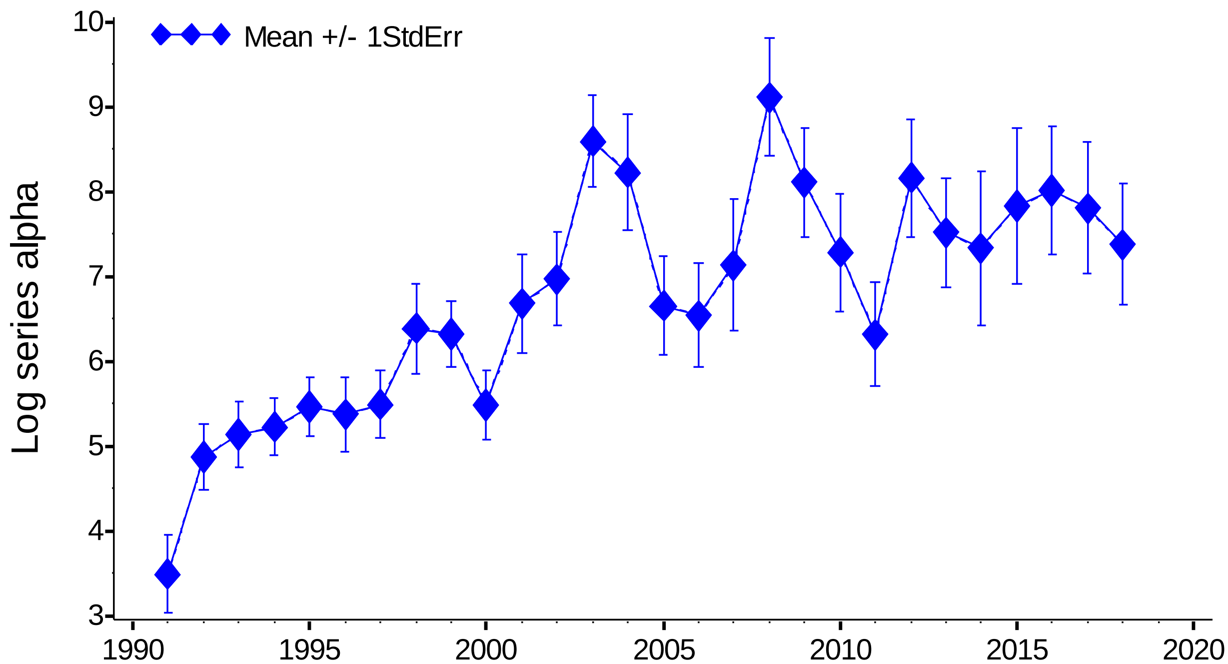
Revised Figure 3-11. Mean species richness at eight Boston harbor stations (T01-T08), 1991-2018.



Revised Figure 3-12. Mean community evenness at eight Boston Harbor stations (T01-T08), 1991-2018.



Revised Figure 3-13. Mean Shannon-Weiner diversity at eight Boston harbor stations (T01-T08), 1991-2018.



Revised Figure 3-14. Mean log-series alpha diversity at eight Boston Harbor stations (T01-T08), 1991-2018.

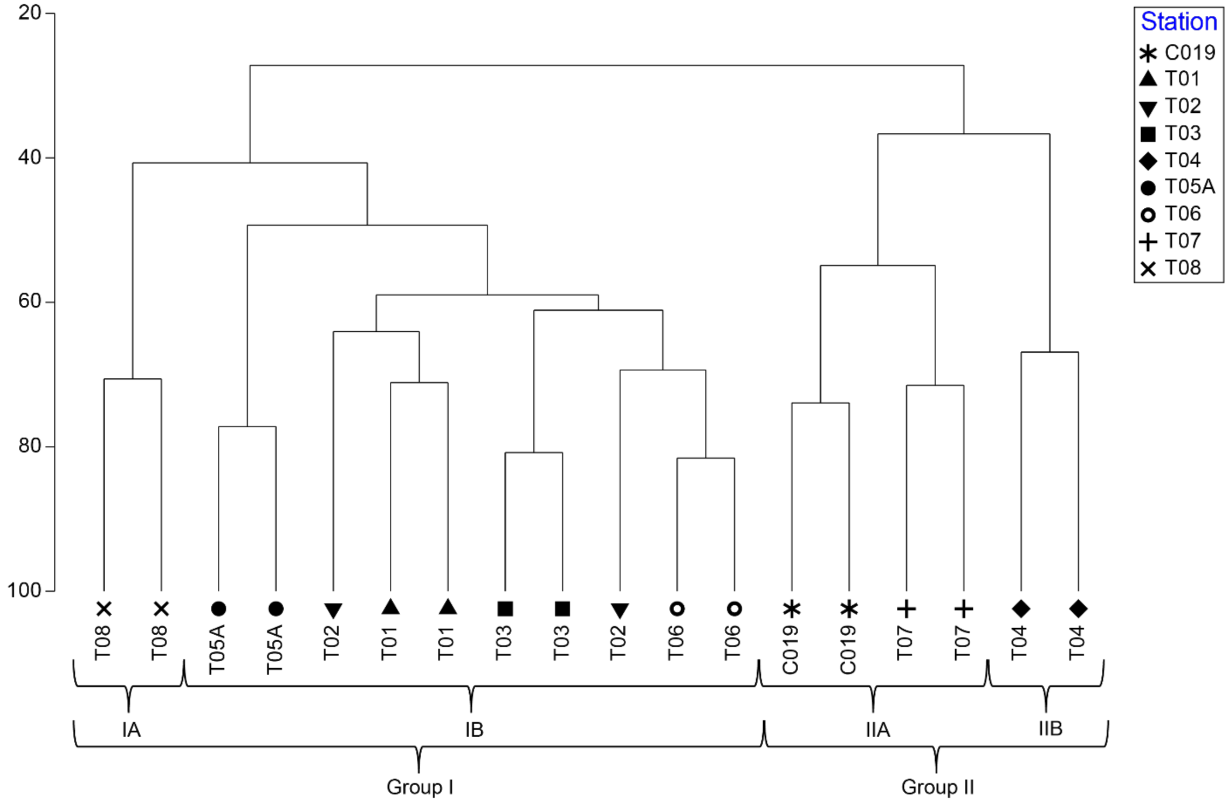
Infaunal Assemblages

Multivariate analyses were used to assess spatial and temporal patterns in the faunal assemblages at the Boston Harbor sampling stations. Replicates within each station exhibited high similarities in community structure and generally grouped together. Four main assemblages were identified in a cluster analysis of the 18 samples from 2018 (Revised Figure 3-15). Patterns identified through cluster analysis were confirmed in the MDS ordination plot for the 2018 Harbor samples (Revised Figure 3-15). The Group IA assemblage was found at outer Harbor Station T08; the Group IB assemblage was found at outer Harbor to mid-Harbor stations (T01, T02, T03, T05A, and T06); the Group IIA assemblage was found at Stations T07 (Quincy Bay) and C019 (Inner Harbor); and the Group IIB 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.

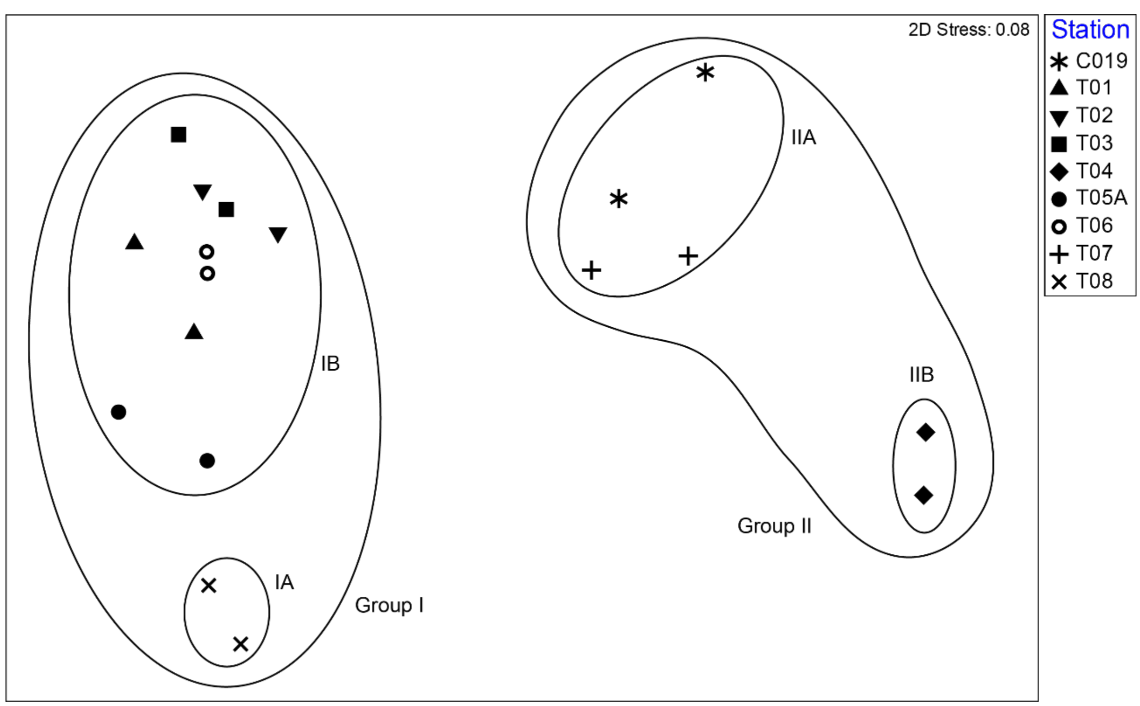
Main Group I encompassed six stations (T01, T02, T03, T05A, T06, and T08) characterized by relatively high abundance (averaging 3,034 individuals) and species richness (averaging 50 species per collection). Six species (*Polydora cornuta*, *Aricidea catherinae*, *Limnodriloides medioporus*, *Scoletoma hebes*, *Tharyx acutus*, and *Ameplisca* spp.) had relatively high abundances (Revised Table 3-5). Within Group I, Stations T08 was distinct enough to form Subgroup IA dominated by *Polygordius jouinae*, *Tharyx acutus*, and *Ameritella agilis*, and characterized by moderately high species richness (averaging 39 species per collection). Subgroup IB was comprised of Stations T01, T02, T03, T05A, and T06 characterized by high abundance and species richness (averaging 53 species per collection). Dominants included *P. cornuta*, *A.*

catherinae, *L. medioporus*, and *S. hebes*. The main Group II consisted of Stations C019, T04, and T07 dominated by three species, *Streblospio benedicti*, *Bipalponephtys neotena*, and *Cossura* sp. 1 (Revised Table 3-5). Stations C019 and T07 formed Subgroup IIA and were dominated by the three species that dominated the main Group II. This subgroup was characterized by low abundance and species richness (averaging 22 species per collection). Station T04 was distinct enough to form Subgroup IIB dominated by *S. benedicti*, total abundance was moderate and species richness was low.

a.



b.



Revised Figure 3-15. Results of (a) cluster analysis and (b) multidimensional scaling analysis of the 2018 infauna samples.

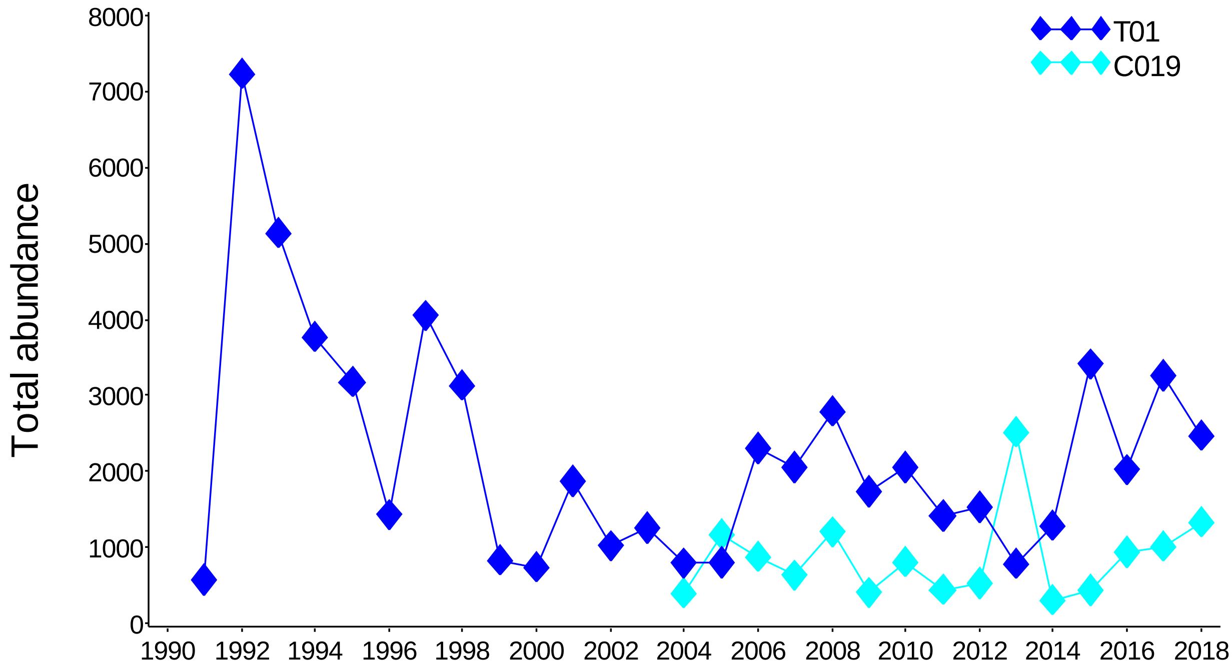
Revised Table 3-5. Mean abundance of dominant taxa in 2018 Boston Harbor station groups defined by cluster analysis.

Major Taxon	Family	Species	I	IA[a]	IB[a]	II	IIA[b]	IIB[b]
Bivalvia	Arcticidae	*Arctica islandica*	**1.7**	-	-	**0.8**	-	-
	Pandoridae	*Pandora gouldiana*	**0.8**	-	-	**0.8**	-	-
	Tellinidae	*Ameritella agilis*	**61.8**	123.5	49.5	**1.7**	1.0	3.0
Polychaeta	Capitellidae	*Capitella capitata complex*	**-**	2.5	11.8	**-**	0.3	1.0
		Mediomastus californiensis	**18.9**	-	-	**0.2**	-	-
	Cirratulidae	*Tharyx acutus*	**80.3**	166.5	63.1	**11.8**	8	19.5
	Cossuridae	*Cossura* sp. 1	**2.7**	-	3.2	**143.0**	214.5	-
	Hesionidae	*Microphthalmus pettiboneae*	**7.0**	-	8.4	**9.5**	13.8	1.0
	Lumbrineridae	*Scoletoma hebes*	**182.1**	1.5	218.2	**4.2**	6.0	0.5
	Maldanidae	*Clymenella torquata*	**98.3**	24.0	113.2	**-**	-	-
	Nephtyidae	*Bipalponephtys neotena*	**28.8**	-	34.5	**151.5**	226.5	1.5
		Nephtys incisa	**0.3**	-	-	**1.2**	-	-
	Orbiniidae	*Leitoscoloplos robustus*	**5.3**	-	-	**1.3**	-	-
	Paraonidae	*Aricidea catherinae*	**569.8**	4.0	682.9	**1.7**	2.5	-
	Pholoidae	*Pholoe* spp.	**6.8**	-	-	**0.7**	-	-
	Phyllodocidae	*Phyllodoce mucosa*	**33.6**	1.5	49.6	**-**	-	-
	Polygordiidae	*Polygordius jouinae*	**99.4**	189.0	81.5	**0.2**	0.3	-
	Spionidae	*Dipolydora quadrilobata*	**39.4**	-	-	**-**	-	-
		Polydora cornuta	**880.7**	18.5	1053.1	**86.8**	111.5	37.5
		Pygospio elegans	**24.2**	-	-	**-**	-	-
		Spiophanes bombyx	**18.0**	40.5	13.5	**-**	-	-
		Streblospio benedicti	**18.2**	-	21.8	**591.8**	139.3	1497.0
	Syllidae	*Exogone hebes*	**19.1**	8.5	21.2	**-**	-	-
	Terebellidae	*Polycirrus phosphoreus*	**4.3**	0.5	5.0	**7.2**	10.8	-
Oligochaeta	Tubificidae	*Limnodriloides medioporus*	**230.5**	10.5	274.5	**7.0**	8.8	3.5
		Naidinae sp. 1	**35.4**	-	-	**0.3**	-	-
		Tubificoides benedeni	**8.6**	-	10.3	**2.8**	0.3	8.0
		Tubificoides intermedius	**173.5**	6.5	206.9	**73.2**	109.8	-
		Tubificoides sp. 2	**-**	-	-	**113.5**	-	340.5
Amphipoda	Ampeliscidae	*Ampelisca* spp.	**130.4**	-	156.5	**0.2**	0.3	-
	Aoridae	*Grandidierella japonica*	**-**	-	-	**-**	-	2.0
	Corophiidae	*Leptocheirus pinguis*	**57.7**	-	69.2	**-**	-	-
	Phoxocephalidae	*Rhepoxynius hudsoni*	**-**	7.5	-	**-**	-	-
Decapoda	Paguridae	*Pagurus longicarpus*	**0.3**	-	-	**1.7**	-	-

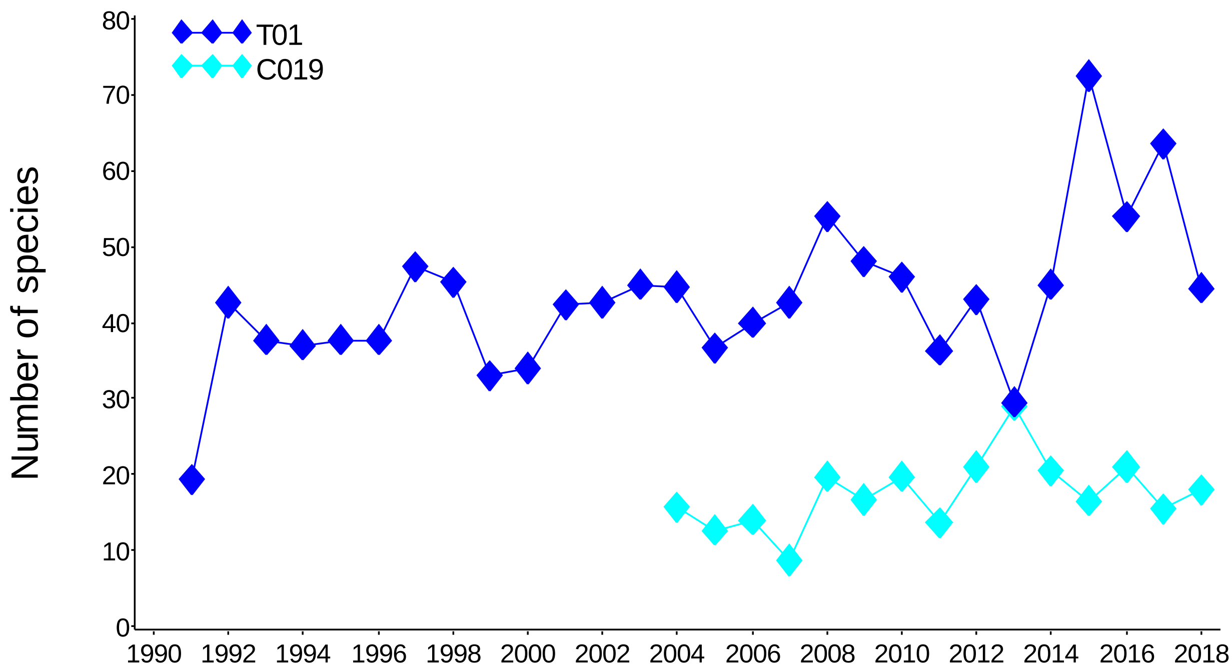
[a] distinct subgroup of Group I
[b] distinct subgroup of Group II

Selected Stations

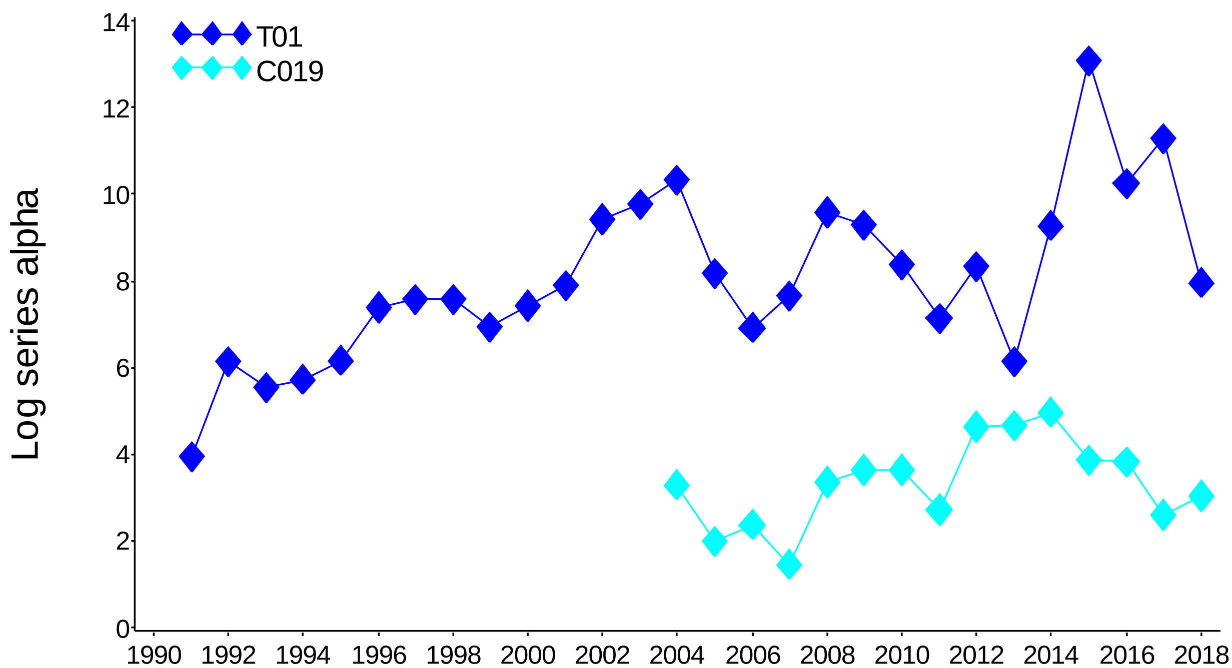
Two stations, T01 and C019, were selected for further review (Revised Figures 3-16 through 3-20). Station T01, located near Deer Island Flats north of President Roads, was selected as the infaunal community conditions at have typically exemplified conditions at most outer and mid- Harbor stations throughout the survey period. C019 was selected as it was excluded from the earlier community parameter analysis as sampling began in 2004 at this station.



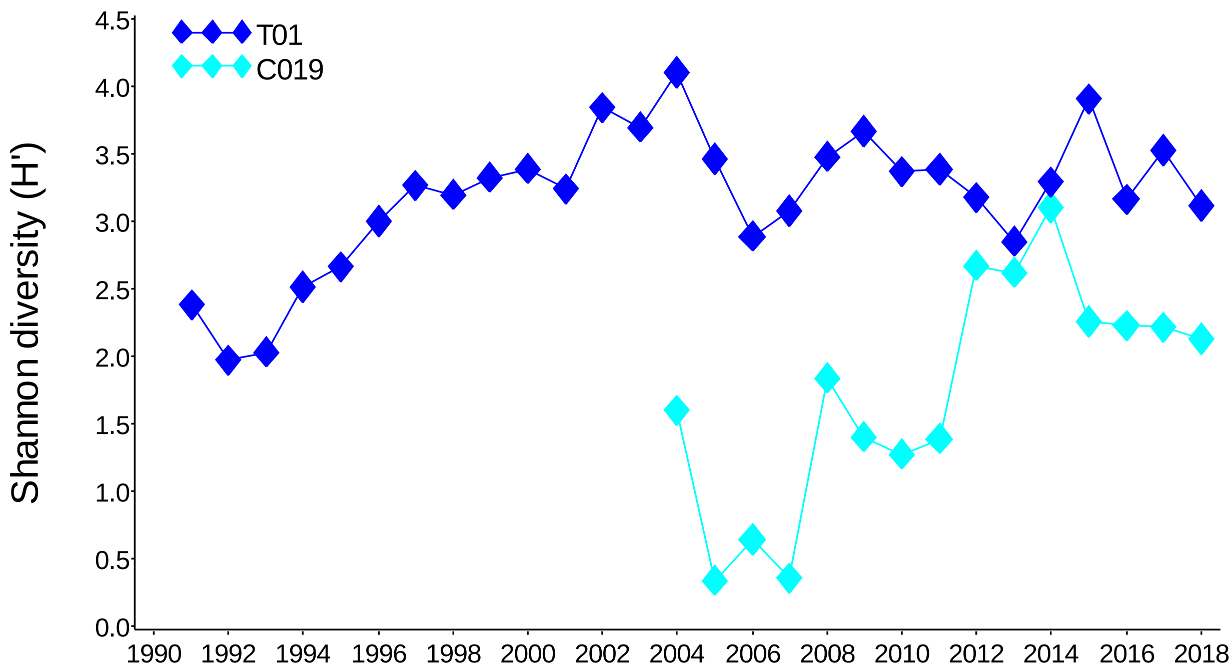
Revised Figure 3-16.   Mean total abundance at Boston Harbor Stations T01 and C019, 1991-2018.



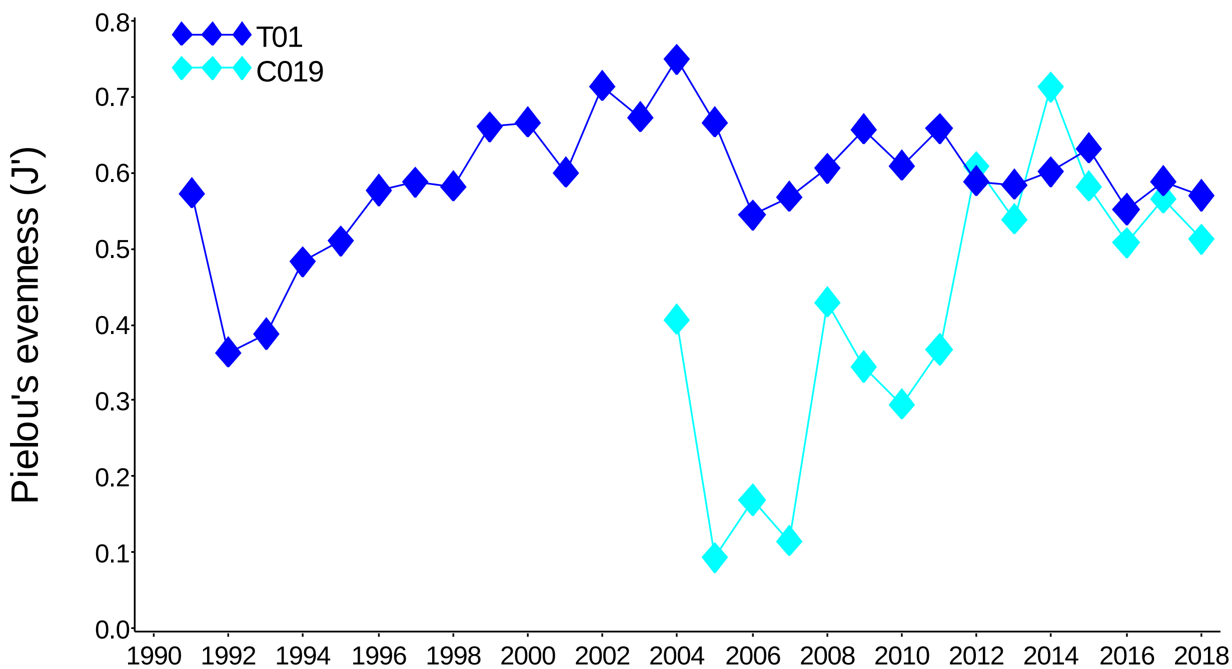
Revised Figure 3-17. Mean species richness at Boston Harbor Stations T01 and C019, 1991-2018.



Revised Figure 3-18. Mean log-series alpha diversity at Boston Harbor Stations T01 and C019, 1991-2018.



Revised Figure 3-19. Mean Shannon-Weiner diversity at Boston Harbor Stations T01 and C019, 1991-2018.



Revised Figure 3-20. Mean evenness at Boston Harbor stations T01 and C019, 1991-2018.

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 (Revised 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 2002-2018 were virtually the same as for 2002-2017 (Rutecki et al. 2019) so it is apparent that this trend has continued.

Revised 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	2,538	121
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	0.54	0.01
Number of Species	25.4	2.1	34.7	1.1	33.6	1.7	41.2	0.9
Years included (with one year offset)	1991-1992		1993-1998		1999-2001		2002-2018	

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