2007 Annual benthic nutrient flux monitoring report

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2007 Annual
Benthic Nutrient Flux
Monitoring Report

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EXECUTIVE SUMMARY

The Benthic Nutrient Flux Studies were initiated in 1990 to examine spatial and temporal trends of benthic processing of organic matter at selected stations in Boston Harbor and Massachusetts Bay. The overall objectives of the studies have been to quantify sediment-water exchanges of oxygen, total carbon dioxide, and nutrients in order to define benthic-pelagic coupling in the harbor and bay. In addition, sediment indicators of organic matter loading and processing, such as organic carbon and pigment concentrations and redox conditions, have also been monitored. Until late in 2000, the focus of these studies was on monitoring the recovery of the harbor as sewage treatment was improved, and in providing baseline information about all of these processes in Massachusetts Bay before the ocean outfall became operational. In 2001, monitoring of the harbor recovery continued, but baseline monitoring of the bay ended. The emphasis changed to monitoring the response of the bay ecosystem to the relocation of the outfall.

We are now examining the baseline and post-relocation data in terms of the Outfall Monitoring Plan that was written in 1991 to guide the monitoring efforts in Massachusetts Bay before and after the harbor outfall was relocated (MWRA, 1991). The two questions that were posed for the benthic flux monitoring of the Massachusetts Bay Nearfield were:

> I. How do the sediment oxygen demand, the flux of nutrients from the sediment to the water column, and denitrification influence the levels of oxygen and nitrogen in the water near the outfall?
>
> II. Have the rates of these processes changed?

MASSACHUSETTS BAY

In comparing seven years of monitoring data on benthic respiration and nutrient cycling in the sediments near the bay outfall to as many as eight years of baseline data, we have seen no evidence of change. In fact, highest values for many of the parameters we measure occurred in the first years of the monitoring program, long before effluent diversion. We have learned a tremendous amount about the variability that is natural to the system, and this knowledge increases our ability to detect change, whether it may be related to the outfall or to other, region-wide phenomena.

Of major concern is whether the diversion of the outfall might cause increased organic matter loading to the nearfield sediments. A comparison of baseline to post-baseline organic carbon content in surface sediments shows there has been no such change at any of our stations. In 2007, the nearfield station average TOC was 1.3%, near the center of the baseline range of 0.9% to 2.3%. The farfield station has shown little variability over the monitoring period. Its average for 2007 was 1.6%, compared to a baseline range of 1.2 to 1.7%.

A notable detail for 2007 was a high TOC value at the northern-most nearfield station, MB01, in May. This elevated TOC may have been caused by deposition of the winter/spring diatom bloom. TOC declined at this station through the season, presumably as this “fresh” carbon was consumed in the sediments, reaching quite low values by October. Similar evidence of the bloom was not observed at the other two nearfield stations.

Sediment chlorophyll *a* content, another measure of organic carbon loading, also has shown no change compared to baseline. Seasonal averages for 2007 were typical of the entire monitoring period, but variable across stations. Station MB01 had the highest inventory for the year (8.7 µg cm^{-2}), elevated by large surface concentrations of chlorophyll *a* in May, consistent with the TOC data and with deposition of the winter/spring bloom. The other two nearfield stations did not have a May peak, but Station MB03 showed a small July peak that may have been related to a coastal diatom bloom. Seasonal inventories at these two stations (4.5 and 7.5 µg cm^{-2} from MB02 and MB03, respectively) were lower than in the previous year and more typical of the long-term dataset Farfield Station MB05 had an average seasonal chlorophyll *a* inventory of 3.2 µg cm^{-2} in 2007, a low value compared to the nearfield and for this station.

Average rates of SOD at the three nearfield stations in 2007 (12.1 mmol m^{-2} d^{-1}) were lower than both the baseline mean (17.2 mmol m^{-2} d^{-1}and the post-baseline (2001-2006) mean (15.7 mmol m^{-2} d^{-1}), and variability was very small. Changes in rates through the season were well correlated with temperature, but not with TOC or chlorophyll. SOD at the farfield station was 11.3 mmol m^{-2} d^{-1}, very similar to the nearfield average, emphasizing that low rate, but quite typical for this station.

Fluxes of DIN in 2007 were also low, averaging 0.4 mmol m^{-2} d^{-1} for the three nearfield stations as compared to 0.8 mmol m^{-2} d^{-1} for the baseline and 0.6 mmol m^{-2} d^{-1} for the post-baseline periods. At Station MB05, average DIN flux was typical at 0.2 mmol m^{-2} d^{-1}. Nitrate comprised the majority of the flux at all stations, a scenario that is consistent with oxidizing conditions within the sediments.

An interesting feature of the DIN fluxes in 2007 was the uptake rather than efflux of NH_4^+ in July at Station MB03, which has become more frequent at this site since 2002. We speculate that this uptake was due to coupled nitrification/denitrification, but cannot entirely discount uptake by primary producers. The seasonal average PO_4^- flux at the nearfield stations in 2007 was a small efflux of 0.01 mmol m^{-2} d^{-1}. In 2006, the average had been an influx of 0.02 mmol m^{-2} d$^{-1\ 1}$. The 2007 average was equivalent to the post-baseline mean, and smaller than the baseline mean of 0.05 mmol m^{-2} d$^{-1.}$ Within-season dynamics included a strong uptake at Station MB03 in July, coinciding with the NH_4^+ uptake noted above.

Average nearfield Si flux was 2.9 mmol m^{-2}d^{-1} compared to the baseline average of 4.9 mmol m^{-2}d^{-1}, and also lower than the post-baseline mean of 3.4 mmol m^{-2}d^{-1}. At MB05, Si fluxes in 2007 were 3.2, slightly higher than the nearfield average, but lower than the baseline and post-baseline means for this station.

The potential contribution of nutrients recycled in the benthos to water column primary production remained small in 2007. For the post relocation period, including 2007, average DIN flux could account for about 4% of primary production, and, for years with efflux (4 out of 7), PO_4^- flux could contribute about the same. Dissolved silica flux, on the other hand, could contribute between 25% and 30% of phytoplankton requirements. These potential contributions are essentially the same as they were during the baseline period.

The average denitrification rate for in the nearfield for 2007 was 1.2 mmol N m^{-2} d^{-1}, lower than in the previous year but similar to 2004 and 2005 and within the range of the long-term dataset. At MB05, the seasonal average was 0.9 mmol N m^{-2} d$^{-1.}$ Denitrification continues to be the major component of the total inorganic nitrogen (DIN + N_2) flux, generally comprising 60-85% of the total in the nearfield, and 80-90% at the farfield station. When DIN flux is directed into the sediments, denitrification makes up 100% of the efflux.

There was no indication of decreased sediment oxidation in any of our measurements. At all four stations, respiratory quotients ranged were just below 1.0, the value indicative of aerobic respiration. Eh profiles indicated oxidizing sediment conditions.

BOSTON HARBOR

The diversion of wastewater disposal from the mouth of Boston Harbor to the offshore location was the final step in minimizing the impacts of the Deer Island Treatment Facility on the harbor, but recovery in the harbor began before this event as various stages of treatment improvements were initiated. In particular, reductions in solids loading to the harbor were very significant to the benthic community, contributing to decreases in sediment organic carbon that were observed well before outfall relocation. Very high rates of benthic respiration "burned off" much of the carbon stores within the sediments, enhanced by the bioturbating effects of the *Ampeliscid* amphipod community that bloomed in the harbor during this period. With the diversion, a large source of nutrients to the water column was removed, leading to decreases in primary production, and thereby further decreases in inputs to the sediments.

The cumulative effects are that organic carbon content of the sediments, benthic respiration, and other nutrient fluxes, as well as spatial and temporal variability, have decreased. Last year, six years after outfall relocation, we suggested that these processes had seemingly stabilized at levels quite typical of many coastal marine environments. In general, that description was valid for 2007, but there was a break in this pattern at Station BH02.

We have often described Station BH02 as showing less or slower improvement than the other three stations, in particular in comparison to the other north harbor station, BH03. We have attributed the relative lack of change partly to the station's location near the mouth of the Charles River as well as it's proximity to shipping channels and Boston's international airport with potential inputs and disturbances from all of these. In addition, we have noted the relative scarcity of benthic infauna at this site; for instance, the amphipod community that played such an important role in accelerating recovery at Station BH03 was rarely present here.

During the July and August surveys in 2007, we were surprised to find sediments at Station BH02 heavily colonized by benthic infauna. Bioturbation had caused a dramatic deepening of the surface oxidized layer. Following the pattern of enhanced fluxes we had observed earlier in the monitoring program at stations colonized by the amphipod mats, summer fluxes at BH02 were anomalously high. In the ongoing monitoring, we will be curious to see if this station is finally "catching up" in the recovery process.

In 2007, average total organic carbon content (TOC) at our four stations ranged from 1.7 % at Stations BH02 and BH08A to 2.6 % at Station QB01. These values are all in the low end of the long-term range, and at BH02 marked a decrease from a very stable 7-yr average of 2.0 %. Lower TOC at Station BH02 was observed before colonization, however, and varied little through the season. At the other three stations, decreases in TOC from the very high values in the early 1990s seem to reflect the step-wise reductions in solids loadings. At BH02, however, large temporal variability has obscured long-term change.

Sediment chlorophyll *a* inventories in 2007 were typical for the trends observed at each station for the previous four years. It has become characteristic at Station BH02 and Station QB01 to have higher chlorophyll levels than the other two stations. In 2007, the average seasonal inventory for these two stations was 23.3 $\mu g\ cm^{-2}$ compared to 9.4 $\mu g\ cm^{-2}$ at BH03 and BH08A (all stations down from the previous year). Higher chlorophyll levels are consistent with the presence of benthic diatoms often observed at Stations BH02 and QB01.

Average sediment oxygen demand in 2007 for all four stations was 48.7 mmol $m^{-2}\ d^{-1}$, lower than the baseline mean of 62.4 mmol $m^{-2}\ d^{-1}$ but higher than the post-baseline (excluding 2007) mean of 34.0 mmol $m^{-2}\ d^{-1}$. Although rates at three of the four harbor stations were within the post-baseline range, the overall average was raised by a high seasonal average for Station BH02, which in turn was driven by unusually high summer rates at this station. Respiration rates were enhanced by the infaunal community. The high seasonal average at BH02 was as high as had been seen during the baseline period.

Fluxes of DIN, and PO_4^- followed the same pattern as SOD. Seasonal averages, 4.2 and 0.24 mmol m-2 d-2, respectively, were lower than the baseline mean but higher than the post-baseline mean. Again, these rates were raised by the summer fluxes at Station BH02, which in the case of DIN exceeded both baseline and post-baseline observations for this station. Most of the increase was in the NO_3^- component of the flux, which is consistent with active bioturbation. For PO_4^-, the 2007 average at BH02 exceeded post-baseline observations, but did not exceed the range observed during the baseline period.

The harbor average dissolved Si flux of 7.0 mmol m^{-2} d^{-1} exceeded both the baseline and post-baseline means. Extremely high summer fluxes drove the seasonal average for Station BH02 to the highest value yet observed at this station. Benthic diatoms are often observed at this station, and we speculate that a large potential pool of Si combined with strong bioturbation may have created these large fluxes.

Since outfall diversion, water column primary production in the harbor has decreased by about 50%. Benthic fluxes of DIN and PO_4^- have decreased a similar amount, about 45%. Dissolved Si fluxes, on the other hand, have decreased only about 15%. Consequently, we have seen little change in the potential contribution of DIN and PO_4^- fluxes to primary production, but an increase in the potential contribution from Si fluxes. For the post-diversion period, DIN and PO_4^- fluxes could account for between 20% and 25% of phytoplankton requirements, respectively, while Si fluxes could account for 44%.

Rates of denitrification have been temporally and spatially very variable at the two harbor stations where it has traditionally been measured, BH02 and BH03. In the previous three years, when measurements from all four stations were made, denitrification had decreased and was less variable. In 2007, three of the four stations continued that pattern, but again, Station BH02 was the outlier, with high summer rates attributable to bioturbation. However, 2007 rates at Station BH02 were not atypical in the long-term dataset. The seasonal average for that station was 3.7 mmol N m^{-2} d^{-1}, whereas at BH03 it was 1.5 mmol N m^{-2} d^{-1}, the lowest rate yet observed at that station. For comparison, the baseline mean for these two north harbor stations was 5.5 mmol N m^{-2} d^{-1}. Rates at BH08A and QB01 for 2007 were 1.9 and 1.0 mmol N m^{-2} d^{-1}, respectively. Despite apparent decreases in denitrification rates, the importance of denitrification in the harbor N budget has shifted due to the large change in loading to the harbor. Denitrification is now the major sink for nitrogen, accounting for about 55% of the total inputs, whereas before relocation it accounted for 14%.

Respiratory quotients (RQs) at all four stations in 2007 were remarkably close to 1.0, the value for aerobic respiration. Often there is large variability across stations in this parameter, with RQs at Station BH02 typically the highest and attributed to anaerobic respiration. Increased oxygenation of the sediments here during the summer created low RQs that offset higher spring and fall values, bringing the seasonal average to 1.0. In contrast, in 2006 the average RQ for this station was 1.6. It is the integration over the season of this interplay between aerobic and anaerobic respiration, including reoxidation of anaerobic end products that gives us the best indication of the redox state of these sites. The 2007 values suggest relative balance in these processes at all four stations.

Profiles of oxidation-reduction potential (Eh) in the top 10 –20 cm of sediment cores continued to show most highly oxidized sediments at Station BH03 and most reduced at Station BH02. However, profiles from Station BH02 showed less reducing conditions than are often present, particularly during July and August. The effects of bioturbation were evident in these profiles, which showed much more positive Eh values through the top 6-8 cm than did profiles from May and October. Profiles from Stations BH08A and QB01 were similar to each other and typical for these sites, with conditions between those of the other two stations.

We stated in the 2006 report that, at these harbor stations: “The role that infauna has played has been significant in areas like BH08A and BH03, and the presence or absence of those benthic communities will no doubt continue to impact benthic nutrient cycling.”. As we have described above, that is exactly what occurred in 2007 at Station BH02. Despite this perturbation to what had become a fairly stable post-relocation baseline, we believe this is a further step in the recovery in the harbor.

CROSS SYSTEMS COMPARISONS

If we compare the long-term datasets for Boston Harbor, the nearfield of Massachusetts Bay, and Stellwagen Basin, most notable is the decreases in SOD and nutrient fluxes that have been observed at the harbor stations. At the beginning of the monitoring program, these fluxes were quite large, and much greater than those in Massachusetts Bay. Overall, harbor fluxes have decreased, in some years approaching Massachusetts Bay levels, and the temporal and spatial variability in those fluxes has decreased as well. Following an onshore-offshore and depth gradient, fluxes of SOD and DIN from the Massachusetts Bay nearfield stations remain lower than the harbor but are typically slightly higher than those from the Stellwagen station. Importantly, there have been no increases observed in bay fluxes since the bay outfall became operational in September 2000.

We have also compared Boston Harbor and Massachusetts Bay, both pre- and post-diversion, to a range of other estuaries (Nixon, 1981). A comparison of summer SOD shows there has been little change in Massachusetts Bay between the two periods. In Boston Harbor, however, there has been a remarkable change. The 1995 data for the harbor exceeded the range of the other estuaries presented. Through 2006, SOD in Boston Harbor has decreased dramatically, reaching its lowest point to date in 2005, when the only two systems that had lower SOD were Kaneohe Bay, HI, and our own Massachusetts Bay (2005 was also the lowest year to date for Massachusetts Bay). In 2007, very high summer SOD at Station BH02 elevated the harbor average back near the high end of the range presented. As mentioned above and detailed in the report, we do not think this represents a deterioration in conditions at this station; rather, we think this station may be in a “catch- up” phase and we wonder if, in fact, conditions have finally improved here enough to support a return of a robust infaunal population in 2008.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

APPENDIX

Appendix A: Station names, survey IDs, date of survey, station locations, near-bottom water sampling depth, temperature, dissolved oxygen (D.O.), and salinity for Boston Harbor and Massachusetts Bay stations visited in 2007.

1.0 INTRODUCTION

We have been conducting studies on benthic metabolism and nutrient cycling in depositional sediments of Boston Harbor and the Massachusetts Bay as part of an extensive monitoring effort designed to assess changes in the harbor and bay related to sewage treatment improvements and outfall relocation. The Massachusetts Water Resources Authority (MWRA) began improvements to the sewage treatment plant servicing the greater Boston metropolitan area in 1989. These included the cessation of sludge disposal in the harbor in December 1991, upgrade to secondary treatment starting in 1997, and culminated in the relocation of the effluent outfall in September 2000, from the mouth of the harbor to a site 9 miles offshore in deep waters of Massachusetts Bay.

The Benthic Nutrient Flux Studies were initiated in 1990 to examine spatial and temporal trends of benthic processing of organic matter at selected stations in Boston Harbor and Massachusetts Bay. The overall objectives of the studies have been to quantify sediment-water exchanges of oxygen, total carbon dioxide, and nutrients in order to define benthic-pelagic coupling in the harbor and bay. In addition, sediment indicators of organic matter loading and processing, such as organic carbon and pigment concentrations and redox conditions, have also been monitored. Until late in 2000, the focus of these studies was on monitoring the recovery of the harbor as sewage treatment was improved, and in providing baseline information about all of these processes in Massachusetts Bay before the ocean outfall became operational. In 2001, monitoring of the harbor recovery continued, but baseline monitoring of the bay ended. The emphasis changed to monitoring the response of the bay ecosystem to the relocation of the outfall and to addressing the following sequence of questions:

a) Will there be an enrichment of organic matter in nearfield sediments?

b) If yes to a, will there be an increase in sediment oxygen demand, nutrient fluxes from the sediments, or denitrification?

c) If yes to b,

    - how would these changes influence the levels of oxygen and nitrogen in the water near the outfall?
    - will increased water-column and benthic respiration contribute to depressed oxygen levels in the sediment?

In the current report, we compare the results from 2007 to those baseline studies and to the previous six years of post-relocation observations to address the monitoring questions. We also review data from Boston Harbor and address the monitoring questions in terms of reductions rather than enrichments in organic matter loading.

The work described below has been accomplished by two groups of researchers. We performed the benthic nutrient cycling studies during 1991-1994 (with colleagues from Battelle and the University of Rhode Island) and 1998-2005 (Giblin et al., 1992; Kelly and Nowicki 1992; Giblin et al., 1993-1995; Kelly and Nowicki, 1993; Tucker et al., 1999-2007). Dr. Brian Howes and his colleagues were responsible for the data collected during 1995-1997 (Howes, 1998a; Howes, 1998b; Howes, 1998c). A detailed description of current field and laboratory methods, including the following changes that occurred in 2004, may be found in Tucker and Giblin (2005). These changes were made after a review of the entire monitoring program and were approved by the Outfall Monitoring Science Advisory Panel (OMSAP) (MWRA, 2003). The changes made to the benthic nutrient flux studies were:

1. Urea measurements were discontinued. Previous years' observations had found that urea flux was always a very minor part of the sediment nitrogen flux.
2. Porewater measurements of nutrients, alkalinity, and sulfides were discontinued. Although useful for better understanding of fluxes from the sediments, these measurements were not critical for monitoring. Measurements of Eh and pH were retained as important indicators of overall sediment conditions. Should significant changes in Eh occur, the more extensive measurements could be reinstated.
3. Denitrification measurements were made using an improved method. The new method enabled us to obtain measurements at all of our stations for the first time; however, it tends to produce lower flux estimates. This caveat has been noted throughout the report.

2.0 MASSACHUSETTS BAY

We have monitored three stations, MB01, MB02, MB03, in the nearfield region of Massachusetts Bay and one station, MB05, in the farfield (Stellwagen Basin) (Figure 1). Stations MB01, MB02, and MB03 have been monitored nearly every year since fall of 1992, and Station MB05 has been monitored since fall of 1993. Station MB02 was not visited in 1997, and no stations in Massachusetts Bay were sampled in 1998. Through 1997, all stations were sampled in March, May, July, August, and October. After 1997, the March surveys were discontinued.

The three nearfield stations are located in depositional areas in about 33 meters of water. Two of these, MB01 and MB02, are located approximately 4 and 3.6 km, respectively, northwest of the center of the bay outfall array, and the third, MB03, is 4.6 km southwest of the site. The Stellwagen station, MB05, is 12 km northeast of the site, in a depositional area about 75 meters deep.

In Massachusetts Bay, physical and climatological factors set the stage for the biology and chemistry of the system. Two thousand seven (2007) was a fairly typical year (Geyer, MWRA 2008 Annual Technical Workshop), with average air temperatures and winds, and no large storms. However, there were a few features of note. A wet spring resulted in a large discharge from the Merrimack River in April and moderately low surface salinities in western Massachusetts Bay. The rest of the year was dry, with very low river flows in the summer. Surface waters in August were cooler than average, associated with several strong upwelling events. Stratification was stronger than typical in October, and bottom water was unusually cool.

Biological events in the water column for 2007 were also described as typical (Libby and Borkman. MWRA 2008 Annual Technical Workshop). Of particular interest to the benthic flux studies are the phytoplankton dynamics. There was a modest winter/spring diatom bloom in the nearfield in March, followed by a very large *Phaeocystis* (mixed with diatoms and microflagellates) bloom in April, throughout most of western Massachusetts Bay and north. Spring *Phaeocystis* blooms have become an annual event for the last eight years. Although these blooms create spikes in water column chlorophyll and POC, we have been unable to detect their effects on the benthos. We believe most of this biomass is advected away before it can be deposited on the bottom. Summer and fall diatom blooms were observed in the nearshore coastal areas, southwest of the nearfield. These blooms represent a return to near mean levels in diatoms after a long-term decline through 2005. It is the diatoms, whose siliceous tests facilitate sinking, that we may detect in measures of sediment chlorophyll or organic carbon.

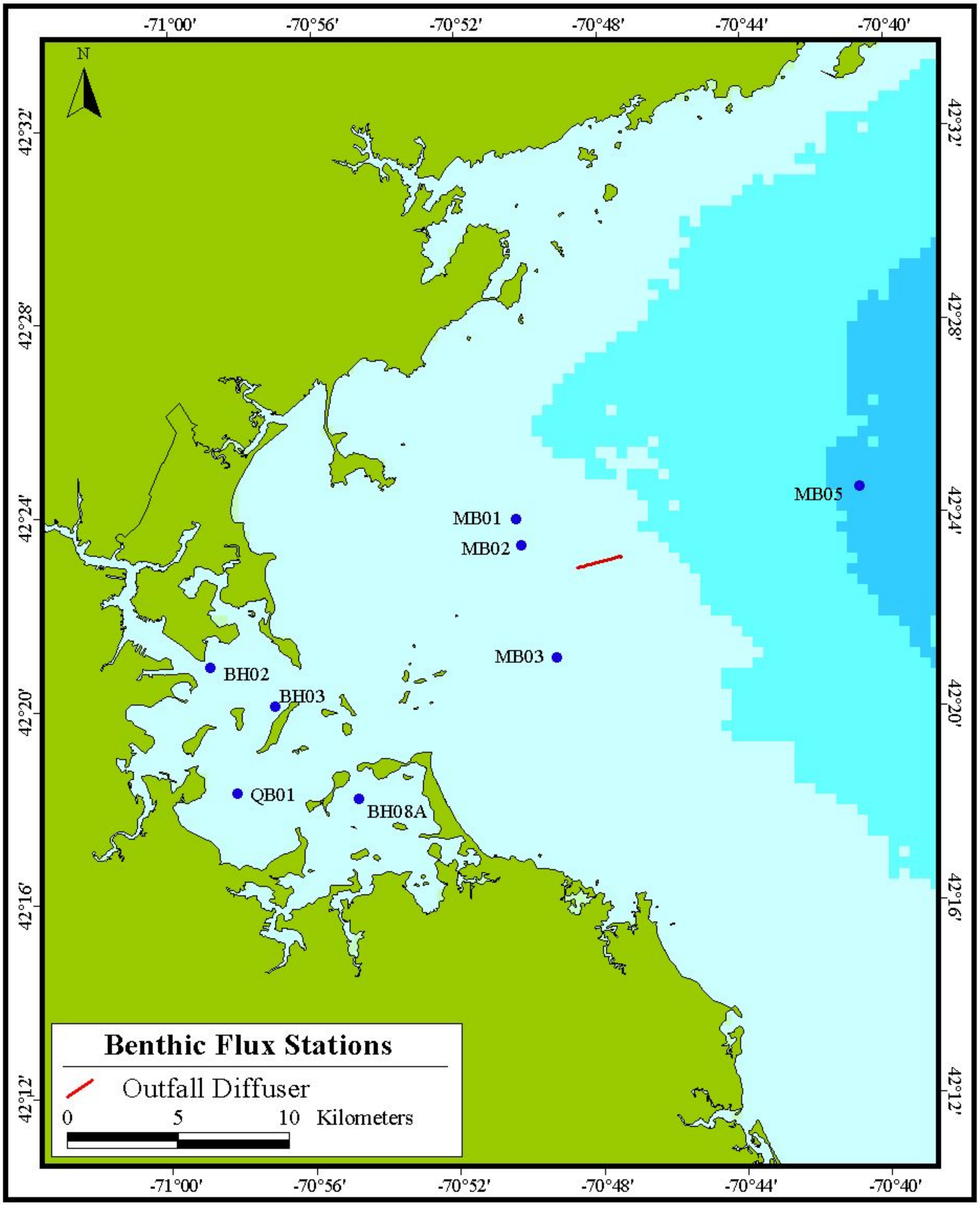

Figure 1. Benthic nutrient cycling stations in Massachusetts Bay and Boston Harbor.

2.1 Organic Matter Loading

Organic matter fuels benthic metabolism, so changes in either the supply of organic matter to the sea floor and/or to the quality of the organic matter can lead to changes in benthic respiration and nutrient fluxes. With the relocation of the outfall to Massachusetts Bay, there was concern that there would be an enrichment effect in the organic matter loading to the benthos. This enrichment might be derived from effluent particulates or it might be derived from enhanced phytoplankton productivity.

We have monitored organic matter content in the sediments two ways. We have measured organic carbon and nitrogen content in surface sediment, and we have measured chlorophyll pigments.

2.1.1 Total Organic Carbon

Total organic carbon (TOC) content of Massachusetts Bay sediments measured during 2007 was typical of previous observations. At the three nearfield stations, seasonal averages (May-Oct) were nearly identical to each other at about 1.3%; at the farfield station the average was a little higher at 1.6% (Figure 2). For comparison, average organic carbon content measured during baseline monitoring ranged from 0.9% to 2.3% for the nearfield, and 1.2% to 1.7% for the farfield. Values on the high end of this range, which occurred in 1993, seemed to correspond to the effects of a very strong storm that occurred in December 1992 that redistributed sediments in the Bay (Bothner, 2002).

In the previous year's report, we noted that the more northerly nearfield station, MB01, did not follow the same year-to-year changes as the other two stations, which had been tracking each other fairly well since 2002 (Figure 2). As already stated, in 2007 the three stations came together and had very similar annual averages. Intra-annually, however, MB01 once again stood out from the other two stations (Figure 4a). In May, TOC content at MB01 was 2.4 %, twice as high as it was at MB02 and MB03. A moderate winter/spring diatom bloom was the likely source, as elevated sediment chlorophyll was also observed at this station at this time (see Sec. 2.1.2 and Figure 6a). Organic carbon levels fell sharply at this station through July and into August, when levels were only 0.9%.

Throughout this period, TOC at stations MB02 and MB03 were fairly constant, ranging from only about 1.1% to 1.3%, and showed no indication of phytoplankton deposition. By October, TOC content varied considerably across the three stations. At MB01, TOC remained quite low (0.8%), whereas levels at MB02 increased to 1.9%. Elevated levels of TOC at Station MB02 in October may have been related to the fall diatom bloom; however, there was no corresponding peak in sediment chlorophyll. Organic carbon at MB03 changed very little over the season, showing only a small increase from May to October. At the farfield station, MB05 there was also little change, with TOC levels falling slightly from 1.7% in May to 1.5% by October.

Ratios of TOC to total N (TOC:TN or C/N; Figure 3) at the nearfield stations (averaged over the May to October period), ranged from 11.1 at MB03 to 13.0 at MB01 in 2007, and were lower at all three stations than in the previous year, reversing a recent upward trend. At Station MB05, C/N was lower, 9.6. It has been a consistent pattern that C/N is lower and varies much less at the deeper farfield station than in the nearfield.

Within-season variability in C/N was generally small (Figure 4b). Largest variability was observed at Station MB01, where TOC was also most variable, but changes in C/N did not always correspond directly to changes in TOC content. At this station, C/N was lowest (12.2) in May, consistent with deposition of the relatively nitrogen-rich phytoplankton bloom. Highest C/N (14.7) was observed in July; this increase might also be consistent with the TOC pattern, which suggested a depletion of the fresh carbon pool between May and July. However, although TOC continued to decrease into August, C/N did not continue to increase.

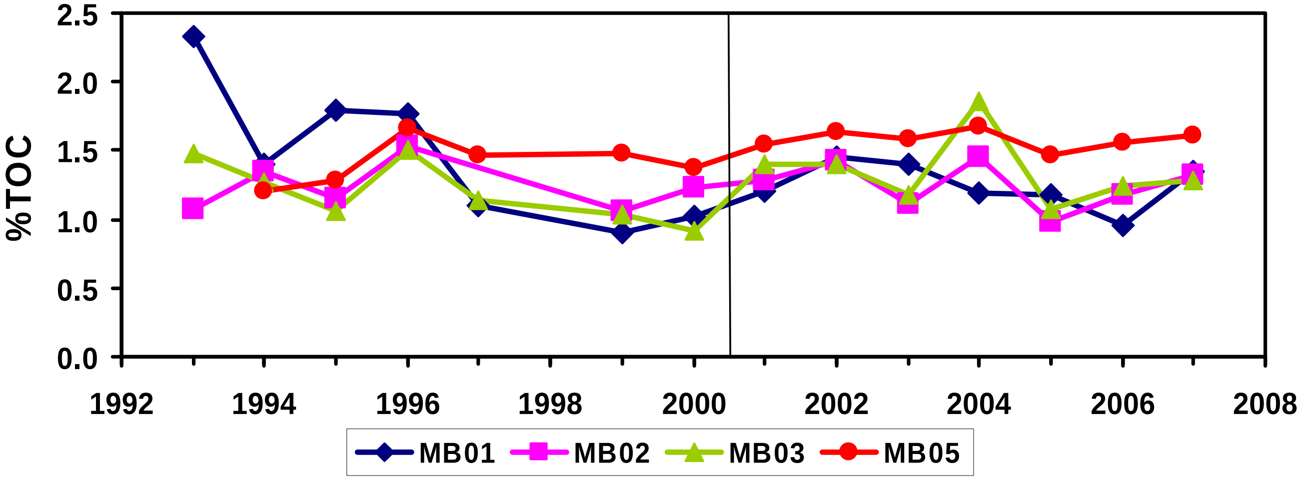

Figure 2. Seasonal average organic carbon content of top 2 cm of sediment at Nearfield stations MB01, MB02, and MB03 and Farfield station MB05. The vertical line marks the transition from baseline to post-relocation observations.

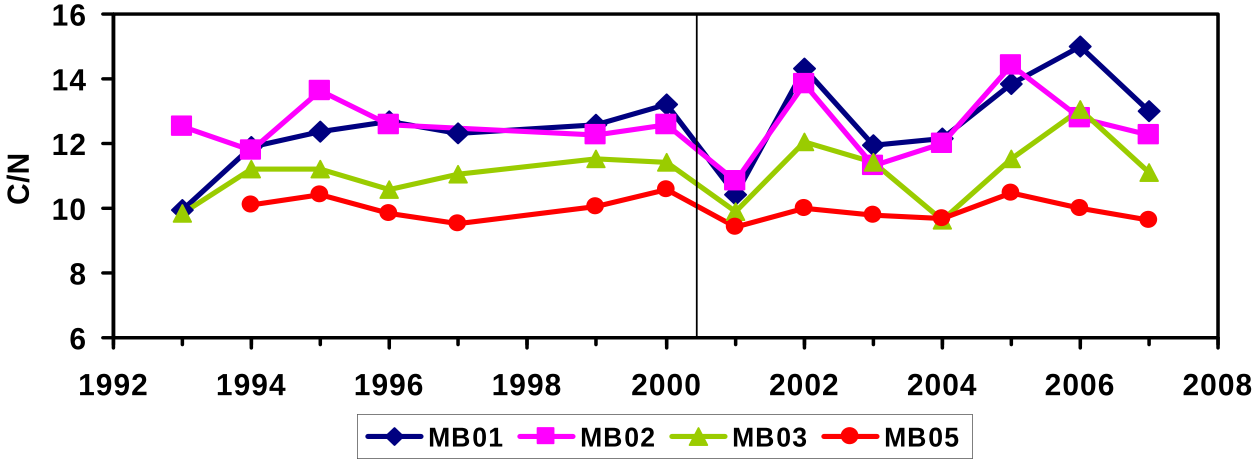

Figure 3. Molar TOC/TON for top 2 cm of sediment. The vertical line marks the transition from baseline to post-relocation observations.

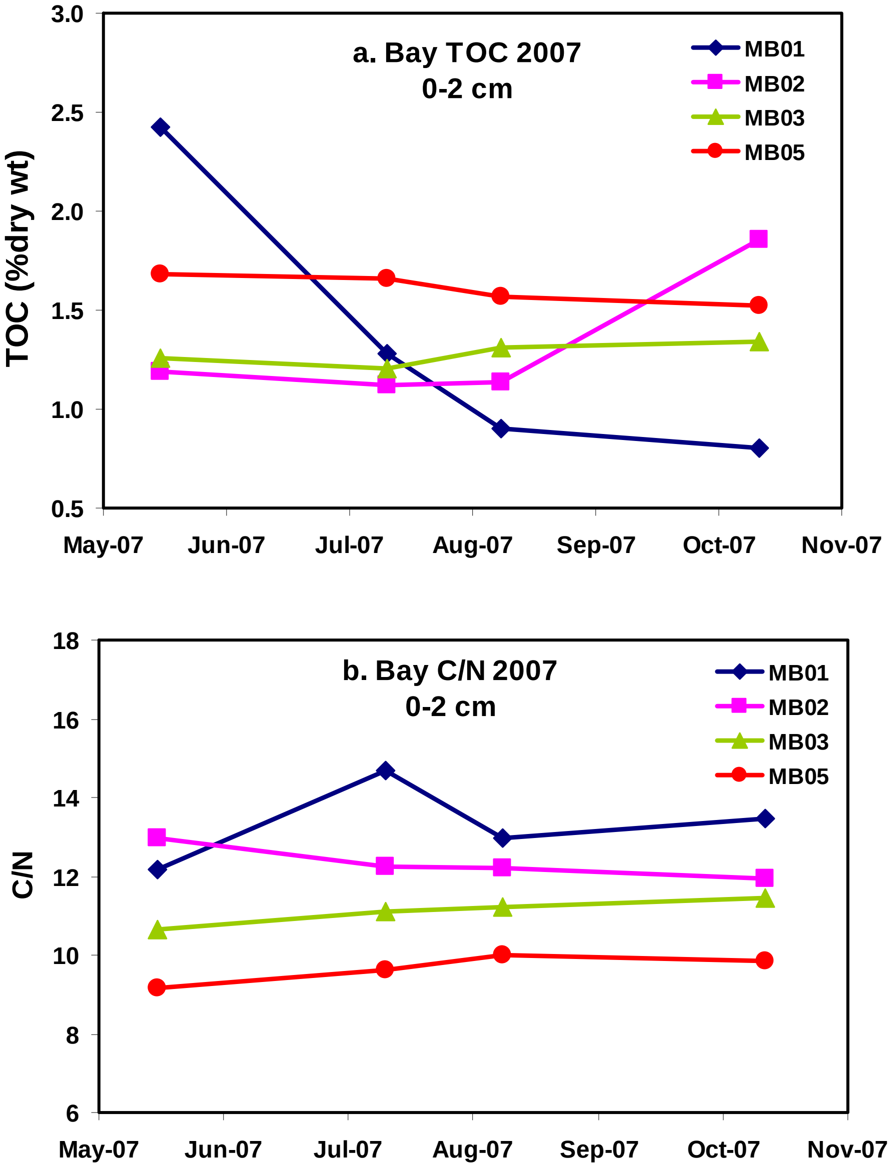

Figure 4. a.) TOC and b.) molar C/N in top 2 cm of sediments at Nearfield stations MB01, MB02, and MB03 and Farfield station MB05 during 2007.

2.1.2 Sediment Pigments

Chlorophyll *a* inventories for the top 5 cm of sediment at the nearfield stations in 2007 averaged between 4.5 (MB02) and 8.7 (MB01) µg cm^{-2} for the season (Figure 5). At Station MB01, this was nearly the same as the relatively high levels observed during the previous year. At Stations MB02 and MB03, 2007 observations marked a return to more typical conditions after very high inventories reported in 2006. At Station MB05, average inventory for 2007 was 3.2 µg cm^{-2}, which was only about half the value of the previous year and low for this station.

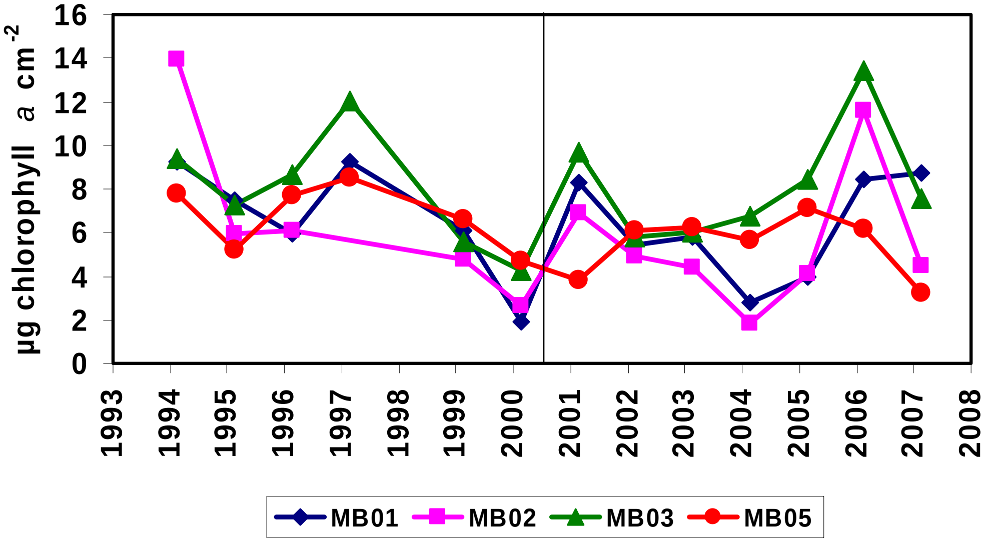

Figure 5. Chlorophyll a inventory for top 5 cm of sediment at Nearfield stations a.) MB01, b.) MB02, and c). MB03, and Farfield station c). MB05. The vertical line marks the transition from baseline to post-relocation observations.

In 2006, high inventories in the nearfield were driven largely by high sediment chlorophyll *a* content observed in May at all stations. In 2007, only MB01 had a May peak (23.1 µg cm^{-2} compared to about 6 µg cm^{-2} at the other two stations), suggesting a localized deposition of the spring phytoplankton bloom. Chlorophyll *a* inventories at Station MB01 had fallen to near-background levels (4-5 µg cm^{-2}) by July, and stayed low for the rest of the season in a pattern very similar to that described for TOC (Section 2.1.1). Station MB03 showed a small July peak in chlorophyll inventory (12.1 µg cm^{-2}) that was not observed at the other stations. A summer diatom bloom in Boston Harbor and coastal area south of the harbor may have been the source. This increase in chlorophyll was not noticeable in the TOC data. Stations MB02 and MB05 showed very little change through the season.

Profiles through the top 5 cm of sediment revealed the details of these seasonal changes (Figure 6). The most striking was the May profile at Station MB01, which showed a strong surface signal of nearly 10 µg cm^{-3} in chlorophyll *a* over the top two centimeters (Figure 6a). The only other feature in the 2007 chlorophyll profiles was observed at MB03 in July (Figure 6c). A small peak, reaching 4.5 µg cm^{-3} at 1-2 cm, was observed at this time. All other profiles showed background levels of chlorophyll *a* concentrations of 2 µg cm^{-3} or less.

Patterns in phaeophytin *a* concentrations typically correspond roughly to chlorophyll concentrations, although concentrations are of course much higher (on the order of 10 X). For example, phaeophytin inventory at MB01 was high in May, and the phaeophytin profile had a shape similar to the chlorophyll profile (Figure 6e). An interesting departure from this general pattern was observed at MB05 in May. In this case, there was very little of note in chlorophyll levels or in the shape of the chlorophyll profile, but phaeophytin concentrations were elevated, with a subsurface peak of 30 *u*g cm^{-3} at 2-3 cm (Figure 6h). There was only a very small corresponding peak in the chlorophyll profile (Figure 6d). One explanation for this apparent disconnect might lie in the greater water depth at this station. The longer travel time from the surface to the bottom would allow for greater degradation of the chlorophyll before deposition.

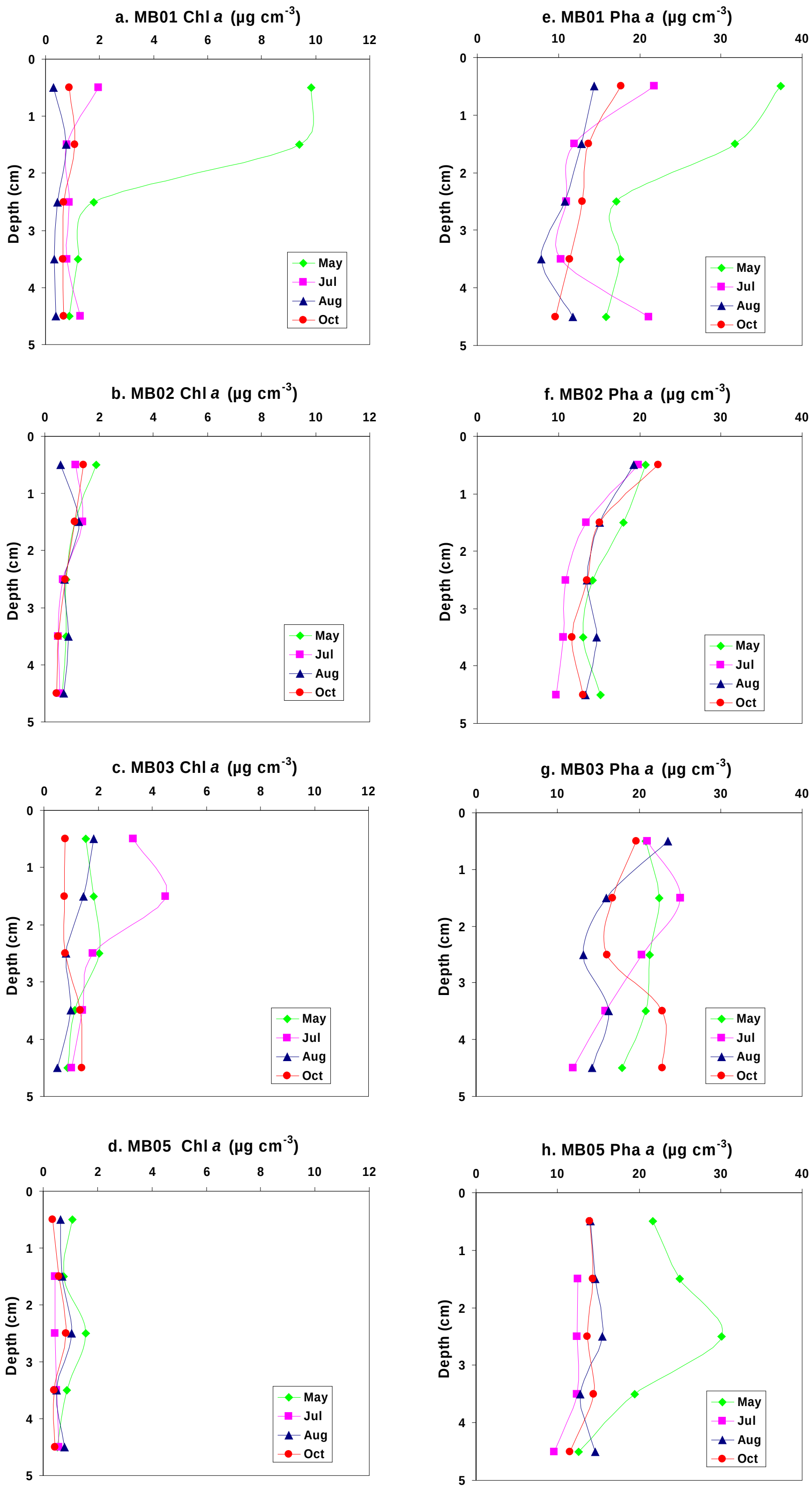

Figure 6. Profiles of chlorophyll *a* (a-d) and phaeophytin *a* (e-h) concentrations (µg cm^{-3}) in top 5 cm of sediment in 2007 from Massachusetts Bay Stations

2.1.3 Pre- and Post- Relocation Comparison

As measured by organic carbon or chlorophyll *a* content, there has been no discernible change in organic matter input to nearfield sediments since the bay outfall became operational at the end of 2000. Seasonal mean values of both of these parameters in 2007 were typical of the entire monitoring program.

Figure 7 shows the means and standard deviations in TOC for the pre- (1993-2000) and post- (2001-2001) relocation periods for each of the three nearfield stations as well as the farfield station MB05. There is no statistical difference between the two periods. [Note that there was some sampling variability in the pre-relocation period: 1.) no samples were collected in 1998 at any station; 2.) there were no samples collected from MB02 in 1997; 3.) there were no samples collected in October 1996 and 1997 at MB01; 4.) sampling started in 1994 at MB05, but there was no sample collected in July of that year.]

Figure 8 shows a similar comparison for sediment chlorophyll *a*. For some years in the pre-relocation period, there was not a full seasonal sampling for pigments. Therefore, for this comparison we have used the means of the spring and fall values only (typically May and October) for years these data were available (1994, 1995, 1996, 1999, and 2000). Mean values of chlorophyll *a* inventories were accompanied by high variability during both periods, such that there is no statistical difference between the pre- and post- years.

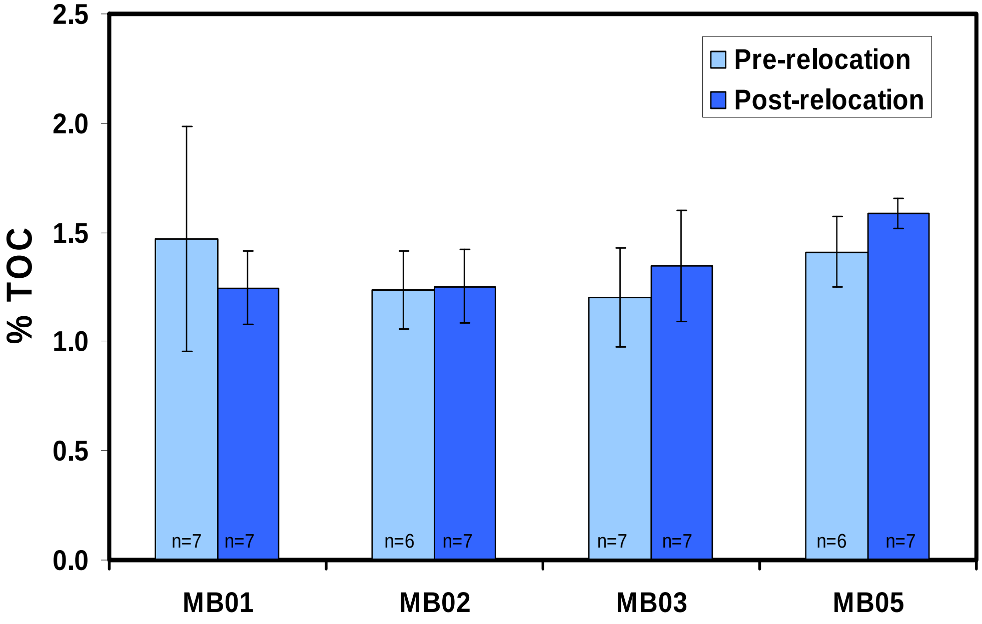

Figure 7. Sediment TOC pre- and post- relocation of the outfall. Data are seasonal averages over all available years for each station. Error bars represent one standard deviation of the mean.

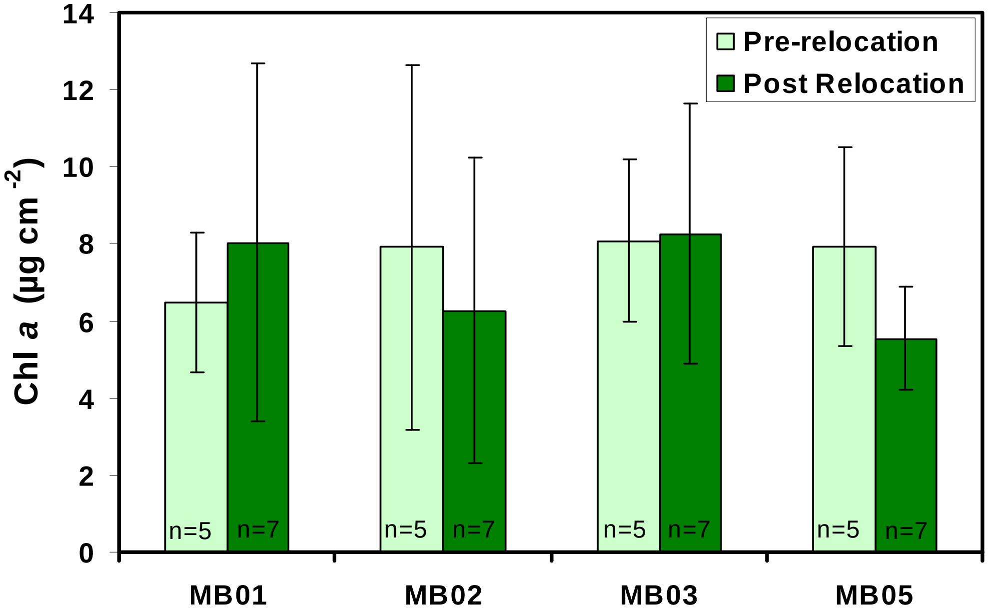

Figure 8. Sediment chlorophyll *a* pre- and post- relocation of the outfall. Data are means of spring and fall data (typically May and October) over all available years for each station. Error bars represent one standard deviation of the mean.

2.2 Sediment Oxygen Demand

Average sediment oxygen demand for the three nearfield stations in 2007 was the lowest yet observed. The rate of 12.1 mmol m^{-2} d^{-1} compares to the baseline mean of 17.2 mmol m^{-2} d^{-1}, and a post-baseline mean (excluding 2007) of 15.7 mmol m^{-2} d^{-1} (Figure 9). The variability across the three stations was also quite low, with rates ranging only from 11.3 to 12.6 mmol m^{-2} d^{-1}. SOD at the farfield station was 11.3 mmol m^{-2} d^{-1}, very similar to the nearfield, but quite typical for this station.

Even though the seasonal average SOD was low and the variability across the stations was small, the range in rates within the season was nearly three-fold. Low rates occurred in May or July, but all stations had peak (and almost identical: 17.3 +/- S.E. 0.13) rates in August. The result was a strong relationship with temperature at Stations MB01 and MB02 (r^2s = .063 and 0.83, respectively) and positive but less strong relationships at Stations MB03 and MB05 (r^2s = 0.28 and 0.48). These relationships have varied by year and by station in both strength and direction so it is notable that all four stations had positive relationships with temperature in 2007. In contrast, we did not find correlations of SOD with measures of organic matter content (TOC or pigment content).

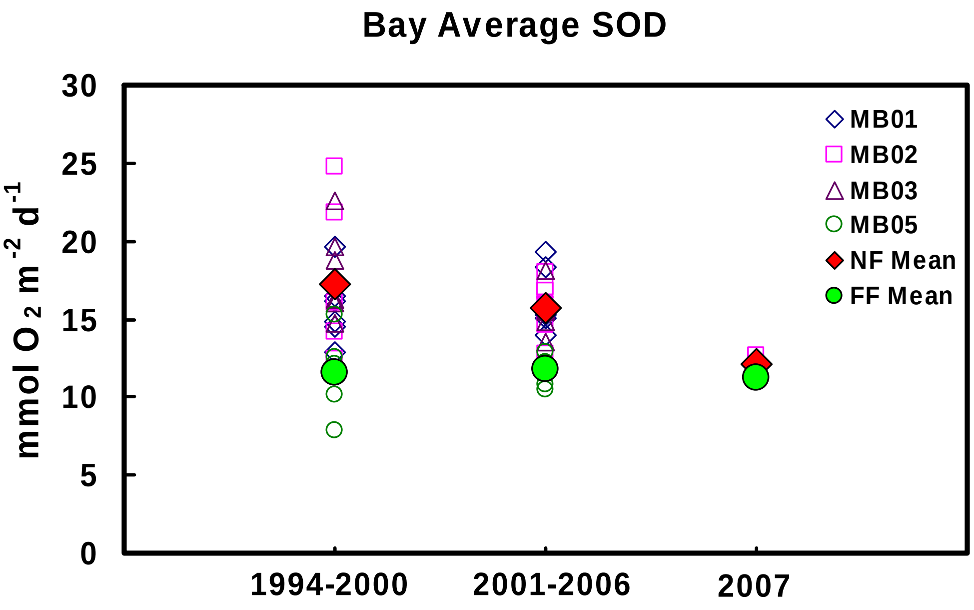

Figure 9. Seasonal (May-October) averages of sediment oxygen demand (S.O.D.) for Massachusetts Bay stations during 1994-2000 (pre outfall relocation), 2001-2006 (post outfall relocation, excluding 2007), and for the current year (2007). Solid symbols represent the average for the region over the period; open symbols represent annual averages for each station.

2.3 Nutrient Flux

The regeneration of inorganic nutrients by sediment decomposition of organic matter is an important part of nutrient cycling in coastal systems, and may play a large role in supporting primary production. The monitoring program recognized the role of sediment regeneration of nutrients and questioned whether nutrient flux to the water column might be enhanced by any organic matter enrichment, particularly in the area near the outfall.

In the seven years that the bay outfall has been operational, we have seen no evidence of increased nutrient regeneration from the sediments. In fact, fluxes of dissolved inorganic nitrogen (DIN = NH_4^+ + NO_3^- + NO_2^-), phosphate, silica, and urea (data for urea not shown) have in general been at the low end of the range of fluxes observed during baseline monitoring.

2.3.1 DIN

In 2007, average DIN flux from nearfield sediments was 0.4 mmol m^{-2} d^{-1} , lower than the baseline average of 0.8 mmol m^{-2} d^{-1} as well as the post-baseline average (excluding 2007) of 0.6 mmol m^{-2} $d^{-1.}$ At the farfield station, average DIN flux was 0.2 mmol m^{-2} d^{-1}, very typical for this station (Figure 10a).

Nitrate (used throughout text as shorthand for NO_3^- + NO_2^-) comprised the majority of the DIN efflux at all stations, ranging from 64% at MB01 to 100% at MB03 (Figure 11). It is often the case that when DIN fluxes are low, NO_3^- is the dominant component of the flux. In fact, there is some tendency in the data for a decrease in NH_4^- flux and an increase in NO_3^+ over time. This scenario is generally consistent with oxidizing conditions in the sediments.

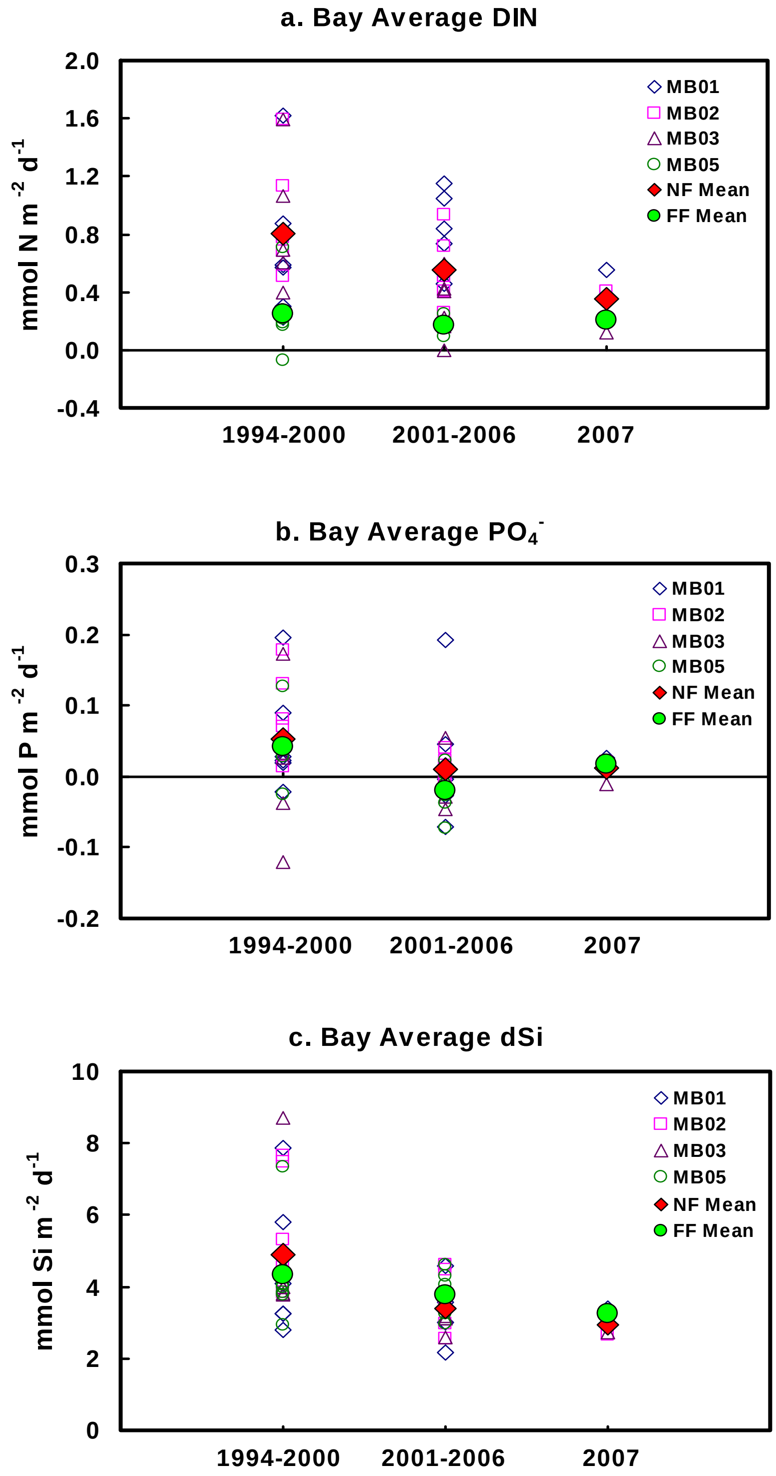

Figure 10. Seasonal (May-October) averages of a.) DIN flux, b.) PO4- flux, and c.) dissolved Si flux for Massachusetts Bay stations during 1994-2000 (pre outfall relocation), 2001-2006 (post outfall relocation, excluding 2007), and for the current year (2007). Solid symbols represent the average for the region over the period; open symbols represent annual averages for each station.

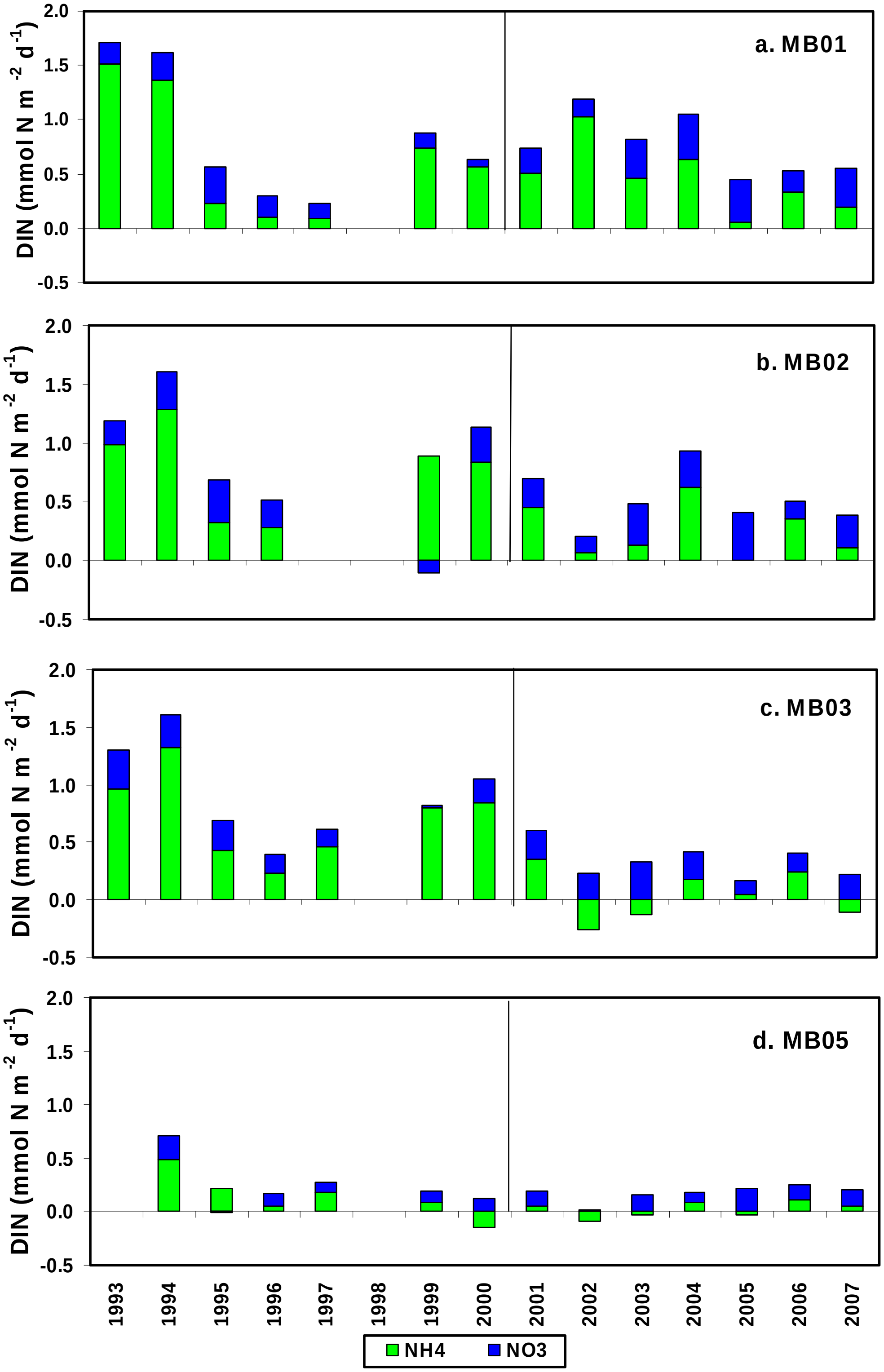

Figure 11. May-October seasonal average DIN flux from 1993-2007 at bay stations, partitioned into NH_4^+ and NO_3^-+NO_2^- a.) MB01, b.) MB02, c.) MB03, d.) MB05. The vertical line marks the transition from baseline to post-relocation observations.

The most notable feature of the within-season pattern was at MB03, where there was strong NH_4^+ uptake in July, and weak uptake in August. This uptake was responsible for shifting the average seasonal efflux to NO_3^-, noted in the previous paragraph (Figure 11c). Although we have occasionally observed NH_4^+ (and NO_3^-) uptake at all four bay stations, the frequency and especially the magnitude of the NH_4^+ uptake, often equivalent to efflux, seems to have increased at Station MB03 beginning in 2002. Uptake by primary producers seems unlikely in sediments from these water depths (~33m), and because incubations are conducted in the dark. However, we did observe a small chlorophyll peak at MB03 in July, and there was a summer, coastal and harbor diatom bloom. In addition, we also observed stronger than usual PO_4^- uptake at this time (see below). A more likely explanation is that the NH_4^+ is being nitrified and /or denitrified. In fact, denitrification (Section 2.4) at MB03 in July was greater than at the other three stations by about the same amount as the NH_4^+ uptake; however, this may be simply coincidental. We do not have enough information to complete the mass balance required to evaluate this link. Enhanced nitrification seems likely given the oxidizing nature of these sediments, and may also be occurring in the water column. Again, we do not have the necessary data (a direct measure of nitrification) to assess the importance of this process.

2.3.2 Phosphorus and Silica

In the nearfield, phosphate fluxes were characteristically small and/or negative in 2007 (Figure 10b). The seasonal average was 0.01 mmol m^{-2} d^{-1}, lower than the baseline mean of 0.05, but the same as the post-baseline mean. This seasonal average was comprised of overall effluxes of ~0.02 mmol m^{-2} d^{-1} PO_4^- at Stations MB01 and MB02, but uptake of 0.01 mmol m^{-2} d^{-1}at Station MB03. Average uptake of PO_4^- at Station MB03 was driven by relatively a strong negative flux of -0.06 mmol m^{-2} d^{-1} in July, in a seasonal pattern that paralleled that of NH_4^+ fluxes. At farfield station MB05, seasonal average PO_4^- flux was 0.02 mmol m^{-2} d^{-1}. This was lower than the baseline average of 0.04 mmol m-2 d-1, but higher than the post-baseline average, which has shown overall PO_4^- uptake (-0.02 mmol m^{-2} d^{-1}). As has been typical for most of the monitoring program, there was little difference between the nearfield and farfield stations in terms of average PO_4^-fluxes.

The nearfield average silica flux in 2007 was 2.9 mmol m^{-2} d^{-1}, which was lower than both the baseline and post-baseline means (4.9 and 3.4 mmol m^{-2} d^{-1}, respectively) (Figure 10c). At MB05, the average flux for 2007 was 3.2 mmol m^{-2} d^{-1} as compared to 4.3 and 3.8 mmol m^{-2} d^{-1} for the baseline and post-baseline periods, respectively. As we noted for PO_4^- fluxes, there was little difference between the nearfield and farfield stations as an average or within the season. This has generally been the case throughout the monitoring program.

2.3.3 Nutrient Flux Contribution to Primary Productivity

Average annual primary production in the nearfield area in 2007 was 255 g C m^{-2} y^{-1}, down a bit from the previous year (average production from Stations N04 and N18; Oviatt, pers. com). Since nutrient fluxes were down as well, their potential contribution to primary production did not change very much. Following Redfield considerations, the 2007 annual production would require 8.8 mmol m^{-2} d^{-1} of N or Si, and 0.5 mmol m^{-2} d^{-1} of P. Using the seasonal average DIN flux from our three nearfield stations, we find that benthic DIN flux represented only 4.1% of phytoplankton requirements; in 2006, it was 4.7%. PO_4^- fluxes in 2007 could contribute only 1.8% of requirements, whereas dissolved Si fluxes could contribute 33%. If we add the 2007 data to the post-relocation average, we calculate a potential contribution of 3.9% of nitrogen and 27 % of silica. For years with PO_4^- efflux (4 out of 7), that potential contribution was 3.8%. These potential contributions are virtually the same as they were before outfall relocation (3.7% for N, 3.6% for P, and 24.3% for Si).

There are several caveats on this calculation, including the fact that we used annual rates for primary productivity compared to seasonal (May through October only) rates for benthic fluxes, which would cause an overestimation of the contribution of benthic fluxes. Another reason this may be an overestimation is that our sampling sites are biased to the depositional and presumably more active sediments of the bay.

2.4 Denitrification

Over the course of the monitoring program, direct measurements of denitrification have been made with varying frequency depending on year and station (Figure 12). In 1993 and 1994, measurements were made at all three nearfield stations during each of five annual surveys: March, May, July, August, and October. Denitrification measurements were not made from 1995 through 1998. Measurements resumed in 1999, but were only conducted at Stations MB02 and MB03, and only in May and October (in 1999 the March surveys were discontinued). Beginning in 2004, a change in analytical method allowed us to measure denitrification at all stations, including MB05 for the first time, and during all (four) annual surveys: May, July, August, October.

These measurements have revealed considerable temporal and spatial variability in the rates of denitrification during most of the monitoring program, although there is some tendency for more consistent patterns in the more recent measurements made by the N_2/Ar method. However, an overall pattern of lower rates and more consistent spatial and temporal patterns are similarly suggested in the DIN fluxes.

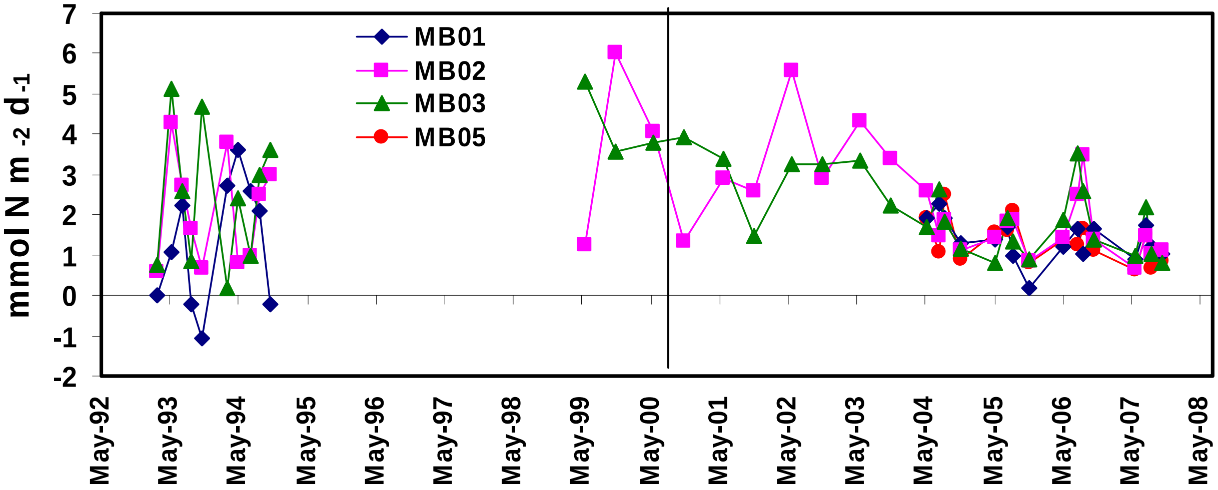

Figure 12. Denitrification at Massachusetts Bay stations. Denitrification measurements were not conducted in Massachusetts Bay in 1995-1998. Data from 2004-2007 were produced using the N_2/Ar analytical method. The vertical line marks the transition between baseline and post-relocation of the outfall.

For 2007, the magnitude and seasonal pattern for denitrification for the nearfield stations as well as the farfield stations were remarkably similar. The seasonal average in the nearfield was 1.2 mmol m^{-2} d^{-1} and at Station MB05 it was 0.9 mmol m^{-2} d^{-1}. For Stations MB02 andMB03, rates were lower than in the previous year, but similar to 2004 and 2005. All stations experienced a seasonal peak in July. The highest rate observed at this time occurred at Station MB03, and was 2.2 mmol m^{-2} d^{-1}. As mentioned above (Section 2.3.1), the higher denitrification rates at MB03 compared to the other three stations was of about equal magnitude to the NH_4^+ uptake observed at this station at the same time.

Denitrification continued to be the major component of the total inorganic N flux (DIN efflux + denitrified N) from Massachusetts Bay sediments (Figure 13). Data collected at all four stations since 2004 show that in the nearfield, denitrification generally accounted for 60-85% of the total efflux, and sometimes as much as 100%. At farfield Station MB05, the average was somewhat higher, with denitrification accounting for 80- 90% of the total, and also has accounted for the entire efflux at specific times. A review of the longer record at Stations MB02 and MB03 show that this pattern has been consistent throughout the monitoring period.

2.5 Redox

One of the concerns of the monitoring effort is whether any increased organic matter loading will lead to higher sediment respiration, and subsequently to depressed oxygen levels in the sediments. Although we have not seen evidence of increased sediment respiration, further insight into this question may be gained by examining other indicators of sediment redox conditions; e.g. respiratory quotients and Eh.

2.5.1 Respiratory Quotient

In 2007, seasonal average RQs were just below 1.0 (0.8 to 0.9) at all stations (Figure 14a), reflecting an overall oxidation state of the sediments near that indicative of aerobic respiration. Average RQs near 1.0 have been reported for every year since 1999, in contrast to some much higher values observed in the early years of monitoring (Figure 14; note that CO_2 data are not available for 1995-1998). Within the season, however, there were considerable departures from 1.0 (Figure 14b). In May and July, RQs were variable among stations, but all four stations had RQs greater than 1.0. A high value of 1.7 was observed at Station MB03 in July. These high values indicate anaerobic respiration with storage of the end products of these processes in the sediments. In August and October, RQs at all stations were less than 1.0, indicating the reoxidation of those stored end products. The lowest RQ during this period was 0.6, observed at Station MB02 in August. The highest RQ, 1.7, was observed at Station MB03 in July, and the lowest, 0.6, at MB02 in August.

2.5.2 Eh profiles

Oxidation-reduction potential measured as Eh in 2007 continued to be indicative of highly oxidized conditions in sediment cores from Massachusetts Bay (Figure 15). That is, we have not observed any degradation in redox conditions in these sediments. In fact, there has typically been no distinct color change that would mark a redox potential discontinuity (RPD) within the 18-20 cm depths of our cores, and that is still the case seven years after relocation of the outfall. Values continue to be well above those that would indicate the presence of dissolved sulfides (-100 to -200 mV). There was no consistent seasonal pattern among the stations.

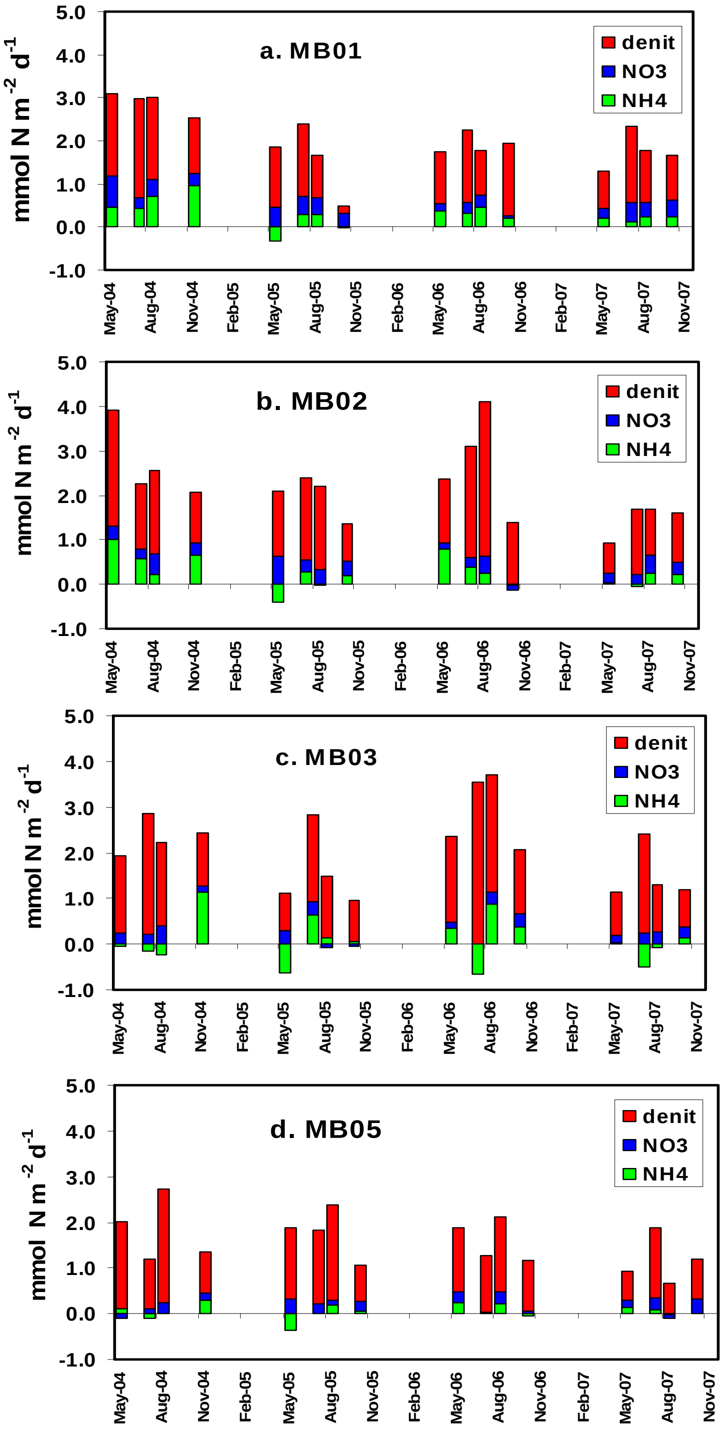

Figure 13. Nitrogen flux at all four Massachusetts Bay Stations 2004-2007, partitioned into components of N from denitrification, NH_4^+ flux, and NO_3^- flux.

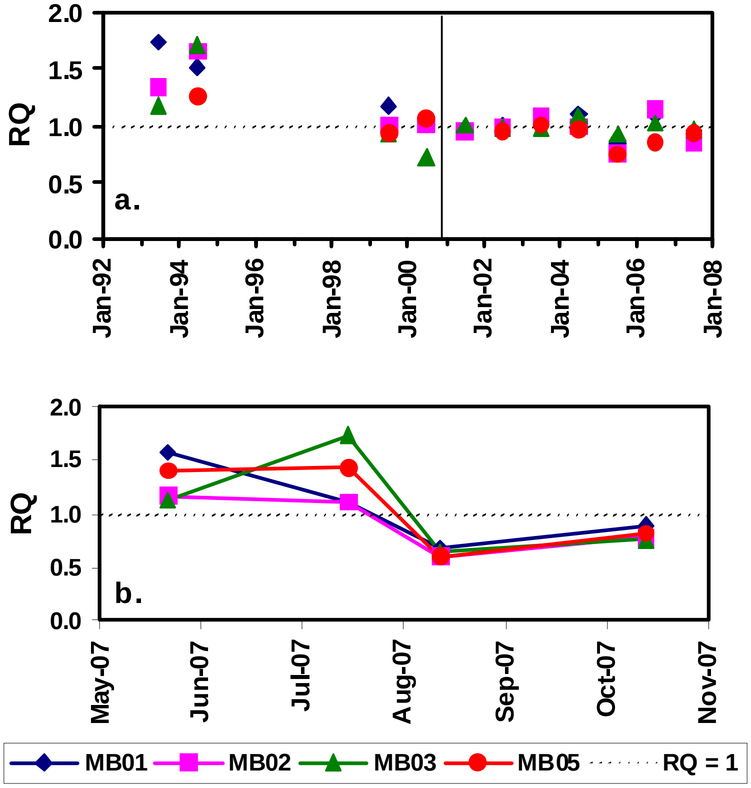

Figure 14. Respiratory quotients for Nearfield stations MB01, BM02, MB03, and Farfield station MB05 as a.) seasonal (May-October) averages from 1993-2007 and b.) during 2007, showing a seasonal shift from values above to values below 1.0. The value of 1.0 is represented by the dotted line in both Figures, and the vertical line in a. marks the transition from baseline to post-relocation observations.

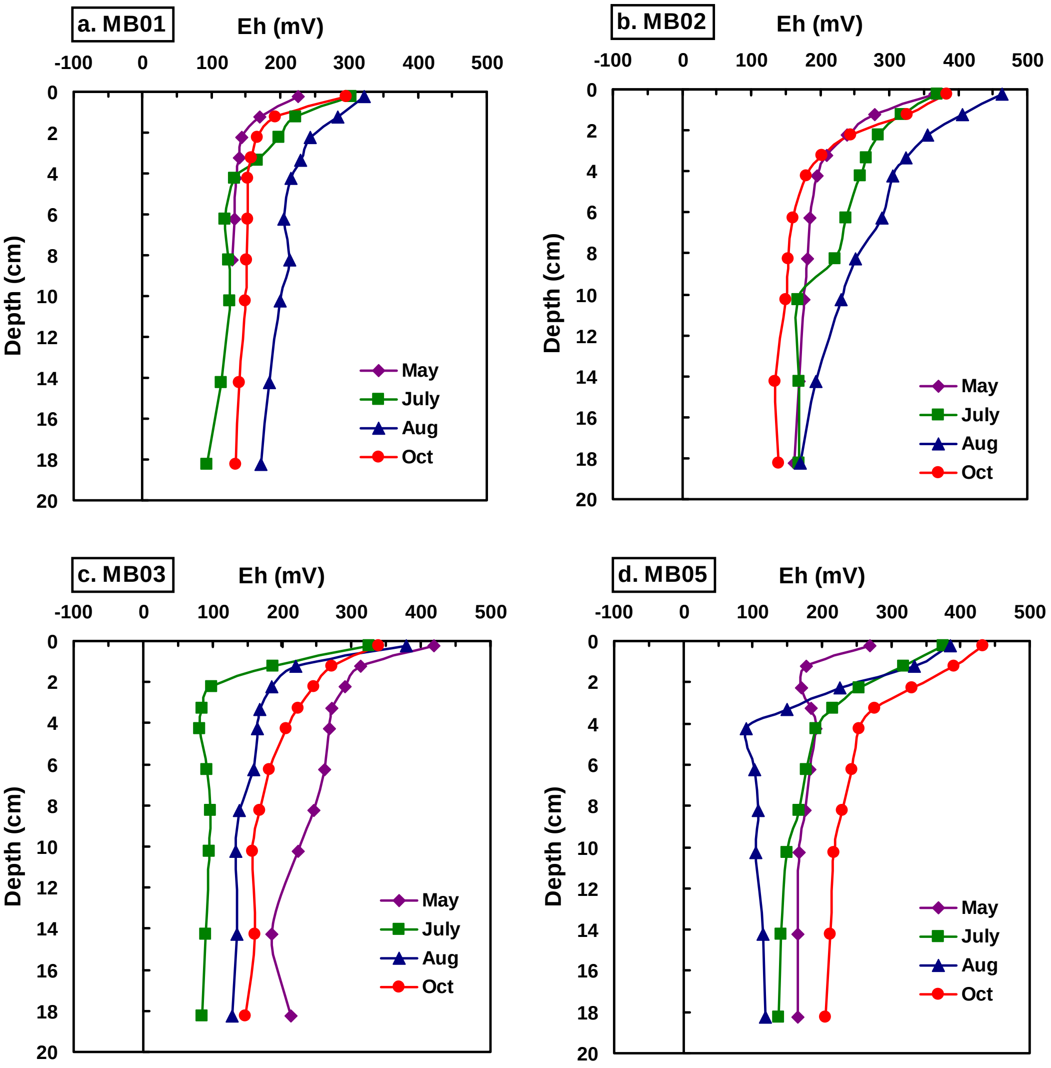

Figure 15. Eh profiles for May through October 2007, from Nearfield stations a.) MB01, b.) MB02, c.) MB03, and Farfield station d.) MB05.

3.0 BOSTON HARBOR

Four harbor stations have been repeatedly sampled in the benthic nutrient cycling program throughout the monitoring period (Figure 16). Two stations, BH02 and BH03, are located in the northern section of Boston Harbor and have been sampled routinely since September 1991. The other stations, BH08A and QB01, are in the southern harbor, and have been visited since 1995. Through 1997, these stations were visited in March, May, July, August, and October. After that time, the March surveys were discontinued.

The reduction of solids loading to the harbor, initially by the cessation of sludge disposal at the end of 1991 and subsequently by treatment improvements at Deer Island and the diversion of the Nut Island influent to the Deer Island Plant in the summer of 1998 (Taylor, 2001b), was the primary agent of change in Boston Harbor until offshore diversion occurred in September, 2000. Benthic habitats in the north harbor that were directly affected by sludge disposal, in particular Station BH03, have undergone large changes in their biology and chemistry. In contrast, areas in the south harbor exhibited less change during this time.

The diversion of all MWRA effluent offshore marked the final phase in MWRA's Deer Island project, and has resulted in dramatic improvements in water quality in the harbor. For example, after five years, DIN concentrations had shown a decrease of 55% (Taylor, 2006). Accordingly, primary production decreased, and the prolonged summer bloom that had been characteristic of the harbor is no longer typical (Libby et al, 2007).

It has now been seven years since the effluent diversion. Throughout this post-baseline period, sediment oxygen demand and benthic nutrient fluxes in the harbor have in general remained much lower and less variable than had been observed in the early years of the monitoring program. We interpret these patterns as indicative of a state of recovery.

In 2007, however, data from one station, Station BH02, was anomalous for the post-baseline period. An unusual colonization of this site by a dense infaunal population was responsible. We do not believe this occurrence was cause for concern; rather, we speculate that it may signal a progression in the successional stage of the benthic community at this site, which has lagged behind the other sites. Specifics of results from this station are described where pertinent below.

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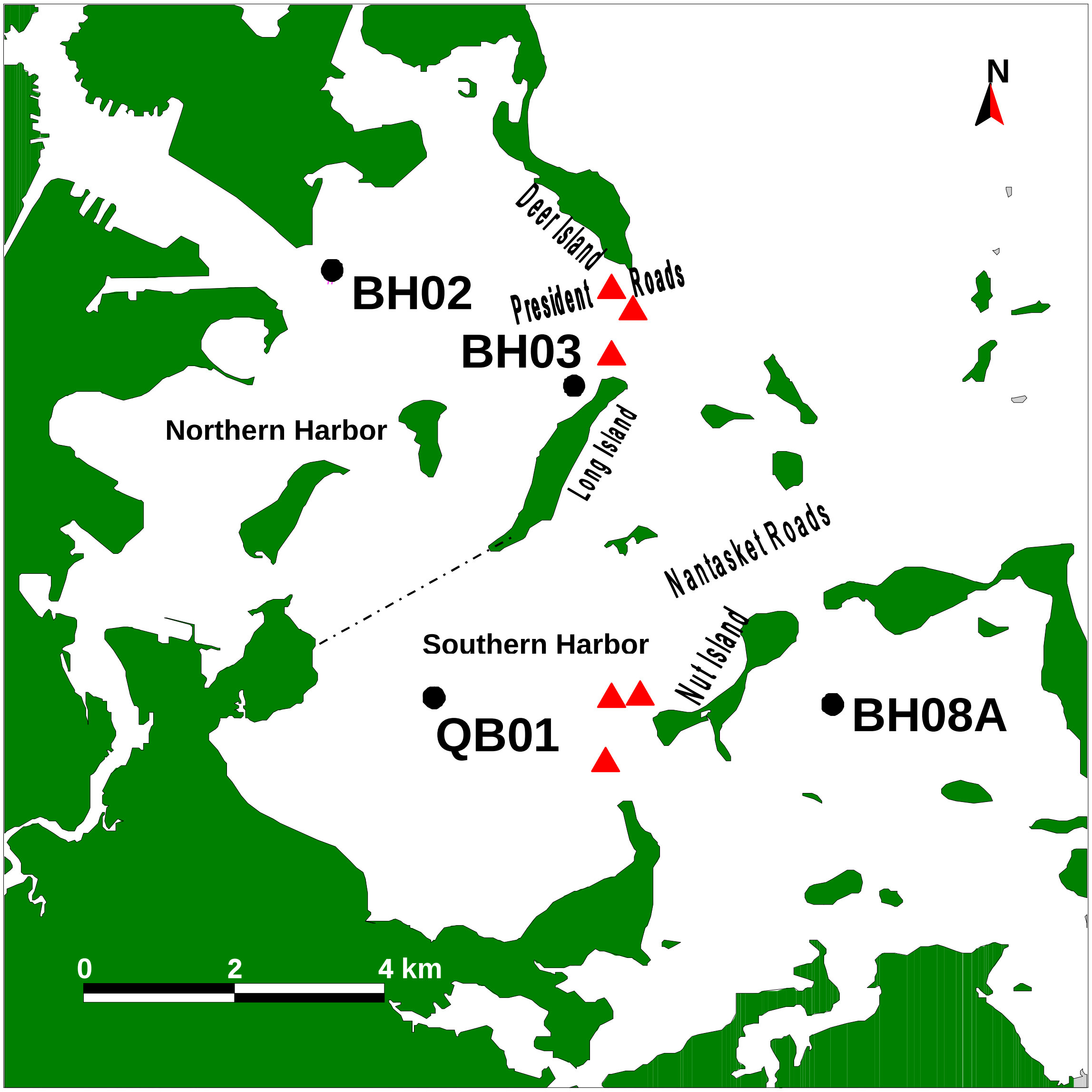


Figure 16. Locations of four Boston Harbor stations. Triangles (▲) mark the location of the out-of-service Harbor outfalls, the last of which was taken out of service on Sept. 6, 2000.

3.1 Organic Matter Loading

3.1.1 Total Organic Carbon

We have observed a decrease in the organic matter content of sediments in Boston Harbor since monitoring began as direct inputs decreased and carbon stores were metabolized. The very high percentages of organic carbon (over 4%) that were observed at some of our stations at various times before 1999 have not recurred. Temporal and spatial variability have also decreased. Data from 2007 are consistent with this trend, with average TOC content ranging from 1.7% at Station BH08A to 2.6 % at Station QB01 (Figure 17).

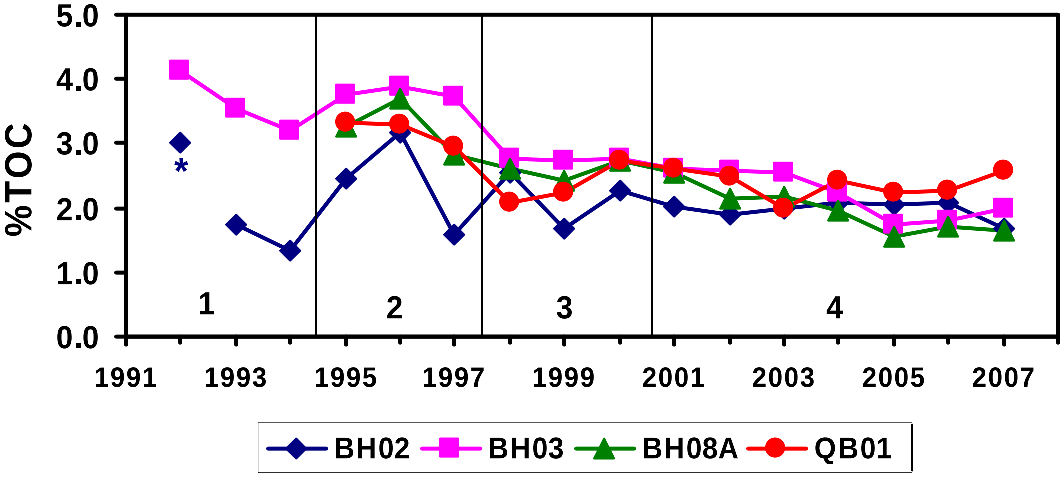


Figure 17. Seasonal average TOC (% dry weight) for top 2 cm of sediment, with time divided into treatment periods 1-4 (see text for details). The asterisk beside the 1992 data point for BH02 denotes a two-point rather than a 4-point average.

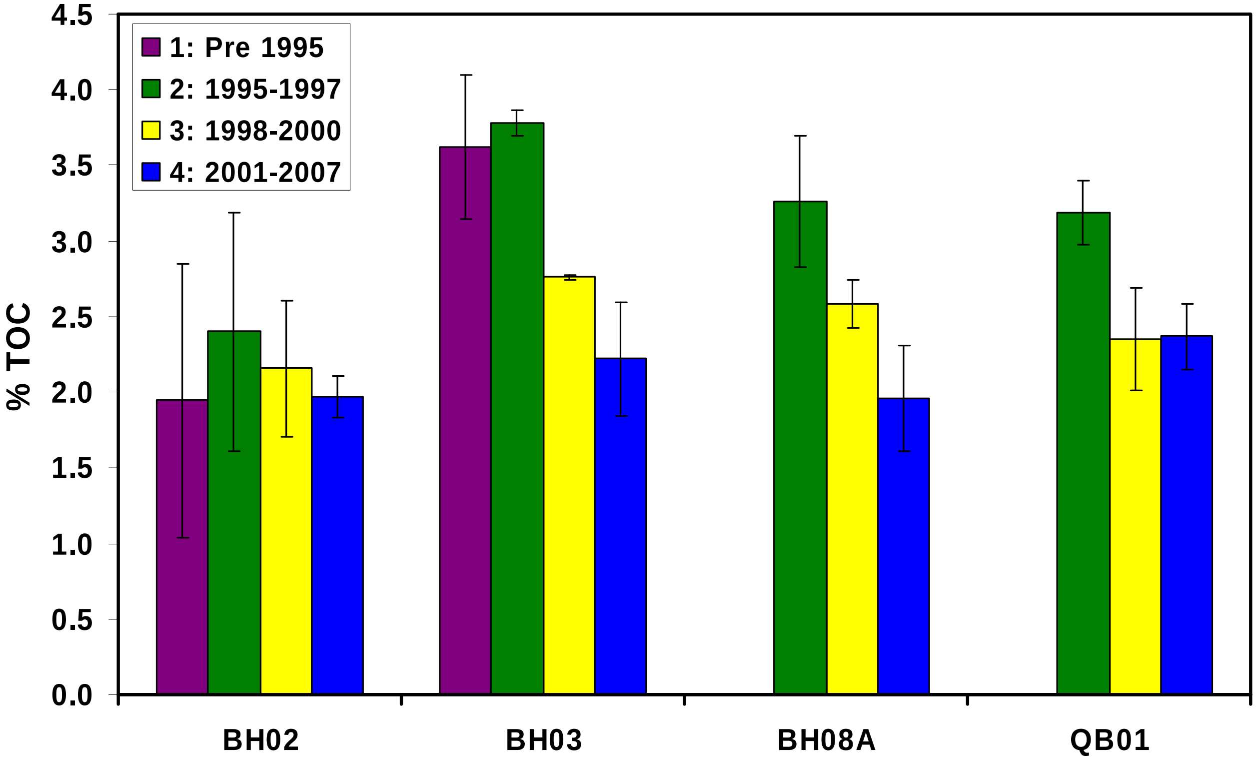


Figure 18. Sediment TOC for each station by treatment periods 1-4 (see text for details). Data are seasonal averages over years for each period. Error bars represent one standard deviation of the mean.

As mentioned above, TOC content in harbor sediments seemed to reflect the changes in solids loading to the harbor, many of which occurred before outfall diversion. Therefore, in this report and the previous one (Tucker et al, 2007) we have divided the data into four time periods that mark the most significant changes in solids loading (Figure18; for a more detailed description of changes in loading, see Taylor, 2006). Period 1 is 1992- 1995, before full primary treatment was implemented and just after sludge disposal was discontinued (1991). Period 2 is from 1995 to 1997, after full primary treatment came on line. Period 3, 1998-2000, marks the beginning of secondary treatment and the transfer of all Nut Island discharge to Deer Island. This combination resulted in the largest decrease in solids loading while effluent was still being discharged into the harbor. The final period starts in 2001, after the divergence of all discharge from Deer Island to the ocean outfall, which effectively ended solids loading from effluent to the Harbor.

Decreases in organic carbon that follow the four periods in the harbor cleanup are most evident in the data from BH03 and BH08A (Figure 18). These are the two stations that frequently had high densities of benthic infauna (the Ampeliscid amphipod mats), particularly during Periods 2 and 3, which we think played a significant role in reducing the carbon stores at these sites. At BH03, TOC averaged about 3.7% during the first two periods, but has decreased to 2.2 % in Period 4. Similarly, at Station BH08A, average TOC has fallen from 3.3% in Period 2 to 2.0% in Period 4. At Station QB01, there was a sizable decrease in average TOC between periods 2 and 3, but no change thereafter. Little change has been observable at Station BH02, in part due to the large interannual variability at this station before 2001. For this comparison, we have included the two data points we had for BH02 from 1992, measured in April and August, which indicate a pattern in TOC parallel to that at BH03. Without these points, the average for this period appears, in our judgment, artificially low.

3.1.2 Sediment Pigments

We have noted in previous reports that, during the baseline period, sediment chlorophyll inventories in Boston Harbor did not directly follow the timeline of sewage treatment improvements. Rather, they appeared to be indirectly related through the presence and extent of the amphipod mat community. Low inventories for all four stations occurred in 1995-1996 (Figure 19), during the peak of harbor coverage of the amphipod mat community, which presumably limited deposition of phytoplankton chlorophyll by filter-feeding, as well as limited *in situ* production by grazing down benthic microflora. *(Note that a difference in extraction of pigments during this time may have caused the phaeophytin a fraction of the chlorophylls to be artificially low. However, chlorophyll a inventories were also low at this time.)* Low inventories have persisted throughout the monitoring program at stations BH03 and BH08A, where a vibrant benthic community has typically been present. In contrast, at Stations BH02 and QB01, chlorophyll inventories have increased, often with spring peaks and consistent with observations of benthic diatoms. This pattern held true in 2007, with seasonal average chlorophyll *a* inventories at Stations BH02 and QB01 over twice those at BH03 and BH08A (Figure 19). Increasing trends between the baseline and post-baseline periods can be seen in data averaged over those two periods, but variability precludes a statistical difference (Figure 20).

Although the averages at Stations BH02 and QB01 were nearly identical (23.9 and 22.7 µg cm^{-2}), they were produced by quite different seasonal patterns. Details of these patterns may be seen in concentration profiles for the top 5 cm (Figure 21). Station BH02 had a very high inventory in May, with moderate to low inventories the rest of the season. Station QB01 had moderately high inventories that persisted throughout the season. The lower annual averages at Stations BH03 and BH08A were also quite similar to each other (9.7 and 9.1 µg cm^{-2}) and in this case, the seasonal patterns were very similar. Both stations had highest inventories in May, followed by low values for the rest of the season.

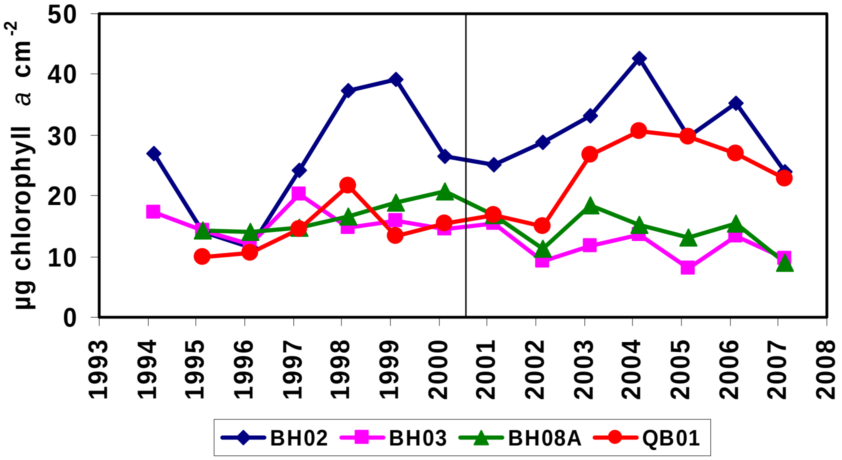


Figure 19. Average chlorophyll a inventory for top 5 cm of sediment at harbor stations. The vertical line marks the transition from baseline to post -relocation observations

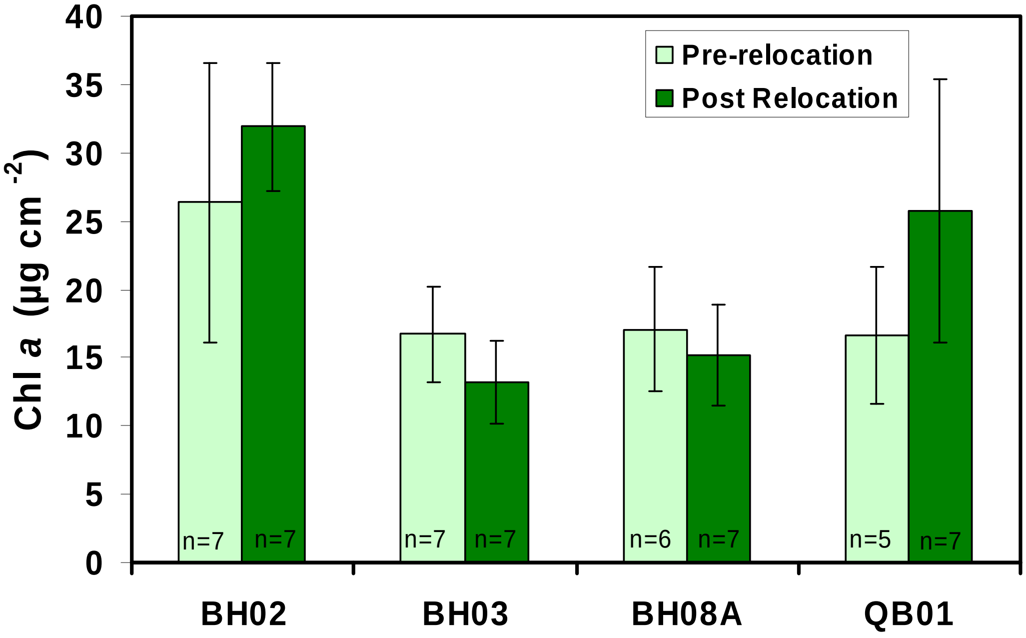


Figure 20. Sediment chlorophyll a pre- and post- relocation of the outfall. Data are means of spring and fall data (typically May and October) over all available years for each station Error bars represent one standard deviation of the mean

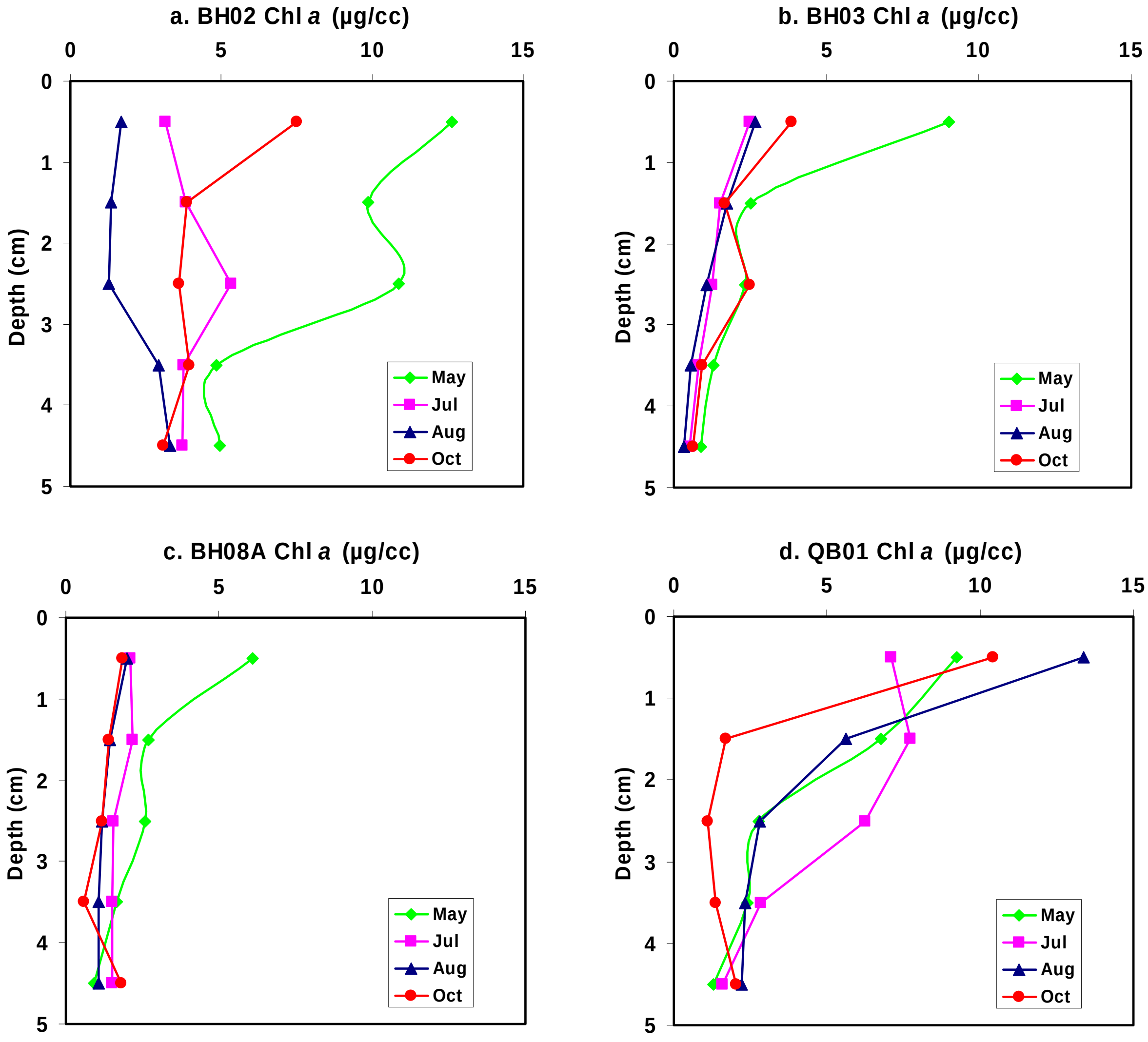


Figure 21. Profiles of chlorophyll *a* in top 5 cm of sediment at Boston Harbor stations in 2007 a.) BH02, b.) BH03, c.) BH08A, and d.) QB01.

3.2 Sediment Oxygen Demand

Changes in sediment oxygen demand (SOD), or benthic respiration, have provided compelling evidence for recovery of the harbor benthos. Much like the changes we observed in TOC, and of course related to those changes, the decreases in SOD began before the diversion of the outfall. During the initial period of the monitoring program, we frequently observed high rates of SOD, particularly at our Station BH03. At this station, rich stores of carbon in the sediment and the colonization of the sediments by the amphipod mat community combined to produce very high rates, with the extreme being 410 mmol m^{-2} d^{-1} in July of

1993. Summer rates over 100 mmol m-^{2} d^{-1} were not uncommon at this station through 1999, but began to decease as the carbon content decreased and the amphipod community declined. High rates were also measured at Station BH02 at times during the early period, but not as consistently. At this station, carbon content was more variable (refer back to Figure 17) and there were only sporadic occurrences of the amphipod community. As we began sampling Stations BH08A and QB01 in 1995, we found similar and high carbon content at these sites, but only Station BH08A supported the amphipod colony. At this station, we observed high rates of SOD, but not as high as were still present at BH03. SOD decreased at BH03 and began to climb at BH08A such that the two stations had similar rates in 1998-1999, after which rates at BH08A were higher. By 2002, all four stations had similar and low rates, and we have been speculating about a new "equilibrium" in the harbor since that time, more stable and more typical of coastal environments. To summarize, seasonal averages across all stations during each of the four treatment periods discussed above show a step-wise decrease in SOD as well as a reduction in variability: Period 1 (in this case 1993-1994, BH02 and BH03 only= 90.2 *SE 38.5*; Period 2 = 70.0 *SE 13.3*; Period 3 = 51.8 *SE 6.1*, and Period 4 = 36.1 *SE 2.7*.

For simplicity, however, and in order to make direct comparisons, we will consider the SOD and nutrient flux (Section 3.3) data in three periods covering the years during which all four stations were visited: 1995-2000 for the prediverson period, 2001-2006 for the post-diversion period, excluding the current year, and the current year, 2007, to be compared against the two other periods (Figures 22 and 24).

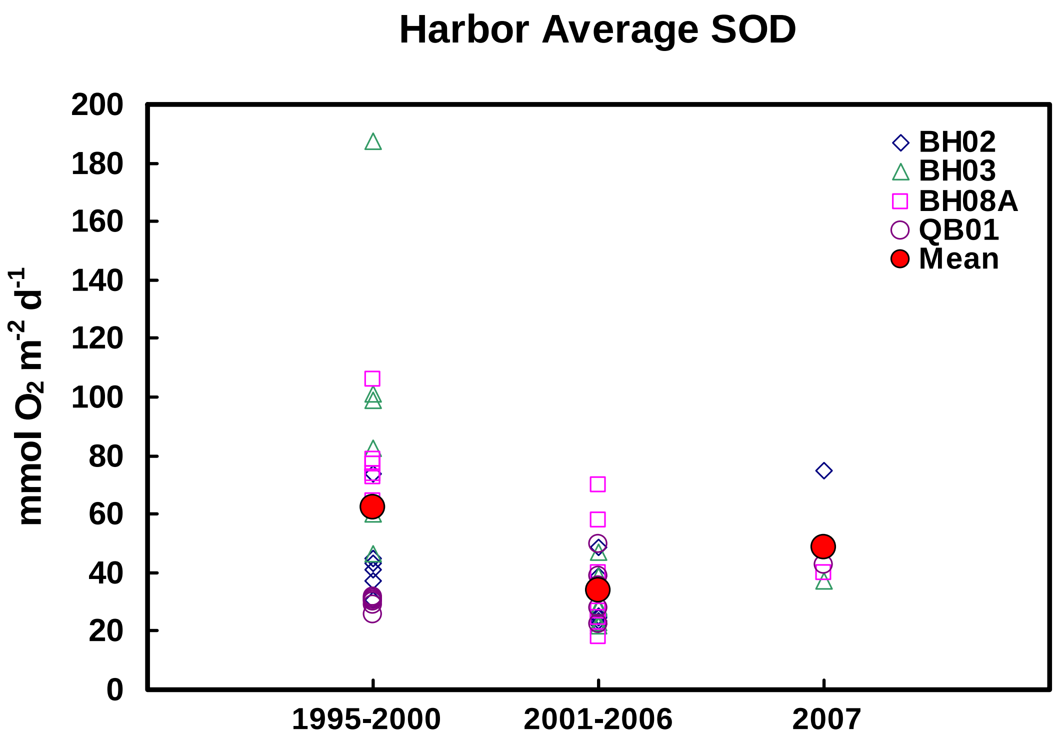


Figure 22. Seasonal (May-October) averages of sediment oxygen demand (S.O.D.) for Boston Harbor stations during 1995-2000 (pre outfall relocation), 2001-2006 (post outfall relocation, excluding 2007), and for the current year (2007). Solid symbols represent the average for the harbor over the period; open symbols represent annual averages for each station.

The grand average SOD for the pre-diversion period was 62.4 mmol m^{-2} d^{-1}, but annual averages for a given station during that period ranged from 25.9 mmol m^{-2} d^{-1} at Station QB01 in 1997 to 187.4 mmol m^{-2} d^{-1} at BH03 in 1995 (Figure 22). For 2001-2006, the grand average was 34.0 mmol m^{-2} d^{-1}, with a range in annual averages from 18.3 mmol m^{-2} d^{-1} at BH08A in 2005 to 70.1 mmol m^{-2} d^{-1} at the same station in 2003. The average for the four stations in 2007 was 48.7 mmol m^{-2} d^{-1}, with the low rate at station BH03 of 37.4 mmol m^{-2} d^{-1} and an unusual high rate of 74.6 mmol m^{-2} d^{-1} at Station BH02. Including the 2007 data increases the post-diversion grand mean to 36.1 mmol m^{-2} d^{-1}

At Stations BH03, BH08A, and QB01, seasonal average SOD at all stations in 2007 was a bit higher than in recent years, but still well below the baseline period. At station BH02, however, the seasonal average was higher than both the pre-and post baseline average for this station, and was as high as the single highest year during the baseline period. Although spring and fall rates at BH02 were very typical of the post-diversion period (23.1 and 27.3 mmol m^{-2} d^{-1}, respectively), summer SOD was very high (117.0 and 131.1 mmol m^{-2} d^{-1} for July and August, respectively) (Figure 23). The cause of this increased respiration was the presence of a dense benthic infaunal community, including many amphipods and polychaetes, visible at the surface and through the top several centimeters of the sediment. For most of the monitoring program, animals were sparse at this site, and we considered that absence to be one reason sediments here had shown less change over time than had sites where the amphipod mat community had played a large role (BH03 in particular, as well as BH08A). It will be interesting to see whether this was a single occurrence, or whether it marks a change in the successional stage of the infauna at this site, much like occurred early in the monitoring program with the amphipod mat at BH03 and a little latter at BH08A.

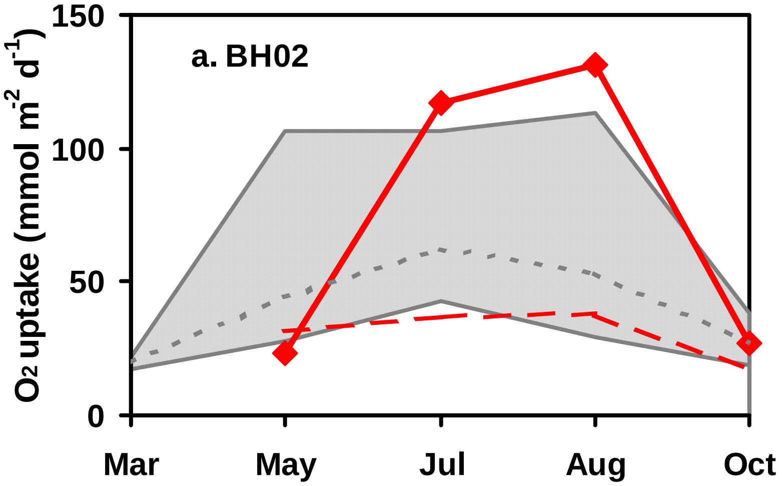


Figure 23. SOD at Station BH02. The gray stippled area represents the range of data during the baseline period. The gray dotted line is the baseline mean. The red dashed line is the post-baseline mean, excluding 2007, and the solid red line with symbols is the 2007 data.

One other result outside of the baseline range occurred in August at Station QB01. One core sample at this time had a very high SOD of 103 mmol m^{-2} d^{-1}whereas the other had a much more typical value of 35.1 mmol m^{-2} d^{-1}. The result was a high average of 69.2 mmol m^{-2} d^{-1}. The description of the core with the high rate stated that a large burrow was present. Presumably, this burrow was occupied, leading to the high rate of respiration. Curiously, this is the same situation we reported for the previous year, at which time we considered the capture of large macrofauna in one of our core from this station a rarity related to low abundance of such macrofauna, and the resulting high SOD not representative of this site. Given the recurrence this year, however, it may suggest some change in the benthic community.

3.3 Nutrient Fluxes

3.3.1 DIN

DIN Flux in 2007 generally followed the same pattern as we observed for SOD (Figure 24a). The annual average across all four stations was 4.2 mmol m^{-2} d^{-1}, lower than the baseline mean of 5.1 mmol m^{-2} d^{-1}, but higher than the post-diversion mean (excluding 2007) of 2.7 mmol m^{-2} d^{-1}. As was the case for SOD, this uptick in DIN flux was caused by very high summer rates at Station BH02, 12.2 and 15.4 mmol m^{-2} d^{-1}in July and August, respectively. The resulting seasonal average at this station was 8.4 mmol m^{-2} d^{-1}, more than twice that of the other three stations. Also following the SOD pattern, there was an atypically high average DIN flux at Station QB01 in August, produced by a large flux in one of the duplicate cores. In this case, the resulting seasonal average did not exceed the post-baseline range.

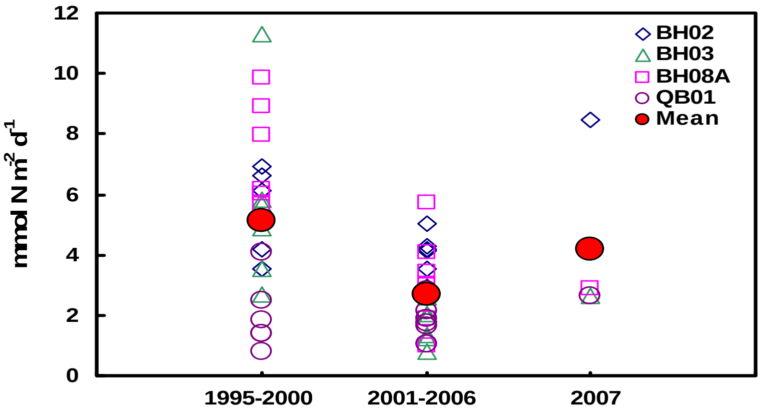
The increase in DIN at Station BH02 was primarily in the NO_3^- component, and again, most of the increase occurred in the summer when the dense infaunal community was present. This pattern of increased NO_3^- flux related to bioturbation and resulting enhancement of nitrification is consistent with earlier observations at Stations BH03 and BH08A. For example, in 1995, at a peak in the amphipod population, NO_3^- comprised 88% of the seasonal DIN flux at Station BH03 (Figure 25). At Station BH02 in 2007, NO_3^- was 46% of the DIN flux. Only once before at this station, during the 1995 amphipod peak, had the NO3- flux contributed more than 25%; more typically NO_3^- accounts for between 10 and 20% of the DIN flux here. At Stations BH03 and BH08A, NO_3^- comprised 25% and 18% of the DIN flux, respectively, for 2007, whereas it was negligible at Station QB01

3.3.2 Phosphate and Silica

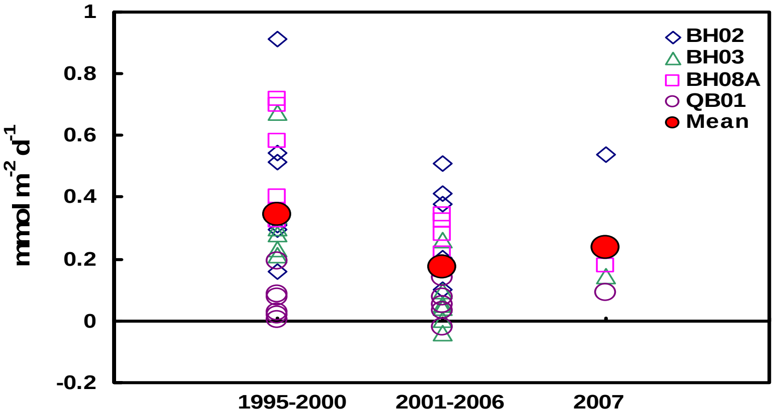
Phosphate flux averaged across our four harbor stations for 2007 was 0.24 mmol m^{-2} d^{-1} (Figure 24b). Following the trend observed in SOD and DIN, this rate was lower than the baseline mean of 0.34 mmol m^{-2} d^{-1}, but higher than the 2001-2006 mean of 0.18 mmol m^{-2} d^{-1}. Again, summer rates at Station BH02 were responsible for elevating both the harbor-wide and station averages, but in the case of PO_4^-, the summer peak did not exceed previous observations. The average for the station for the year was 0.54 mmol m^{-2} d^{-1}, as much as three times the rates of the other stations, but not unlike rates observed at this station in several previous years.

Seasonal average silica flux at Station BH02 in 2007 was 13.4 mmol m^{-2} d^{-1}, the largest flux yet observed at this station (Figure 24c). Although the other three stations had typical seasonal averages, the harbor wide mean of 7.0 mmol m^{-2} d^{-1} slightly exceeded the baseline average of 6.8 mmol m^{-2} d^{-1}, and was also larger than the post-baseline average of 5.2 mmol m^{-2} d^{-1}. Summer fluxes at BH02 were very high, 26.3 mmol m^{-2} d^{-1} in July and 20.6 mmol m^{-2} d^{-1}in August. Rates of similar magnitude have been observed before at this station, but not sustained over subsequent months. Benthic diatoms are often present at BH02, therefore bioirrigation may have flushed an accumulated pool of Si from these sediments.

a. Harbor Average DIN Flux



b. Harbor Average PO_4^- Flux



c. Harbor Average dSi Flux

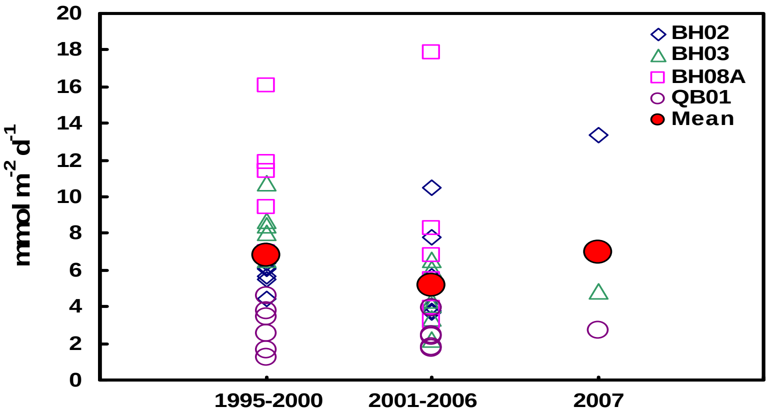


Figure 24. Seasonal (May-October) averages of a) DIN Flux, b.) PO_4^- flux, and c.) dissolved Si flux for Boston Harbor stations during 1995-2000 (pre outfall relocation), 2001-2006 (post outfall relocation, excluding 2007), and for the current year (2007) . Solid symbols represent the average for the harbor over the period; open symbols represent annual averages for each station.

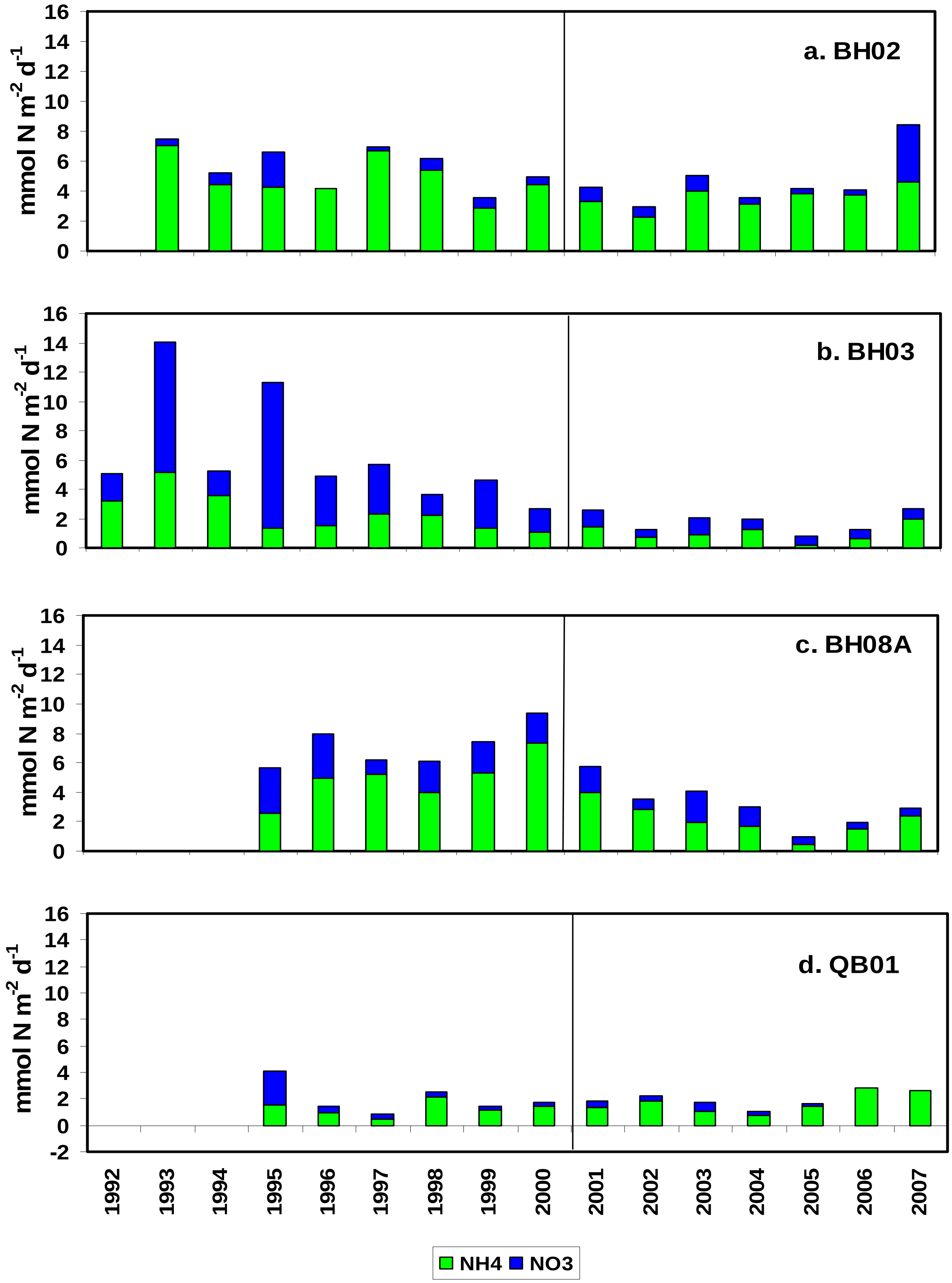


Figure 25. Seasonal (May-October) averages of DIN Flux, partitioned into components of NH_4^+ and NO_3^-, for Station a.) BH02, b.) BH03, c.) BH08A, and d.) QB01. The vertical lines mark the transition between baseline and post-relocation observations.

3.3.3 Benthic Flux Contribution to Primary Production

The relocation of the sewage outfall ended the direct input of a large source of nutrients to the Harbor. With this change, we expected that the relative contribution of nutrients supplied to the water column by benthic recycling might increase. We can use Redfield relationships to make rough estimates of these contributions using pre- and post-relocation rates of primary production and benthic fluxes.

This year we have refined this comparison to more closely match the primary production data; that is, for the baseline data, we are using the years 1995-1999. We start in 1995 because that is the first year in the primary production baseline data and because it is the first year we have benthic flux data from all four stations. We exclude 2000 because the bay outfall came online in September of that year. The post baseline data spans the years 2001-2007. Annual average primary production at water column station F23 at the mouth of the harbor has decreased from a pre-relocation average of about 719g C m^{-2} y^{-1} to a post-relocation average of 361 g C m^{-2} y^{-1}, nearly a 50% decrease (Libby et al., 2008). Seasonal average nutrients fluxes have also decreased. In the case of DIN and PO_4^-, post-baseline fluxes have decreased about 45%. In contrast, Si fluxes have decreased only about 15%. Therefore, in terms of potential contributions to water column production, we have seen little change in N and P. Benthic fluxes continue to account for between 20 and 25% of the estimated requirements. In contrast, the potential contribution of dissolved silica fluxes has increased from 26% to 44%. Interestingly, the DIN:DIP ratio of the fluxes remained constant over the two periods, and quite close to the Redfield ratio (15.6 for the baseline and 15.8 for the post-baseline).

As noted for similar estimates made for our bay sites (Section 2.2.3) there are caveats on this calculation regarding annual averages for primary production versus seasonal averages for the nutrient fluxes, and a bias towards depositional and presumably more active sites, both of which would lead to overestimates of the potential flux contribution. In addition, we have no information on how much of the regenerated N, P, and Si is intercepted by benthic primary producers, which may be considerable in Boston Harbor.

3.4 Denitrification

Our long-term dataset for denitrification in the harbor comes from the two northern harbor stations BH02 and BH03 (Figure 26). At Station BH03, the seasonal average rate for 2007 was 1.5 mmol N m^{-2} d^{-1}, the lowest rate yet observed, continuing a decreasing trend at this site. At BH02, however, denitrification increased in 2007 from the low rates of the previous three years. As we have seen for the other fluxes, May and October rates were low and typical, but summer rates were high, 5.8 and 6.5 mmol m^{-2} d^{-1}, for July and August, respectively. The resulting seasonal average was 3.7 mmol m^{-2} d^{-1}, ranking near the middle of the overall range of rates reported for this station. Again, we invoke the presence of the infaunal community during the summer to explain these high rates. Bioirrigation increases the flushing and oxygenation of the sediment porewaters, thereby enhancing nitrification, and subsequently denitrification.

The change in analytical method in 2004 (see Tucker and Giblin, 2005) allowed us to add measurements at southern harbor Stations BH08A and QB01. The seasonal averages for these two stations in 2007 were 1.9 and 1.0 mmol N m^{-2} d^{-1}, respectively. We now have four years of data from all four stations and all surveys (Figures 26 and 27). All four stations returned to the more typical pattern of peak rates in summer, following temperature, whereas in the pervious year the pattern was almost the inverse. The overall average denitrification rate for 2007 was 2.0 mmol N m^{-2} d^{-1}.

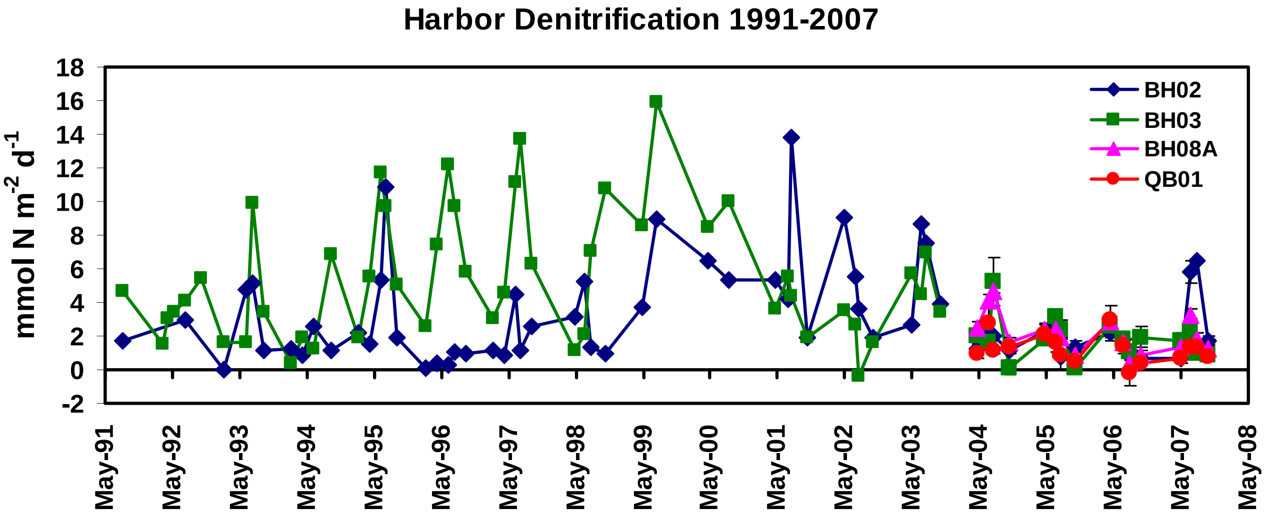


Figure 26. Denitrification in Boston Harbor, showing the long-term dataset from Stations BH02 and BH03, and incorporating data from all stations since 2004.

In 2007, denitrification was typically less than half of the combined inorganic nitrogen flux (DIN flux plus denitrification), whereas at times in previous years, denitrification had been by far the dominant component (Figure 27). Even at Station BH02 during summer when rates were high, denitrification comprised only about 30% of the total. During this period, the benthic community may have accelerated benthic processes such that efficient completion of the series of reactions involved in coupled denitrification was prevented. The result was a fairly even distribution between NH_4^+ flux, NO_3^- flux, and denitrification. NO_3^- was the smallest component of the flux in May and October at this station, and throughout the season at the other four stations. For much of the season NH_4^+ flux and denitrification were proportionally equivalent. At these stations, relatively less oxygen penetration into the sediments (compared to that enhanced by bioturbation) might slow the nitrification step such that proportionally more NO_3^- is denitrified.

The decrease in N loading to the harbor from 1842 kmol d^{-1} to 338 kmol/d^{-1} effected by the relocation of the sewage outfall has shifted the importance of denitrification in the overall N budget. In an earlier paper (Giblin et al, 1994), we constructed a nitrogen budget for the harbor in which denitrification accounted for 14% of total nitrogen inputs from land. Export, calculated as the N not accounted for by denitrification or burial, was the major sink during this period (1991-1994) and burial was minor (Figure 28a). We have constructed a new budget for the post-diversion period (2001-2007). We assumed that burial rate has not changed, and used the average denitrification rate at Station BH02 and BH03 (3.1 mmol N m^{-2} d^{-1} as compared to 5.5 mmol N m^{-2} d^{-1} in the early model). We compared the new rate to the new loading rate for total nitrogen inputs to the harbor (338 kmol d^{-1} as compared to 1842 kmol d^{-1}; Taylor, 2005). In this new budget, denitrification has become the major N sink, accounting for about 55% of the total inputs (Figure 28b).

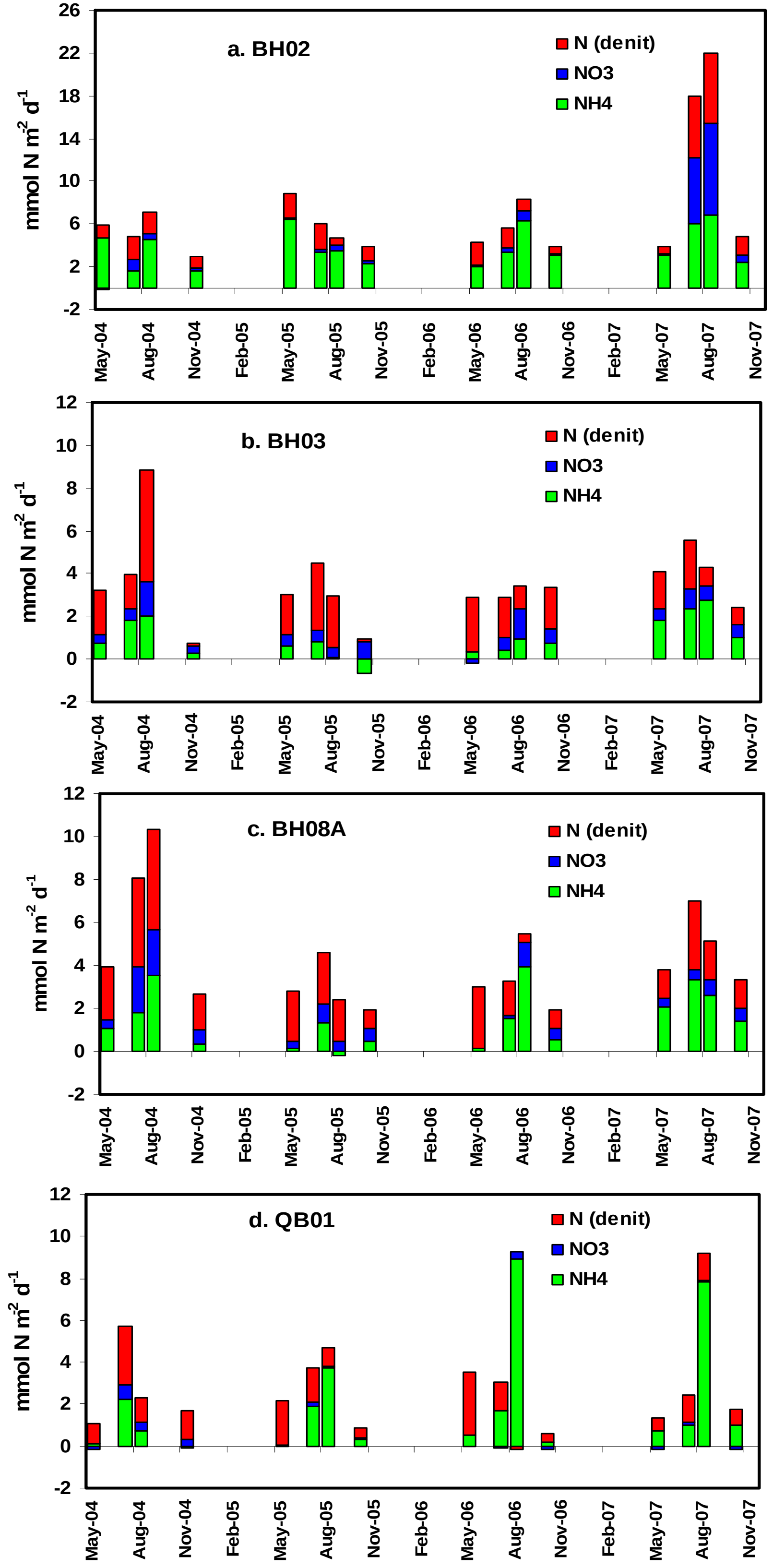


Figure 27. Nitrogen flux at all four Boston Harbor Stations, 2004-2007, partitioned into components of N from denitrification, NH_4^+ flux, and NO_3^- flux.

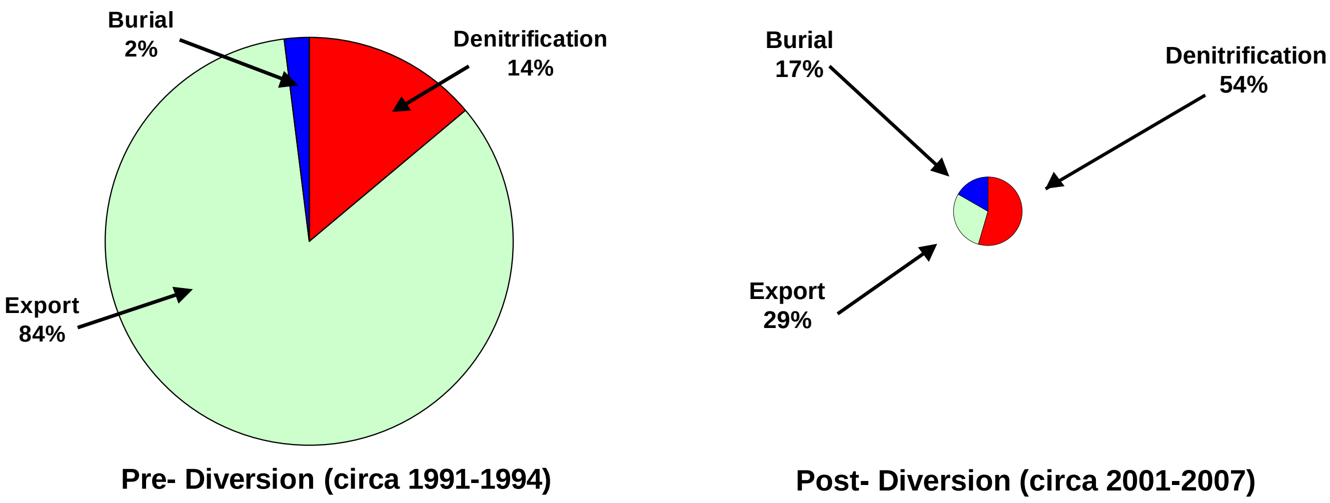


Figure 28. Nitrogen budgets for Boston Harbor, showing change in relative importance of denitrification after outfall diversion. The total N loading during the two periods is represented by the size of the "pie."

3.5 Redox

Indicators of redox conditions in harbor sediments have varied temporally and spatially. Within that variability, however, there are some broad, site-specific trends in the long-term dataset. In general, redox measurements have shown most "improved" conditions (more oxic sediments) at Station BH03 and least improved (typically more anoxic) at Station BH02, with Stations BH08A and QB01 in between. Much of the difference has been attributed to the presence or absence of an active benthic community such as the amphipod mat community, or other mechanisms that would facilitates oxygen penetration into sediment porewaters. Station BH03 was colonized by the amphipod community early in the monitoring program, with an immediate positive change in the redox status of this station. More recently, a change in grain size at this site towards sandier, even gravelly sediments provides a physical structure that facilitates porewater flushing. In contrast, Station BH02 has typically had a relatively depauparate benthic community and its sediment composition has remained primarily silt and clay.

The two intermediate stations often appear similar in their redox state, but achieve this state as a result of different benthic processes. Station BH08A has followed a very similar progression as that described for Station BH03; that is, colonization by the mat community and later changes towards coarser grain size (*sans* gravel). However, the changes at this site were less dramatic than at Station BH03, possibly because this site was never as degraded as was BH03, or because we missed that early phase of this station since we started sampling here 3 years later and are missing some redox data (DIC) from 1995-1997. The mechanisms dictating the redox conditions at Station QB01 are not obvious. Although the site had somewhat sandier sediments than the other three stations at the beginning of monitoring, it has more recently been characterized as primarily silt and clay. This station (which has the same data limitations as BH08A) has not had a particularly dense benthic population, although recent summer flux measurements indicate the presence of some larger, deeper-burrowing infauna. These observations suggest that the community at this site may be at a more advanced successional stage, generally considered consistent with benign redox conditions. In addition, Station QB01 is a very shallow site that often has high sediment chlorophyll concentrations and the presence of benthic diatoms throughout the year. It may be that *in situ* production of oxygen helps create the moderate redox conditions observed at this site.

3.5.1 Respiratory Quotients

In 2007, average respiratory quotients (RQs; ratio of CO_2 efflux to O_2 uptake) did not show the generalized site-to-site differences described above. Instead, values from all sites were remarkably similar, and all very close to 1.0, the value for aerobic respiration (Figure 29). We have suggested that these seasonal or annual average RQs provide a better measure of the overall redox state of the sediments than do instantaneous measurement because this ratio may change substantially over the season. We saw a good example of this at Station BH02 this year. In May when fluxes were low and bioturbation minimal, the RQ was about 1.5, indicating a predominance of anaerobic processes at this time and not unusual for this station. In July, bioturbation had begun to facilitate the reoxidation of stored end products of anaerobic respiration, resulting in a decrease in the RQ to 1.1. This continued into August, with a further drop in RQ to 0.8. By October, the animals were sparse again, and the situation had returned to the more typical one for this station, with and RQ of 1.6. Despite these fluctuations, the seasonal average RQ was 1.0 (note: average RQ = average CO_2 flux/average O_2flux; ≠ average (RQ_{May}, RQ_{Jul}, RQ_{Aug},RQ_{Oct})). The other three sites showed less variability over the season.

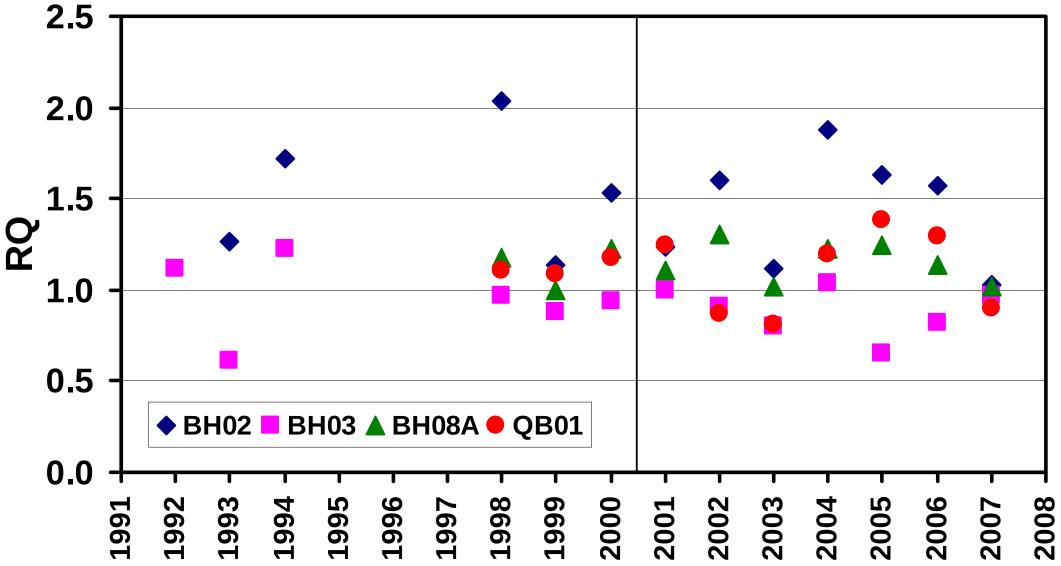


Figure 29. Seasonal (May-October) average respiratory quotients for Boston Harbor stations BH02, BH03, BH08A, and QB01 from 1993-2006. The vertical line marks the transition from baseline to post-relocation observations.

3.5.2 Eh Profiles

Profiles of oxidation-reduction potential (Eh; Figure 30) taken from within sediment cores during 2007 fell within baseline and post-relocation ranges, but had some noteworthy features. At Station BH02, the effects of bioturbation in July and August were evident in the profiles. For those two months, Eh values remained more positive to a deeper depth than in May and October. Descriptions from these sediment cores included observations of amphipods, polychaetes, and associated burrow or tube structures

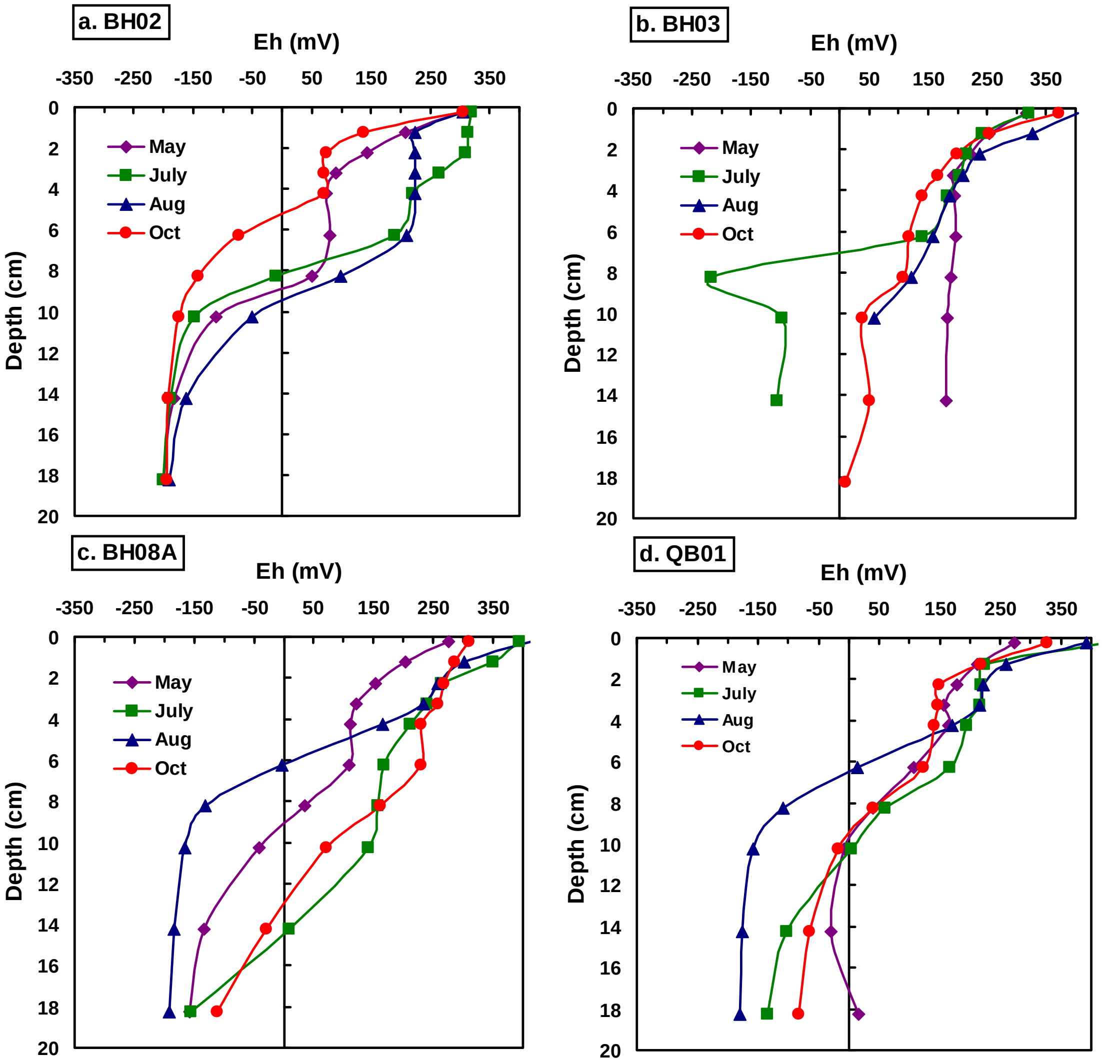


Figure 30. Eh profiles for May through October, 2007, from Harbor stations a.) BH02, b.) BH03, c.) BH08A, and d.) QB01.

penetrating to 6 cm or deeper; in August, some larger burrows were also noted. This depth of about 6 cm corresponded to the visual estimation of the redox potential discontinuity (RPD), and the point at which Eh values began to decline.

At Station BH03, the July profile was distinct from the rest, and showed a sharp decrease in Eh below 6cm to values consistent with sulfate reduction (Eh = -150 to –200). Notes described many quite small burrows visible to about 4 cm, with sediment being dark brown and black below the visual RPD of about 5 cm. Descriptions from the rest of the year noted fewer burrows or tubes, and/or gravel, and/or less distinct color change with depth in the cores. In recent years, this station has experienced a change in grain size to more sand and gravel, but it may be that the July core sampled a siltier sediment patch than has become typical. For the other three profiles, Eh remained positive throughout the length of the core, and Station BH03 continued to be the most highly oxidized of the four stations.

Eh profiles from the other two stations, as well as from Station BH02 showed a healthy oxidized layer grading down to conditions indicative of sulfate reduction at one or more times during the season. These conditions were reached at relatively deep (8 – 10 cm) positions in the cores, and are typical of coastal marine sediments.

4.0 SUMMARY

4.1 Massachusetts Bay

As detailed in this report, and summarized in Table 1, there has been no real change in SOD, NO_3^- fluxes, PO_4^- fluxes or denitrification related to the outfall relocation. In fact, any change has been a decrease, as shown for NH_4^+ and Si fluxes. We continue to observe no adverse impact of the bay outfall in the depositional sediments of our nearfield stations.

Table 1. Average fluxes for all nearfield stations over the pre-diversion (1993 through 2000) or post-diversion (2001-2007) time periods (flux units are mmol m^{-2} d^{-1}). The asterisk denotes the denitrification averages are from only two rather than four stations, and for May and October only.

	SOD	NH4	NO2+NO3	PO4	Si	Denit (N)*
Flux Pre-diversion	17.2	0.7	0.2	0.1	5.1	3.4
Flux Post-Diversion	15.2	0.3	0.3	0.0	3.3	2.1

4.2 Boston Harbor

Nutrient fluxes and SOD continue to show an overall marked decrease compared to the pre-diversion period, despite unusually high summer fluxes at Station BH02. Reductions in these various fluxes are shown in Table 2, with a comparison of the post-diversion period excluding 2007 and including 2007. The post-diversion fluxes were increased slightly by the 2007 data, and consequently the percent reduction decreased, but these changes were minor. Our data continue to show a remarkable state of improvement in the benthic environment of Boston Harbor.

Table 2. Average fluxes (May-October) for all harbor stations over the pre-diversion (1992-1995 through 2000) or post- time periods, 2001-2006 or 2001-2007, to show the impact of high rates at Station BH02 in 2007, and the % reduction in fluxes between the two periods. Flux units are mmol m^{-2} d^{-1}. Note that denitrification averages are from only two rather than four stations.

	SOD	NH4	NO2+NO3	PO4	Si	Denit (N)
Flux Pre-diversion	69.4	3.6	2.2	0.5	8.0	5.5
Flux Post-Diversion (2001-2006)	34.0	2.0	0.7	0.2	5.2	3.2
Reduction	*51%*	*45%*	*67%*	*65%*	*35%*	*42%*
Flux Post-Diversion (2001-2007)	36.1	2.1	0.8	0.2	5.5	3.1
Reduction	*48%*	*41%*	*63%*	*63%*	*31%*	*44%*

4.3 Cross-System Overview

We have frequently used a comparison of sediment oxygen demand in Boston Harbor and Massachusetts Bay to a series of other coastal systems as a marker for change in either system. The comparison dataset (Nixon, 1981, Figure 31) cites summer SOD for systems covering a broad range of SOD, roughly along a eutrophication gradient. To make a more direct comparison to these systems, we have used averages of our July and August data from the four stations in each system for 1995, a year of very high SOD in the harbor during the baseline period, and a series of years from the post-baseline period.

The 1995 data from Massachusetts Bay place it near the bottom of this ranking of systems. The lowest rates yet observed, 11 mmol m^{-2} d^{-1}, occurred in 2005 (the same year as the harbor all-time low), after outfall diversion, and placed Massachusetts Bay at the bottom of the list. Data from 2007 were only slightly higher. Clearly, in this comparison there is no indication of a outfall-related impact on SOD.

At the opposite end of the scale, data from Boston Harbor in 1995 placed it at the top of the list of systems with a very high average summer SOD of 138 mmol m^{-2} d^{-1}. By 2003, that rate had dropped by more than half. The lowest summer SOD in the harbor, 24 mol m^{-2} d^{-1}, was observed in 2005 and had Boston Harbor SOD approaching levels as low as Massachusetts Bay in 1995. SOD was higher in 2006 (35 mmol m^{-2} d^{-1}), but harbor rates remained in the middle of this scale. We attributed these decreases to reductions in carbon loading to the harbor, as well as to an accelerated “burning off” of existing stores by animal respiration and porewater flushing. We speculated that the harbor had reached a new post-diversion baseline that would fluctuate in the range of the 2005 and 2006 data.

As stated previously in this report, this pattern was upset in 2007 by unusually large fluxes at Station BH02. Since this system comparison focuses on summer SOD, we see the most extreme effect of the very high summer SOD observed at this station. The resulting harbor average for 2007 was 71 mol m^{-2} d^{-1}, placing Boston Harbor back near the top of range of estuaries. However, although Station BH02 had very high summer SOD, these rates were still well below the extremes observed at Station BH03 in 1993 and 1995 (Figure 32, originated by M. Mickelson, MWRA, for OMSAP meeting, 2008). We consider this episode at BH02 to be a step forward in the recovery of this station rather than a reversal, following the scenario that seems to have already played out at Station BH03. We look forward to seeing what happens in summer 2008.

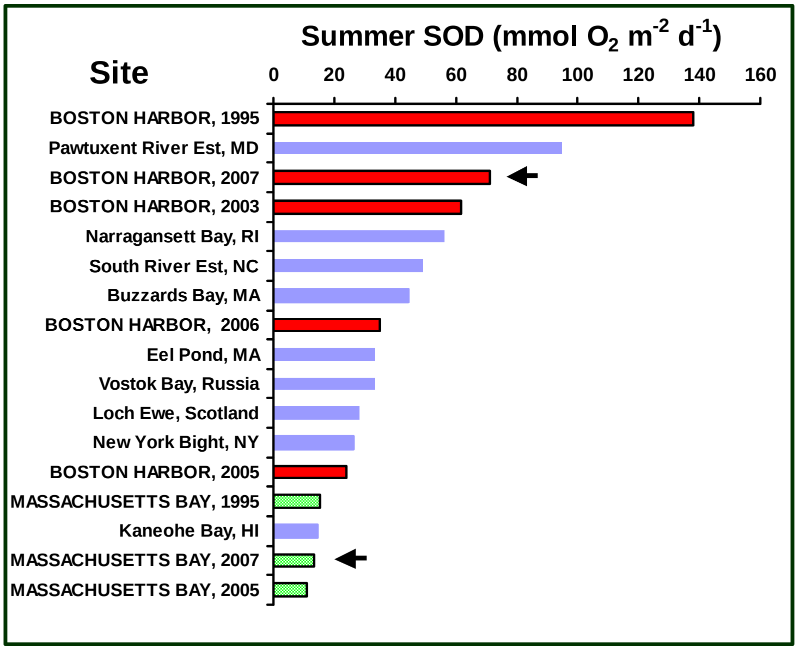


Figure 31. Average July-August sediment oxygen demand (SOD) in Boston Harbor and the nearfield of Massachusetts Bay compared to summer SOD reported for other coastal ecosystems (Nixon 1981). Arrows point to 2007data.

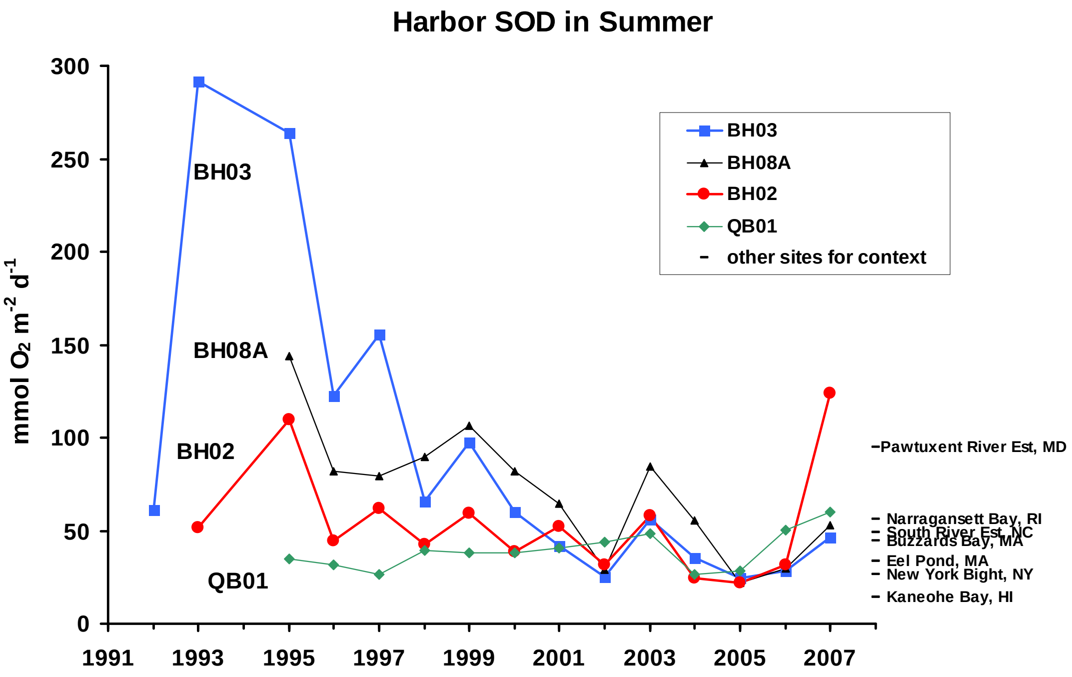


Figure 32. Long-term trends in summer (average of July and August) SOD at the four harbor stations, showing extreme rates at BH03 in 1993 and 1995 as context for the high rates at BH02 in 2007. Summer SOD for some of the same systems as presented in Figure 31 provide further comparison (graph adapted from Mickelson, OMSAP 2008).

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Appendix A

Station names, survey IDs, date of survey, station locations, near-bottom water sampling depth, temperature, dissolved oxygen (D.O.) and salinity for Boston Harbor and Massachusetts Bay stations visited in 2006.

Appendix A

Station names, survey IDs, date of survey, station locations, near-bottom water sampling depth, temperature, dissolved oxygen (D.O.) and salinity for Boston Harbor and Massachusetts Bay stations visited in 2007.

Station	Survey	Date	Latitude	Longitude	Depth (m)	Temp. (^{o}C)	D.O. (mg/L)	Salinity (psu)
BH02	NC071	5/21/2007	42.34358	-71.00235	8.4	9.85	8.66	30.3
	NC072	7/17/2007	42.34375	-71.00210	7.5	14.51	8.56	31.8
	NC073	8/14/2007	42.34357	-71.00235	10	16.9	8.32	31.6
	NC074	10/16/2007	42.34355	-71.00204	9.5	14.1	7.95	31.5
BH03	NC071	5/21/2007	42.33070	-70.96165	7.1	10.13	9.31	29.5
	NC072	7/17/2007	42.33062	-70.96160	6.7	14.71	8.69	31.9
	NC073	8/14/2007	42.33087	-70.96200	8.5	16.6	8.3	31.6
	NC074	10/16/2007	42.33064	-70.96194	7.8	13.6	8.35	31.3
BH08A	NC071	5/21/2007	42.29092	-70.92212	7.3	10.02	9.11	30.6
	NC072	7/17/2007	42.29110	-70.92239	6.5	14.66	8.84	32
	NC073	8/14/2007	42.29103	-70.92223	7.5	16.5	8.33	31.7
	NC074	10/16/2007	42.29095	-70.92205	7.5	13.3	8.16	31.7
QB01	NC071	5/21/2007	42.29343	-70.98782	2.4	10.57	9.3	29.7
	NC072	7/17/2007	42.29353	-70.98780	3	17.29	8.52	31.5
	NC073	8/14/2007	42.29342	-70.98799	3.6	18.2	8.05	31.5
	NC074	10/16/2007	42.29338	-70.98775	3	13.3	8.34	31.8
MB01	NC071	5/22/2007	42.40290	-70.83743	30.4	7.68	9.58	32.3
	NC072	7/16/2007	42.40307	-70.83735	32.7	7.13	8.47	33
	NC073	8/13/2007	42.40285	-70.83725	33.4	8.12	8.34	32.5
	NC074	10/15/2007	42.40312	-70.83749	33	9.2	7.12	32.2
MB02	NC071	5/22/2007	42.39253	-70.83438	31.7	7.82	9.63	32.1
	NC072	7/16/2007	42.39255	-70.83427	34.5	7.12	8.43	33
	NC073	8/13/2007	42.39248	-70.83437	34	8.2	8.52	32.6
	NC074	10/15/2007	42.39250	-70.83438	33.5	9.9	7.42	32.5
MB03	NC071	5/22/2007	42.34795	-70.81612	33	7.38	9.8	32.6
	NC072	7/16/2007	42.34783	-70.81620	32.5	7.15	8.4	32.5
	NC073	8/13/2007	42.34782	-70.81617	33.4	8.12	8.23	32.6
	NC074	10/15/2007	42.34793	-70.81625	30	9.9	7.45	32.3
MB05	NC071	5/22/2007	42.41652	-70.65199	47.5	5.52	7.25	33
	NC072	7/16/2007	42.41647	-70.65202	43.3	5.62	9.15	32.8
	NC073	8/13/2007	42.41650	-70.65179	46.2	6.71	8.64	33.2
	NC074	10/15/2007	42.41643	-70.65217	37.5	8.9	7.82	32.2

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