Barnegat Bay— Year 2

Benthic Invertebrate Community Monitoring and Indicator Development for the Barnegat Bay-Little Egg Harbor Estuary

Dr. Gary Taghon, Rutgers University, Principal Investigator

Judith P. Grassle, Charlotte M. Fuller, Rosemarie F. Petrecca, Patricia Ramey, Rutgers University, Co-Managers

Project Manager:
Tom Belton, Division of Science, Research and Environmental Health

Thomas Belton, Barnegat Bay Research Coordinator

Dr. Gary Buchanan, Director—Office of Science

Bob Martin, Commissioner, NJDEP

Chris Christie, Governor

June, 2015

June 3, 2014

Final Report

Project SR12-006: Benthic Invertebrate Community Monitoring and Indicator Development for Barnegat Bay-Little Egg Harbor Estuary: Year 2

Gary L. Taghon, Rutgers University, Project Manager
taghon@marine.rutgers.edu

Judith P. Grassle, Rutgers University, Co-Manager
jgrassle@marine.rutgers.edu

Charlotte M. Fuller, Rutgers University, Co-Manager
fuller@marine.rutgers.edu

Rosemarie F. Petrecca, Rutgers University, Co-Manager and Quality Assurance Officer
petrecca@marine.rutgers.edu

Patricia Ramey, 1700 Joyce Street, Coldbrook, Nova Scotia, Canada, B4R 1A4
ramey@marine.rutgers.edu

Thomas Belton, NJDEP Project Manager and NJDEP Research Coordinator
Thomas.Belton@dep.state.nj.us

Marc Ferko, NJDEP Quality Assurance Officer
Marc.Ferko@dep.state.nj.us

Bob Schuster, NJDEP Bureau of Marine Water Monitoring
Robert.Schuster@dep.state.nj.us

Introduction

The Barnegat Bay ecosystem is potentially under stress from human impacts, which appear to have increased over the past several decades. Benthic macroinvertebrates are commonly included in studies to monitor the effects of human and natural stresses on marine and estuarine ecosystems. There are several reasons for this. Macroinvertebrates (here defined as animals retained on a 0.5-mm-mesh sieve) are abundant in most coastal and estuarine sediments, typically on the order of 10^3 to 10^4 individuals per meter squared. Benthic communities are typically composed of many taxa from different phyla, and quantitative measures of community diversity (e.g., Rosenberg et al. 2004) and the relative abundance of animals with different feeding behaviors (e.g., Pelletier et al. 2010, Weisberg et al. 1997), can be used to evaluate ecosystem health. Because most benthic invertebrates are sedentary as adults, they function as integrators, over periods of months to years, of the properties of their environment.

The Barnegat Bay-Little Egg Harbor (BB-LEH) Estuary is heterogeneous with respect to environmental variables that are well known to affect benthic community composition. Salinity and sediment particle size vary throughout the system. Salinity varies locally along the main axis of the estuary in response to ocean water sources (notably at Barnegat Inlet, Little Egg Inlet, and the Point Pleasant Canal) and fresh-water sources (notably Toms River, Metedeconck River, and Cedar Creek). Long-term data collected by the New Jersey Department of Environmental Protection, Bureau of Marine Water Monitoring show that salinity tends to be lower in northern Barnegat Bay (range 0-20) than in central and southern Barnegat Bay and in Little Egg Harbor (range 20 to >28). Sediment particle size, and the inversely correlated sediment organic content, varies from east to west, with fine-grained sediments predominantly present in the western half and coarser sediments in the east. Sediment organic matter content is likely to also vary in response to variations in nutrient loadings throughout the system. Our objective is to develop quantitative measures to relate benthic community structure to variation in these and other environmental properties in BB-LEH Estuary.

Benthic invertebrates in the BB-LEH Estuary were sampled comprehensively in 2001 as part of the EPA REMAP and NCA efforts, when 96 stations were sampled. In July 2012 we sampled 100 stations throughout the bay in order to obtain a data set comparable to the sampling density in 2001. In July 2013 we re-sampled these stations, using the same methods, in order to evaluate any short-term temporal change, including potential effects from Hurricane Sandy which struck the New Jersey coast between these two sampling periods.

Methods

Field sampling

One hundred stations were sampled between July 1 and 10, 2013. Surface and bottom water salinity, temperature, dissolved oxygen, and pH were measured at each station with a YSI hand-held meter (Yellow Springs Instruments, Yellow Springs OH). The data were stored in the instrument memory for later download to a computer, and were also hand-entered onto waterproof sheets, along with date and time of sampling, station coordinates, water depth, weather, sea conditions, sediment visual characteristics, presence of submerged aquatic vegetation, and general notes about station characteristics.

Three sediment samples were taken at each station, using a 0.044-m^2 Ted Young Modified Van Veen grab. Depth of sediment sampled was recorded. Two of the sediment samples were processed in their entirety for benthic invertebrate macrofauna. Sediment was sieved over a 0.5-mm-mesh screen, and material remaining on the screen was fixed in 3.7% formaldehyde solution in seawater buffered with Borax. Rose Bengal was added to stain organisms to facilitate sorting. Sieved samples were delivered to Cove Corporation (Lusby, MD) for sorting and identification of organisms to lowest possible taxonomic unit, usually species.

The third grab from each station was used for measurement of sediment properties. The top 2-cm layer of sediment was removed with a stainless steel spoon, transferred to a stainless steel bucket, and homogenized by stirring. Subsamples of the homogenized sediment were taken for total organic carbon, total nitrogen, and total phosphorus (~100 mL of sediment transferred to a glass 250 mL jar with a Teflon-lined cap), for grain size analysis (~250 mL of sediment transferred to a Whirl-Pak bag), organics (~250 mL of sediment transferred to a glass 500 mL jar with a Teflon-lined cap), and metals (~100 mL of sediment into a pre-cleaned plastic (HDPE) jar). All samples were stored on ice immediately after collection and during transport to the laboratory. The sediment samples for organics were transferred to a 4° refrigerator and those for metals were transferred to a -20° freezer for possible future analysis (US EPA 2001).

Laboratory analysis: sediment grain size

Sediment for grain size analysis was processed using methods described in detail in the EMAP-Estuaries Laboratory Methods Manual (US EPA 1995). Briefly, sediment was wet-sieved through a 63µm-mesh sieve in distilled water with dispersant to separate the silt and clay fraction from the sand-sized fraction. The sand fraction was dried and then sieved into the following size fractions: <4ϕ (<63 µm, silt), 4ϕ (63-125 µm, very fine sand), 3ϕ (125-250 µm, fine sand), 2ϕ (250-500 µm, medium sand), 1ϕ (500-1000 µm, coarse sand), and 0ϕ (1000-2000 µm, very coarse sand). Each fraction was weighed. The mass of the <4ϕ fraction was determined by drying a known volume of the water-particle mixture passing through the 63µm-mesh sieve.

Grain size statistics were computed using the program GSSTAT, developed by the United States Geological Service (Poppe et al. 2004).

Laboratory analysis: sediment organic carbon, nitrogen, and phosphorus

Sediment was freeze dried and then gently disaggregated. Large shell fragments, pieces of vegetation, or visible organic debris were removed, and then sediment was ground to a fine powder using a ceramic mortar and pestle.

Total organic carbon (TOC) and total nitrogen (TN) were measured using standard methods (elemental analysis EPA Method 440.0 for total C and N (US EPA 1992)). Aliquots were weighed into silver foil sample cups. Two replicates per station were prepared. The silver foil cups with sediment were placed into a sealed chamber with concentrated hydrochloric acid fumes to remove inorganic carbonate. Samples were analyzed using a Carlo Erba NA1500 Elemental Analyzer. Internal standards of acetanilide or NIST Standard Reference Material 2702-Inorganics in Marine Sediment (National Institute of Standards and Technology, Gaithersburg MD) were run after every five unknowns to validate instrument performance. Data were accepted if the measured values for carbon of the standards differed by less than ±10% from the expected values.

Total phosphorus (TP) was measured using standard methods (colorimetric analysis of total phosphate (US EPA 2010, chapter 6). A laboratory reagent blank and an internal standard (NIST Standard Reference Material 2702-Inorganics in Marine Sediment) were run after every 10 unknowns. Data were accepted if the measured value for phosphorus of the standard differed by less than ±10% from the expected value.

Data analysis

Exploratory data analysis was conducted using Microsoft Excel 2007 or Statistix v10 (Analytical Software, Tallahassee FL). In most cases exploratory data analysis involved use of scatterplots to examine potential correlations among variables. Locally weighted scatterplot smoothing (LOWESS), a robust locally weighted regression algorithm, was used to visualize trends in data (Cleveland 1979). Multivariate statistical analyses were conducted using Canoco v4.56 (Microcomputer Power, Ithaca NY) and Primer 6 (Clarke and Gorley 2006).

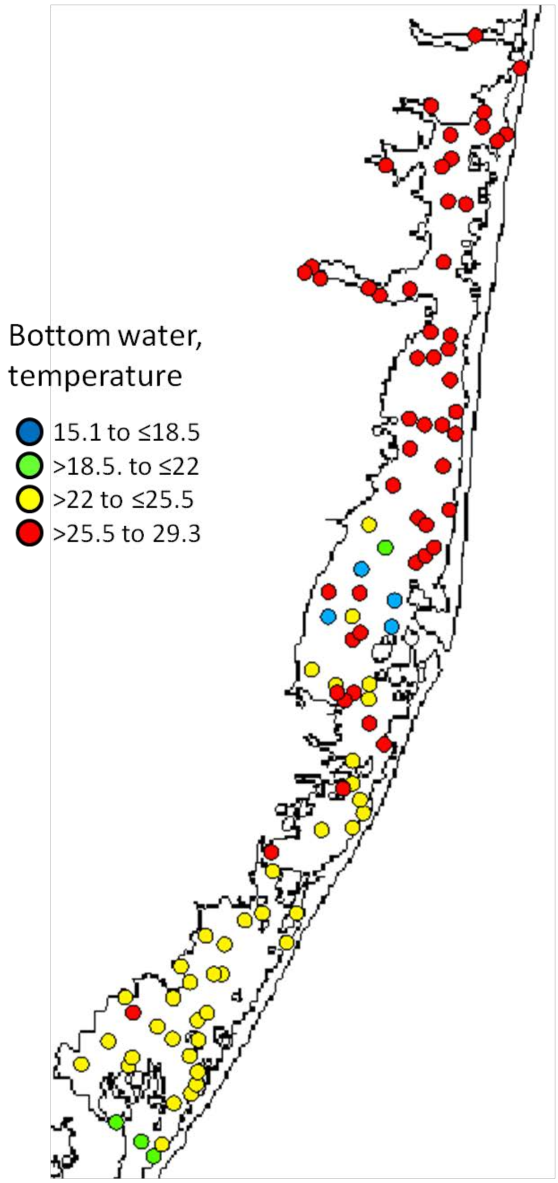
Results and Discussion

Bottom water properties in 2013

Temperature

Bottom water temperatures ranged from 15.5 to 29.3° with the coolest waters present in the central section of the bay near Barnegat Inlet (Figure 1). Warmest waters were in the northern half of the bay.

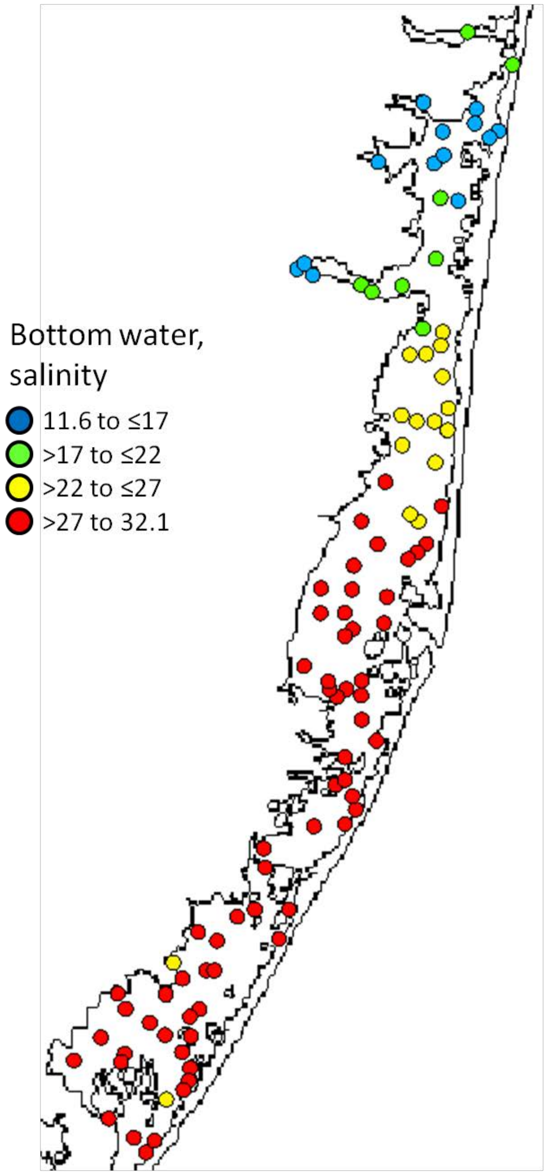
Figure 1. Bottom water temperatures during the period July 1 – July 10, 2013.



Salinity

Salinity ranged from 11.6 to 32.1 (Figure 2). Lowest values were in the northern section of the bay, while highest salinities occurred in the central section of the bay and in Little Egg Harbor.

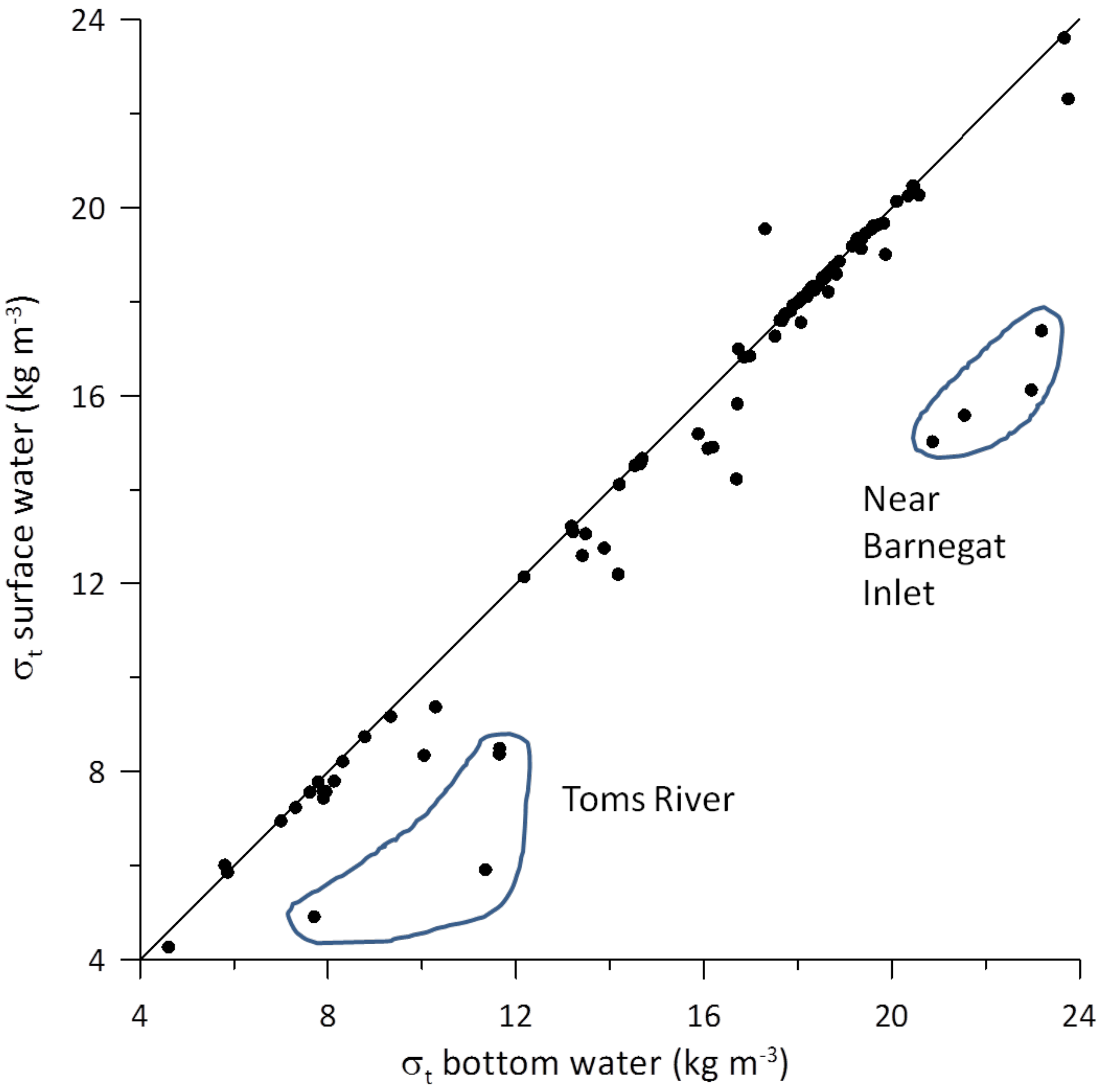
Figure 2. Bottom water salinities during the period July 1 – July 10, 2013.



Stratification

Surface and bottom water densities were calculated using the equations of state in Gill (1982) and expressed as σ_t values (density-1000, kg m^{-3}). In general, the bay was weakly stratified during the sampling period (Figure 3). At some locations, notably in Toms River and several stations near Barnegat Inlet, the water column was more strongly stratified due to colder, more saline bottom waters.

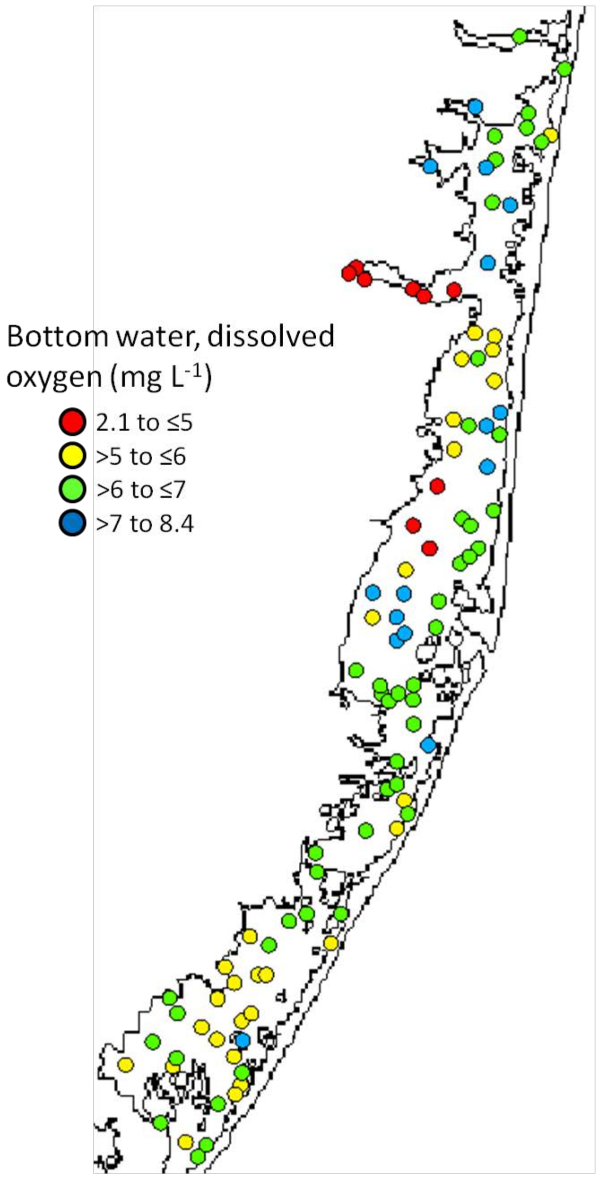
Figure 3. Surface vs. bottom water density. Solid line is 1:1 relationship. Stations with stronger stratification indicated with outlining.



Dissolved oxygen

Dissolved oxygen concentrations ranged from 2.1 to 8.4 mg L^{-1} (Figure 4). The spatial pattern for oxygen was not as distinctive as those for temperature and salinity. Low values, <5, occurred in Toms River and several stations in central Barnegat Bay, while the highest values were found at locations interspersed throughout the Barnegat Bay and Little Egg Harbor.

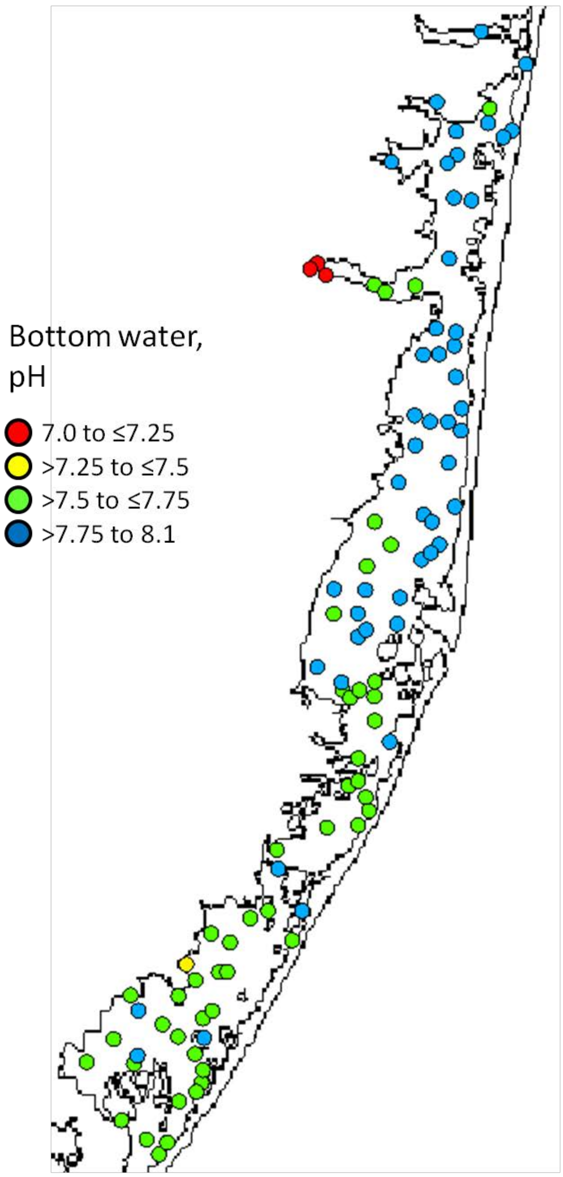
Figure 4. Bottom water dissolved oxygen concentrations during the period July 1 – July 10, 2013.



pH

Bottom water pH varied from 7.0, measured at the head of Toms River, to 8.1, measured at station 034 in northern Barnegat Bay opposite of Windy Cove (Figure 5). At most stations (97 of 100) pH was above 7.5. Highest values, >7.75, were measured in central and northern Barnegat Bay (with the exception of Toms River), while pH was slightly lower in southern Barnegat Bay and Little Egg Harbor.

Figure 5. Bottom water pH during the period July 1 – July 10, 2013.

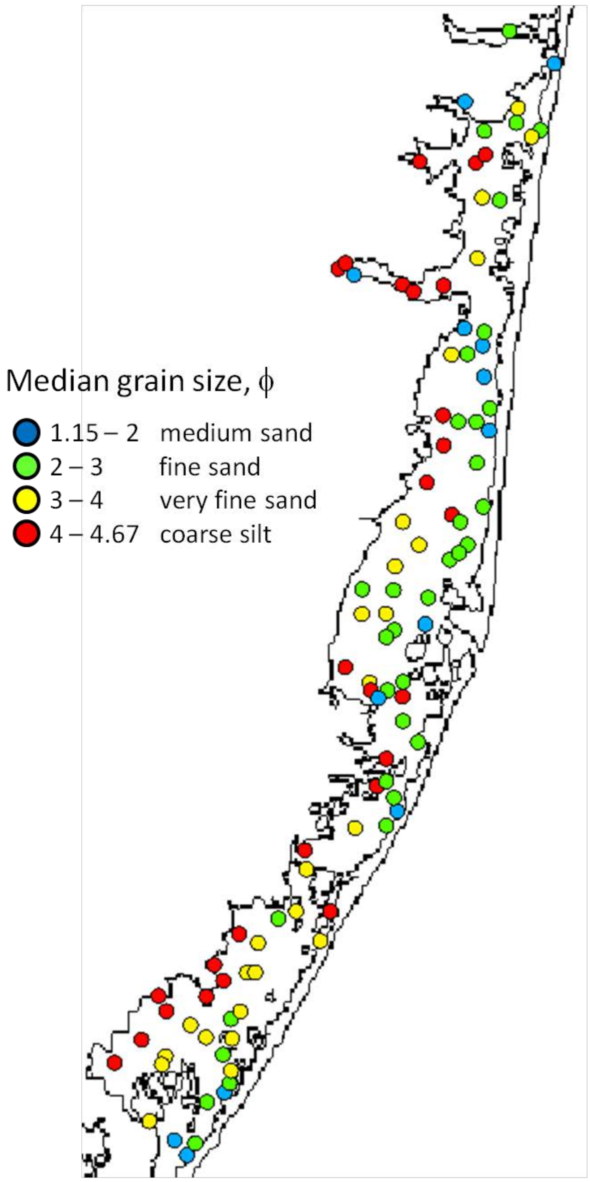


Sediment properties in 2013

Sediment grain size

Sediments ranged from medium sands to coarse silts (Figure 10). Although fine-to-medium sands tended to occur along the eastern boundary of BB-LEH and very fine sand and coarse silt tended to occur on the western side, there was considerable heterogeneity in the distribution of particle sizes. In several cases sediments at two closely spaced stations were at opposite ends of the particle size spectrum.

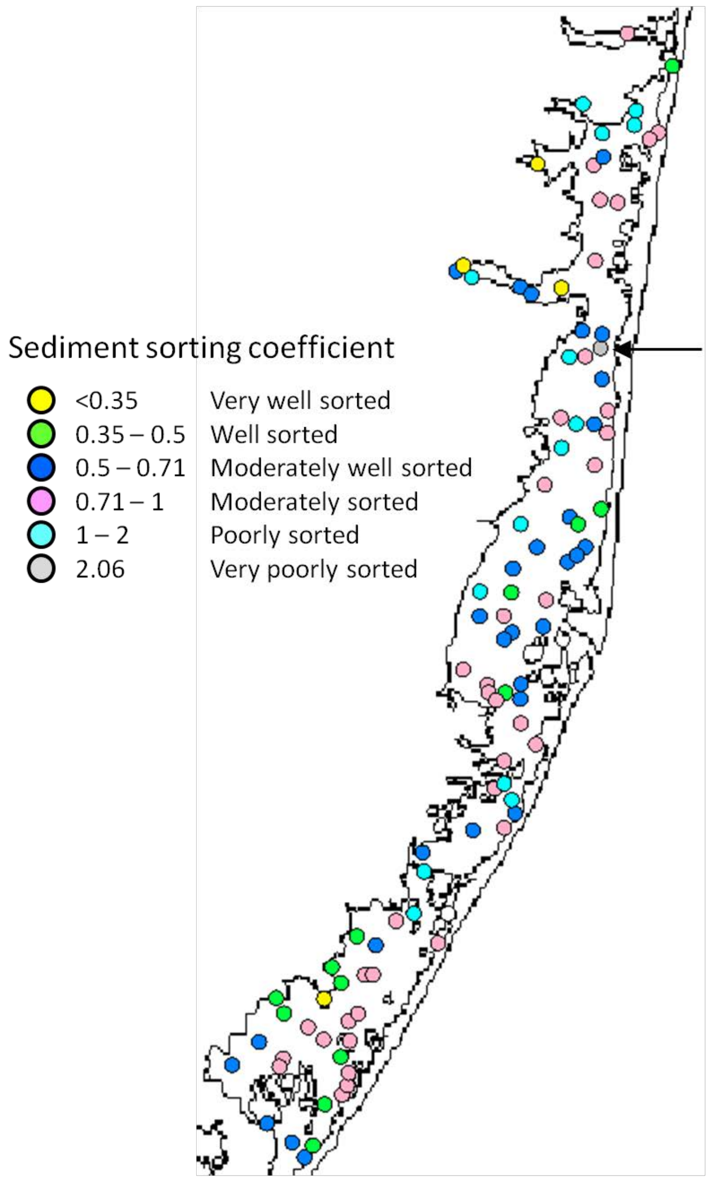
Figure 10. Median sediment size during the period July 1 – July 10, 2013.



Sediment sorting

The sediment sorting coefficient (Inclusive Graphic Standard Deviation, a measure of the variability of sediment particle sizes) varied over the full range from very well sorted to very poorly sorted (Figure 11). At most locations, sediments were moderately sorted (n=38) or moderately well sorted (n=30) and these stations were spread throughout the bay with no apparent pattern. The four stations with very well sorted sediments were on the western side of the bay, but so were most of the stations with poorly sorted sediments. Station 31, west of Seaside Park, had very poorly sorted sediments with a median grain size of 1.15 ϕ (0.45 mm), possibly due to effects from Hurricane Sandy.

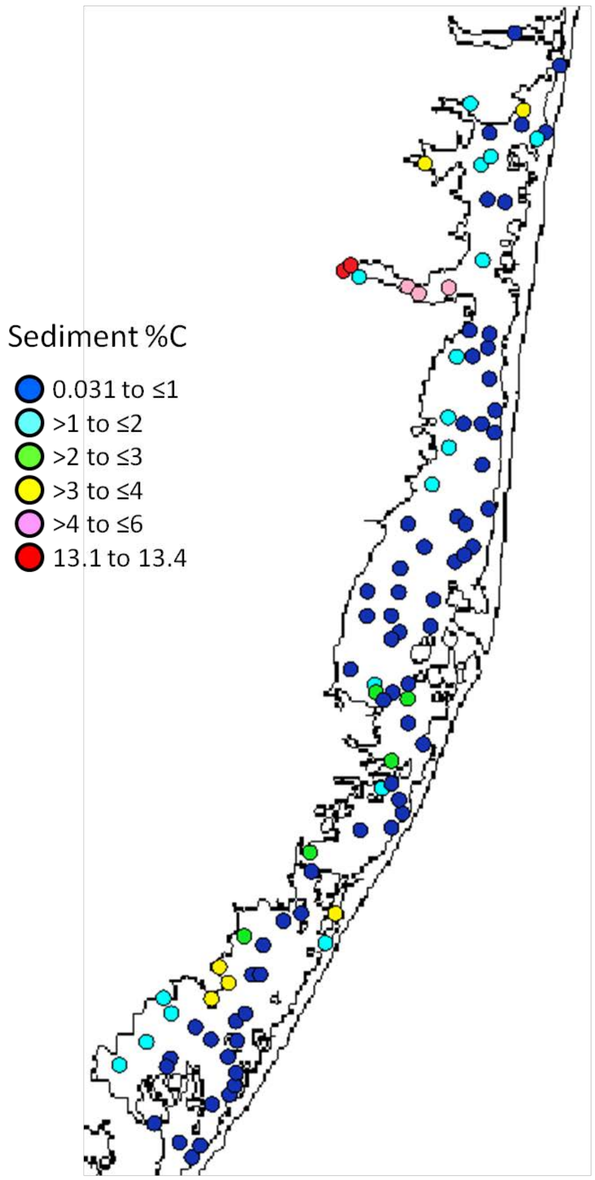
Figure 11. Sorting coefficients for sediment samples collected during the period July 1 – July 10, 2013. Station 31, west of Seaside Park, indicated by arrow.



Sediment carbon, nitrogen, and phosphorus

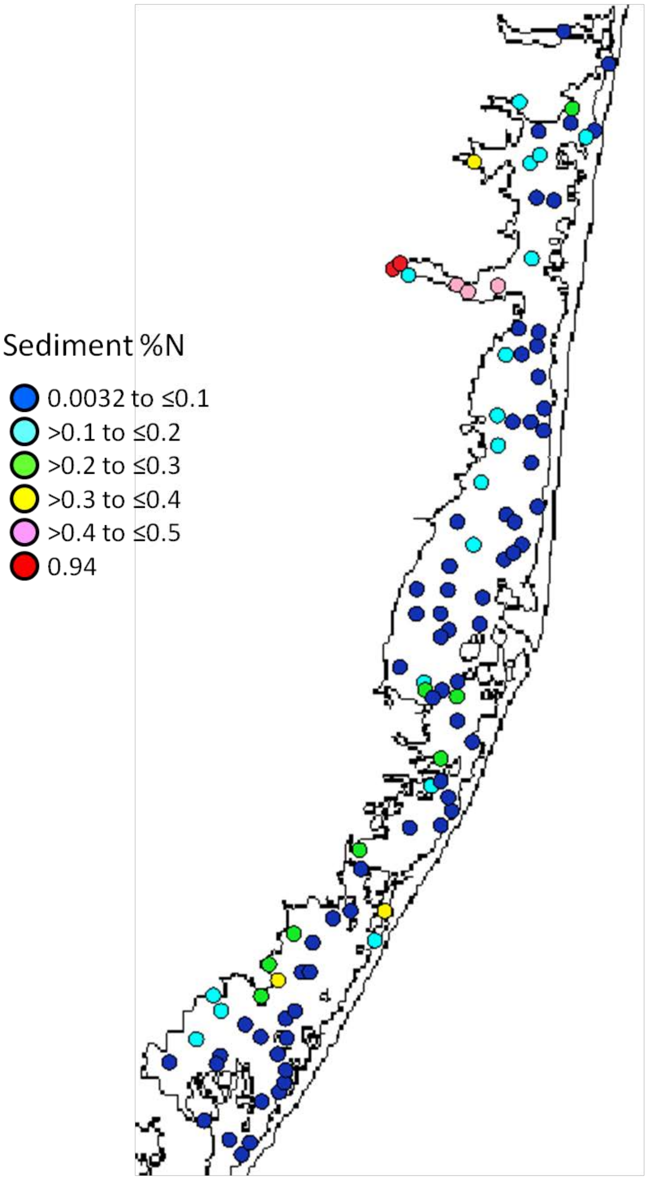
Sediment carbon concentration ranged from 0.031 to 13.4% by weight (Figure 12). Most stations, 67 out of 100, had ≤1% carbon. Stations in the Toms River had highest carbon concentrations.

Figure 12. Sediment carbon concentrations during the period July 1 – July 10, 2013.



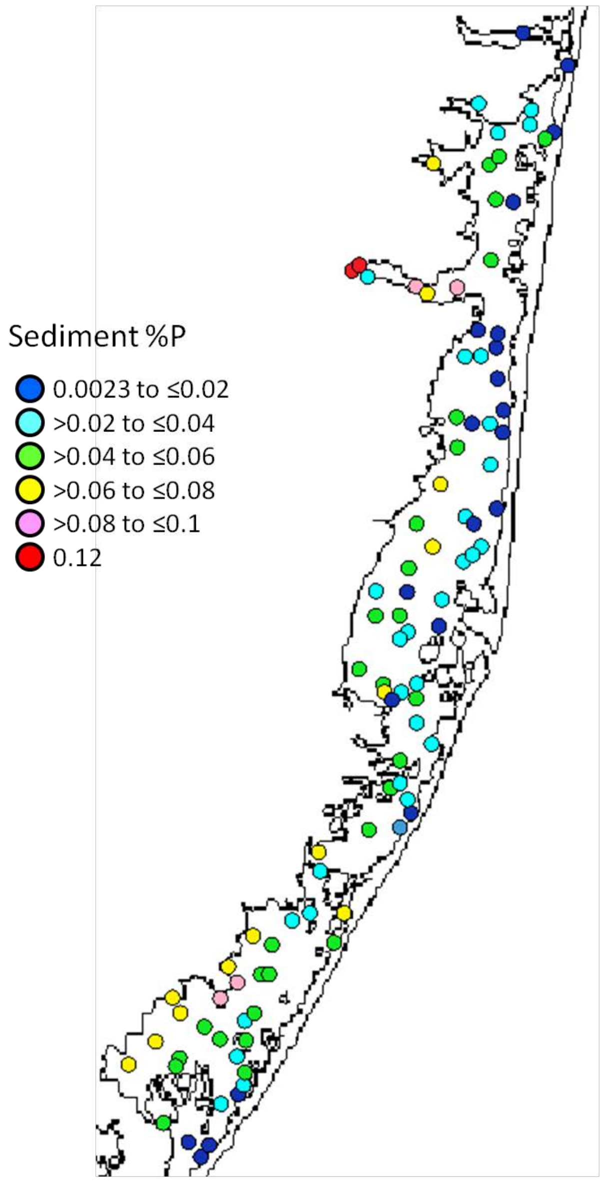
Total nitrogen concentration of sediments ranged from 0.0032 to 0.94% (Figure 13). Most stations (67) had nitrogen concentrations ≤0.1%.

Figure 13. Sediment total N concentrations during the period July 1 – July 10, 2013.



Sediment total phosphorus concentrations ranged from 0.0023 to 0.124% (Figure 14). Most stations (80) had phosphorus concentrations ≤0.06%. Higher values tended to occur on the western side of BB-LEH and lower values on the eastern side.

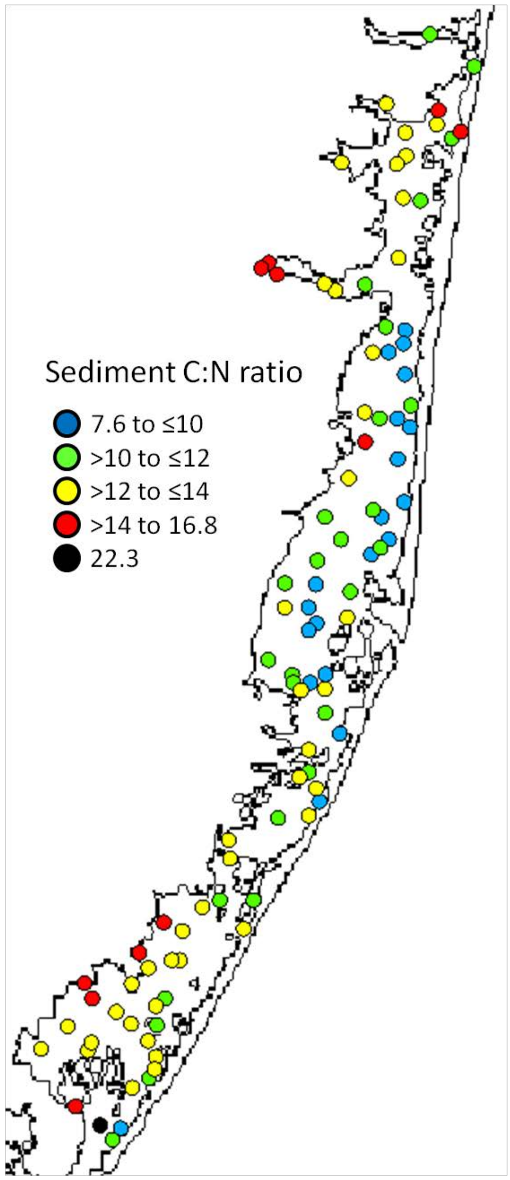
Figure 14. Sediment total P concentrations during the period July 1 – July 10, 2013.



Sediment C:N:P ratios

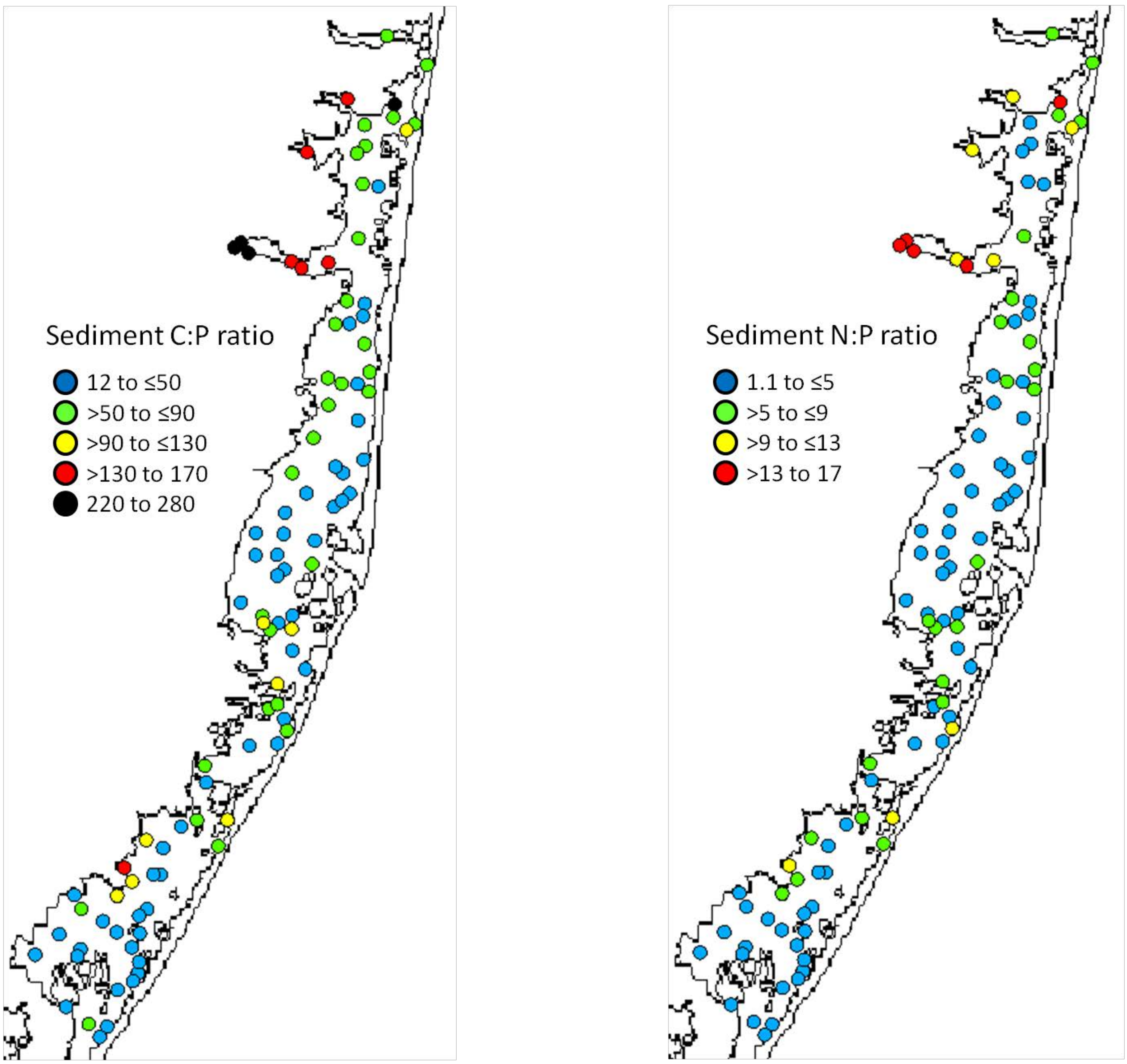
Sediment C:N ratio varied from 7.6 to 16.8 for all stations except for an extreme value of 22.3 at station 97 at Little Egg Inlet Figure 15). These C:N ratios are greater than the putative Redfield C:N ratio of 6.6, as is commonly found in marine sediments due to preferential heterotrophic metabolism of nitrogen-rich organic matter.

Figure 15. Sediment C:N ratio (molar) during the period July 1 – July 10, 2013.



Sediment C:P and N:P ratios at most stations were less than the putative Redfield ratio of 106:1 and 16:1, respectively (Figure 16). This contrasts with the C:N ratios and indicates that sediments in BB-LEH may be a sink for phosphorus. This would only be the case if the C:P and N:P ratios of water column particulates are greater than the ratios in the sediments. We are unaware of any contemporary, direct measures of particulate C, N, and P.

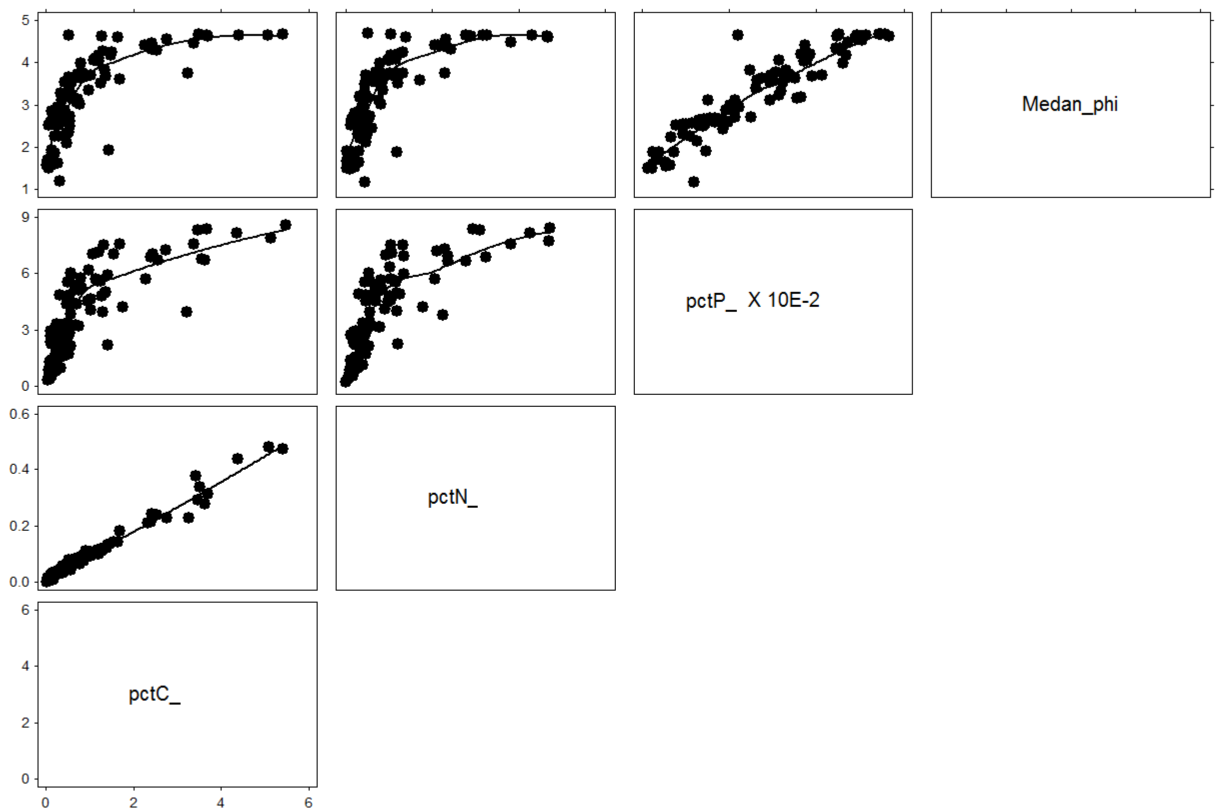
Figure 15. Sediment C:P and N:P ratios (molar) during the period July 1 – July 10, 2013.



Relationships among sediment grain size, carbon, nitrogen, and phosphorus concentrations

Carbon and nitrogen concentrations were tightly and linearly correlated (Figure 15). The correlations between carbon and phosphorus and between nitrogen and phosphorus were less tight, and non-linear, with phosphorus concentrations beginning to level out at higher carbon and nitrogen concentrations. Similarly, both carbon and nitrogen increased linearly as median sediment grain size decreased, until about 4ϕ, the boundary between sand and silt sizes. Further increases in carbon and nitrogen were not associated with decreasing grain size. Total P showed a strong and consistent increase as grain size decreased, unlike carbon and nitrogen.

Figure 15. Scatterplot matrix of sediment properties during the period July 1 – July 10, 2013. Three stations in Toms River with anomalously high TOC, TN, and TP concentrations were omitted. Lines are LOWESS fits, with f=0.25.



Multivariate analysis of environmental properties

Cluster analysis of the environmental data was performed to see if there were “natural groupings” of stations that could delineate different regions of BB-LEH. Data were log transformed for sediment C and N and square root transformed for sediment P to make them normally distributed. The remaining variables – median sediment size and bottom water salinity, temperature, dissolved oxygen, and pH resisted attempts to transform them. The data were then normalized by subtracting the mean and dividing by the standard deviation. Similarities of the transformed and normalized data were calculated as Euclidean distances, followed by hierarchical clustering with group-average linking. Three stations at the head of Toms River (18, 19, and 25) were omitted because only one or two animals were present in samples from these sites (see below). All calculations were performed using PRIMER v6. Stations clustered into seven groups (Figure 16), although the cut-off levels for defining the clusters varied. The tentatively identified clusters were named based on the geographic location of most of the stations within each cluster and color coded (Figure 16). Three stations at the mouth of Toms River were most similar. Next most similar were stations clustering along the eastern side of southern Barnegat Bay/Little Egg Harbor, and stations clustering along the western side. All southern Barnegat Bay/Little Egg Harbor stations then clustered with several stations located farther away from Little Egg Inlet and Barnegat Inlet. The next most similar clusters were stations along the eastern and western sides of northern Barnegat Bay. The least similar stations were those closest to Little Egg Inlet and Barnegat Inlet.

Classification (cluster analysis) is useful and provides a simple way of grouping stations, but it can ‘force’ samples into artificial groups when in fact the underlying data are continually distributed (Field et al. 1982). Therefore, we conducted non-metric multi-dimensional scaling (MDS) to see if this ordination method identified similar groups. MDS produces a two-dimensional ‘map’ using the Euclidean distance data between all possible pairs of stations. It seeks the best possible configuration of stations so that the most similar stations map nearest each other. The MDS map produced (Figure 17) was color coded with the same scheme used in the cluster analysis to permit easy visual comparison of the two methods. Two groups of stations, Toms River and Inlets (distal) clearly stood out in MDS as they did in the cluster analysis. Inlets (proximal) contained stations that were least similar in the cluster analysis and in MDS these stations were widely separated, with some closer to stations that were placed into other groups by cluster analysis. The majority of the stations in southern Barnegat Bay/Little Egg Harbor and northern Barnegat Bay did not form as distinct groups in MDS as they did in cluster analysis. For example, stations 45 and 100 in the southern BB-LEH east side cluster are widely separated in the MDS ordination, with station 45 closer to stations in the northern BB-east side cluster. Using the same color coding on the physical map of station locations confirmed that these clusters should only be thought of as general groupings and that boundaries are not absolute (Figure 18). Especially noteworthy is that stations in east and west clusters often mingle with each other in their actual physical locations. This is another indication that stations physically close together can have widely separated environmental properties.

Figure 16. Dendrogram of stations by hierarchical cluster analysis with group average sorting, based on Euclidean distance similarity matrix of environmental properties.

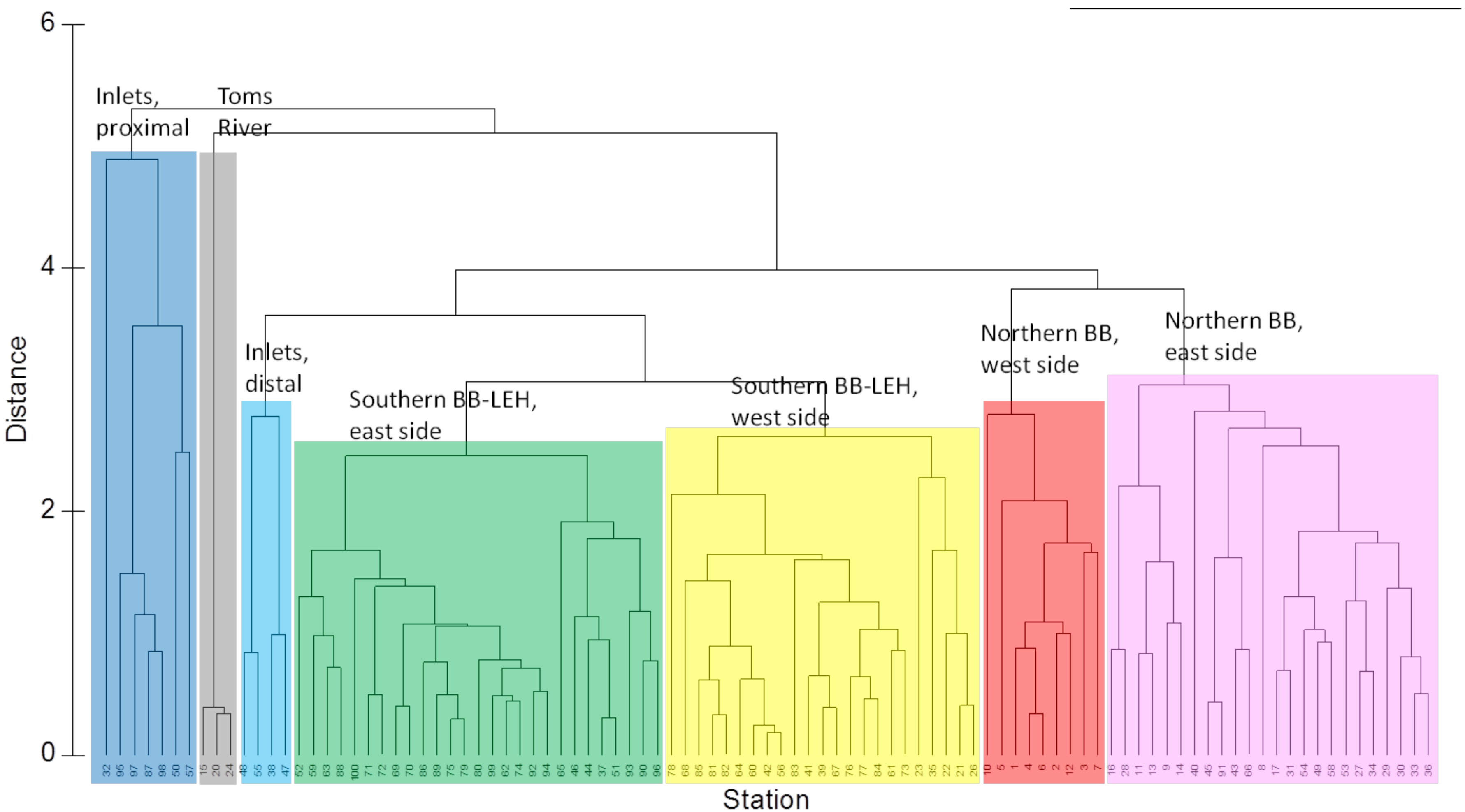


Figure 17. Ordination of stations by MDS, based on environmental properties.

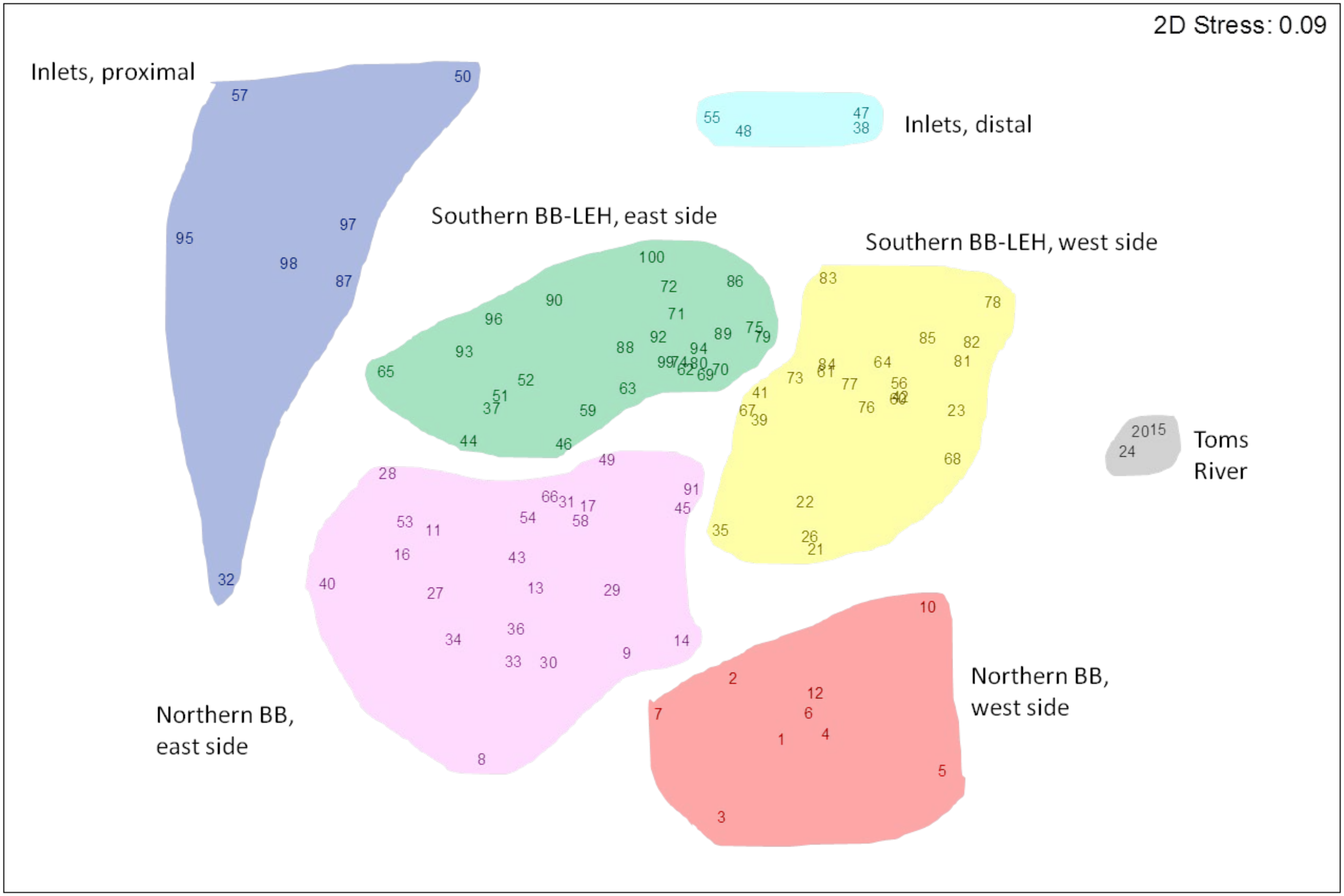
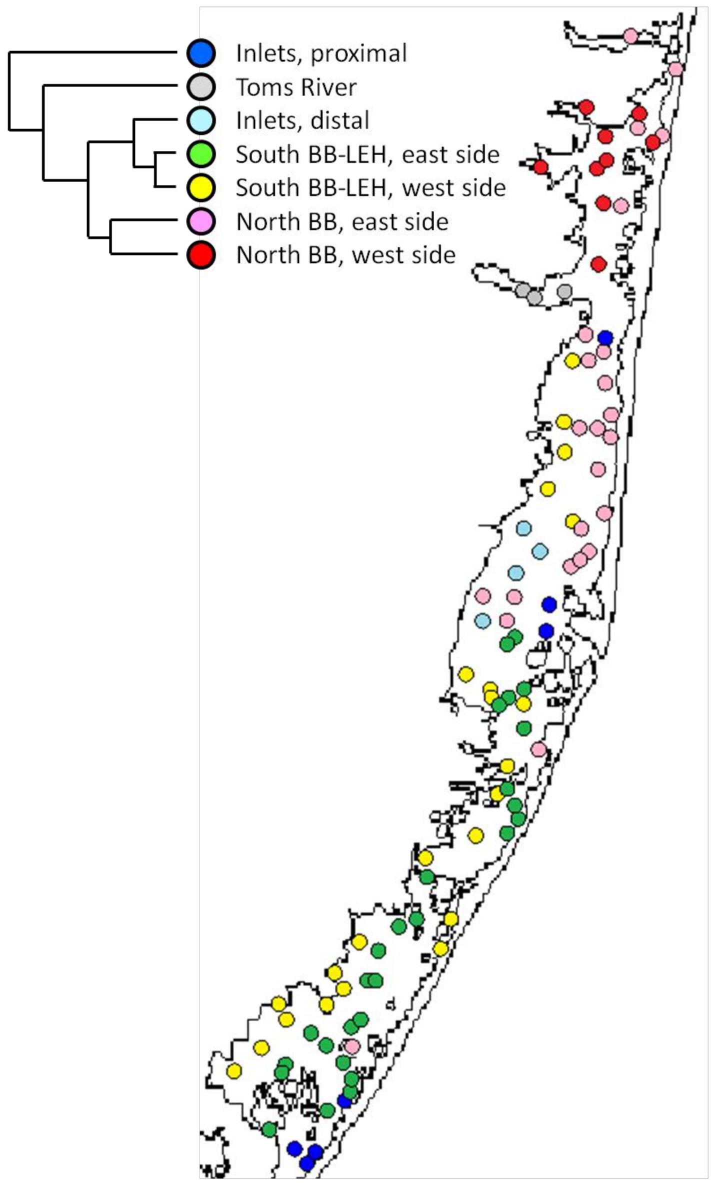
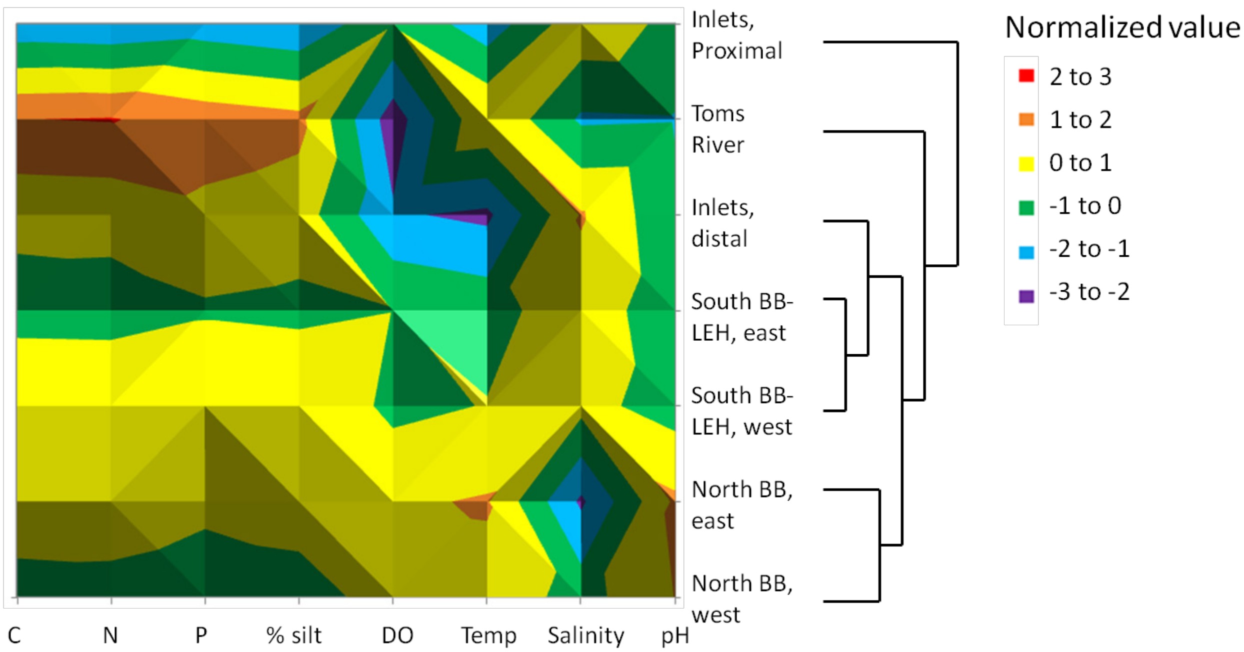


Figure 18. Station clusters as identified by the dendrogram in Figure 16. The clustering of groups is also included for comparison. Note that actual station locations were often located outside of their 'clusters.'



We constructed a heat map to try to identify which of the eight environmental properties differed among the station clusters from the cluster analysis (Figure 19). The southern BB-LEH stations were most similar in all properties, with the east side stations somewhat lower in C, N, P, percent silt, and pH. In northern Barnegat Bay, the east side stations had somewhat higher C, N, P, percent silt, DO, temperature and pH than the west side stations, but lower salinity. The three stations at the mouth of Toms River had greater C, N, P, and percent silt than all other stations. The stations nearest Barnegat Inlet and Little Egg Inlet had lowest C, N, P, and percent silt.

Figure 19. Heat map of the average normalized values of environmental variables for the station clusters from the dendrogram in Figure 16.

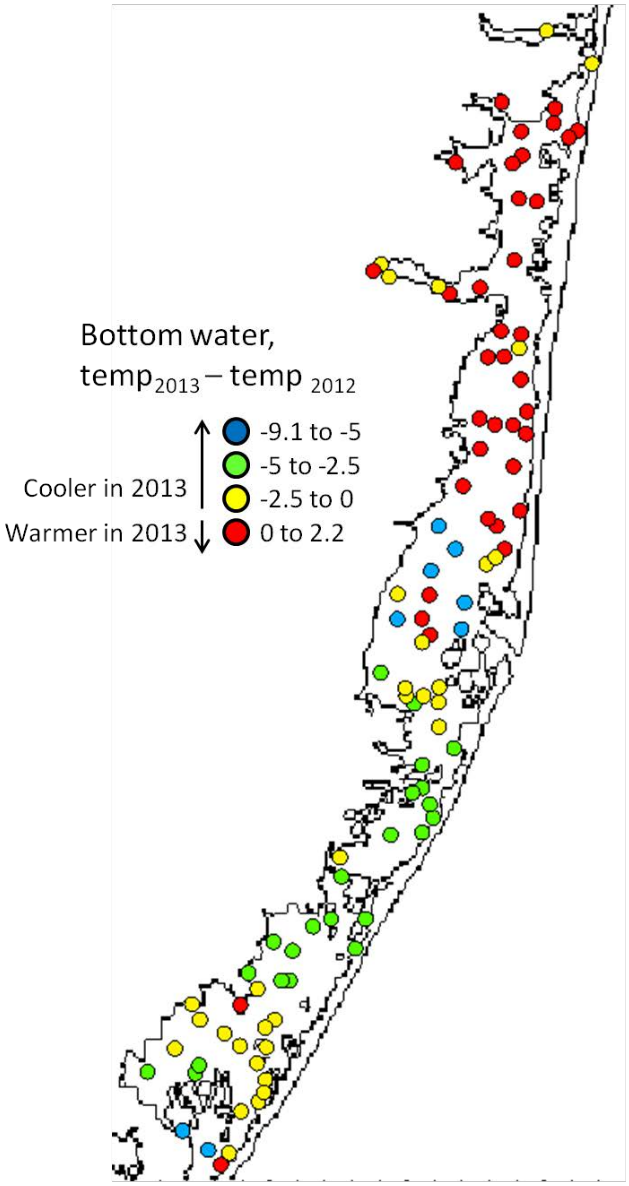


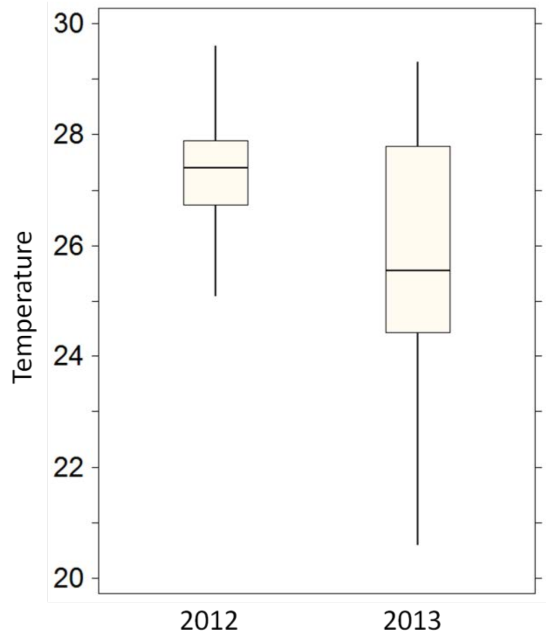
Comparison of water column properties in 2013 with 2012

The same station coordinates were sampled in 2012 and 2013, in early July in both years. To examine any trends in differences between the years, we calculate the differences in the values for 2013 and 2012.

Bottom water temperatures, bay-wide, were significantly cooler in 2013 than in 2012 (Wilcoxon signed rank test, $p<0.0001$) (Figure 20). The average bay-wide temperature was 1.5° lower in 2013. The cooler stations were concentrated south of Barnegat Inlet; locations in northern Barnegat Bay were warmer in 2013 than in 2012.

Figure 20. (Left) differences in bottom water temperature between July 2013 and 2012. (Right) Box and whisker plots enclose the middle half of the data. The box is bisected by a line at the value for the median. The vertical lines at the top and the bottom of the box (the whiskers) indicate the range of "typical" data values.

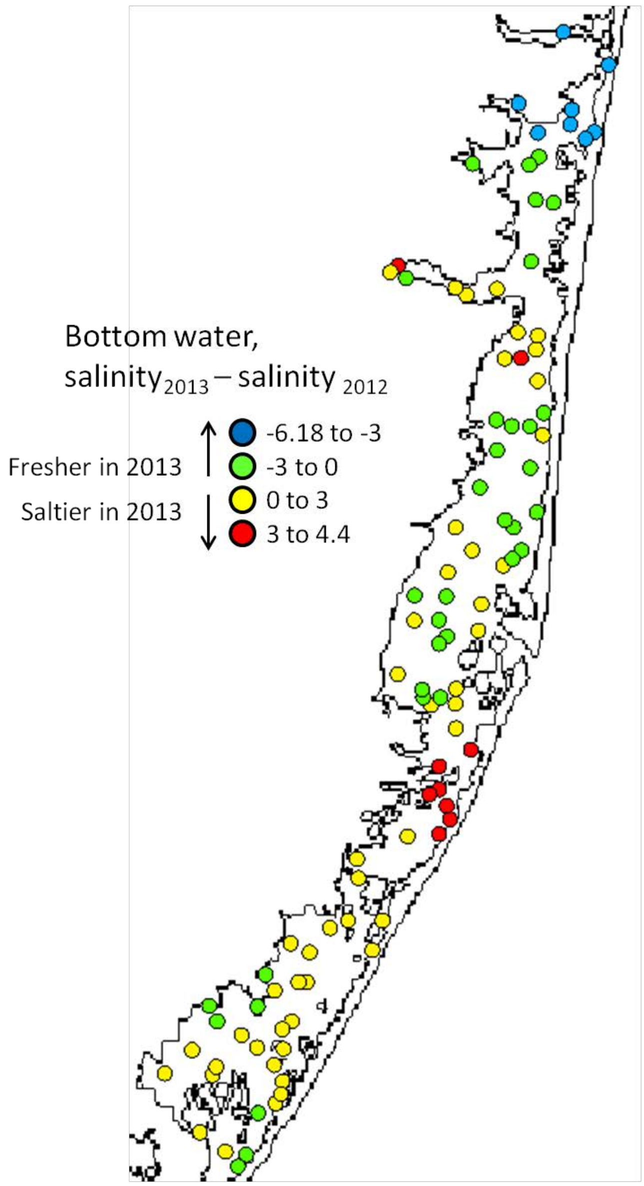


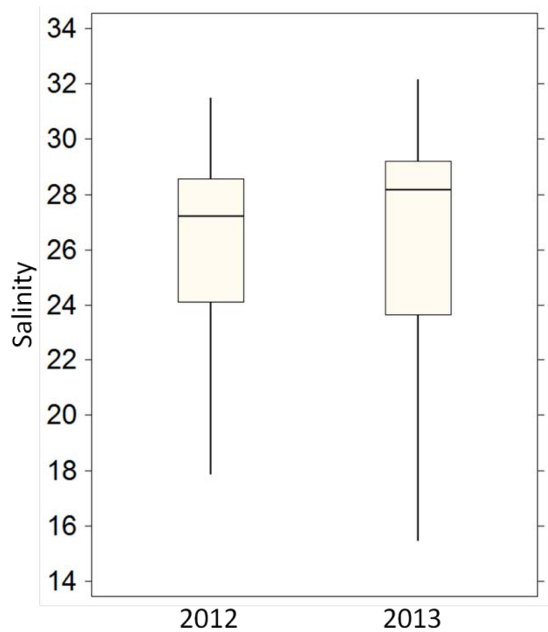


	2012	2013
Average temperature	27.1	25.6
95% confidence interval	26.8 – 27.4	25.1 – 26.2

Bottom water salinities, bay-wide, were not significantly different between 2013 and 2012 (Wilcoxon signed rank test, p=0.065) (Figure 21). Eight stations in the northern-most section of Barnegat Bay were notably fresher in 2013, however.

Figure 21. (Left) differences in bottom water salinity between July 2013 and 2012. (Right) Box and whisker plots enclose the middle half of the data. The box is bisected by a line at the value for the median. The vertical lines at the top and the bottom of the box (the whiskers) indicate the range of “typical” data values.

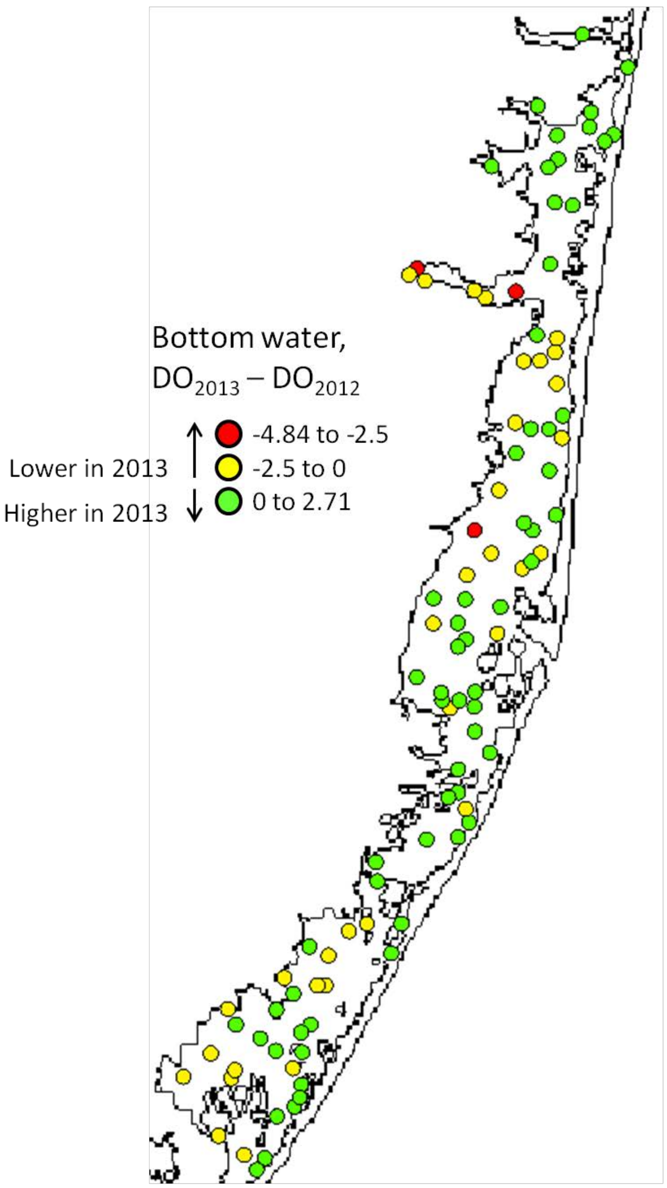


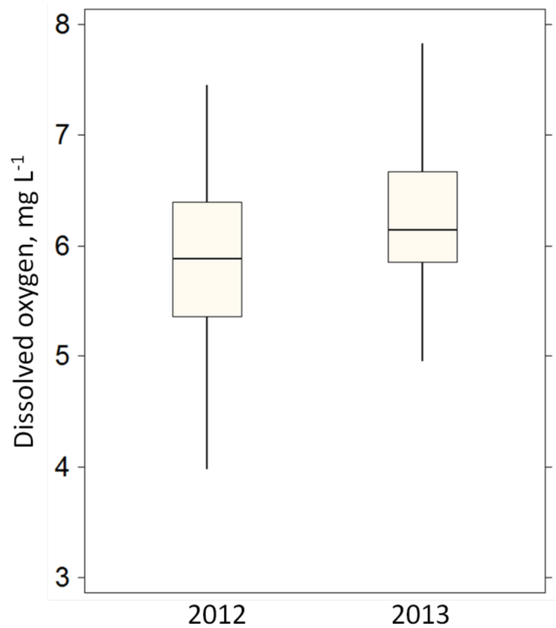


	2012	2013
Average salinity	25.4	25.7
95% confidence interval	24.5 – 26.3	24.7 – 26.7

Bottom water dissolved oxygen concentration, bay-wide, was significantly higher in 2013 than 2012 (Wilcoxon signed rank test, p=0.0003) (Figure 22). Stations where DO differed between the two years were distributed throughout the bay, in general, except for Toms River (consistently lower in 2013) and stations north of Toms River (consistently higher in 2013).

Figure 22. (Left) differences in bottom water dissolved oxygen concentration between July 2013 and 2012. (Right) Box and whisker plots enclose the middle half of the data. The box is bisected by a line at the value for the median. The vertical lines at the top and the bottom of the box (the whiskers) indicate the range of "typical" data values.

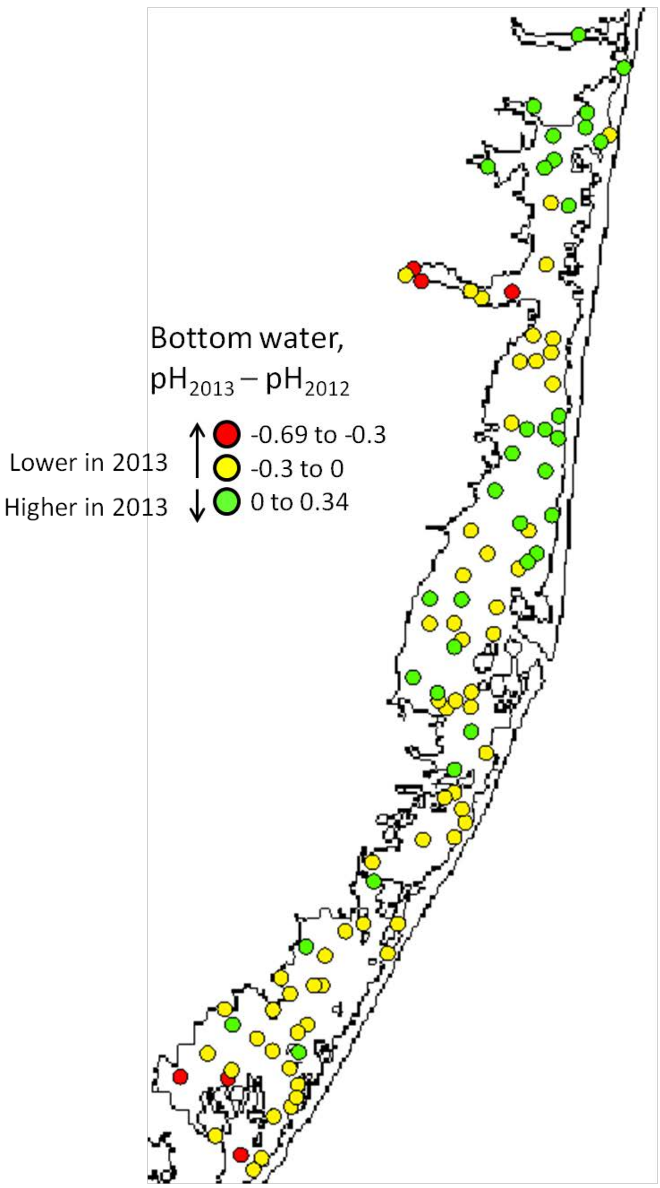


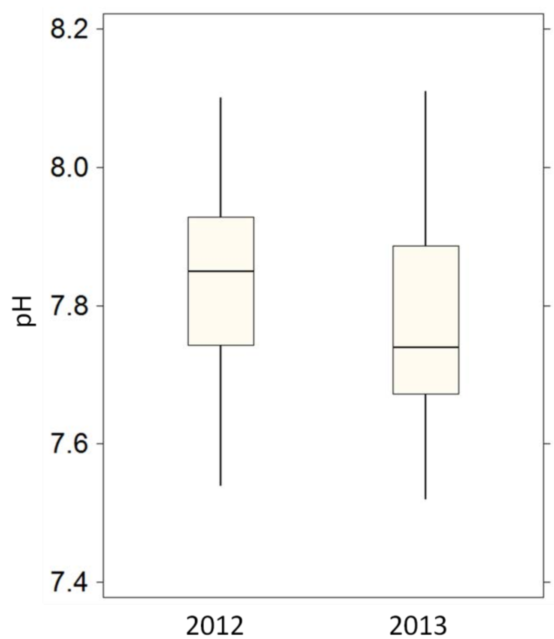


	2012	2013
Average DO	5.85	6.17
95% confidence interval	5.71 – 6	5.98 – 6.36

Bottom water pH, bay-wide, was significantly lower in 2013 than 2012 (Wilcoxon signed rank test, $p<0.0001$) (Figure 23). The average decrease of 0.07 units corresponds to a 17% increase in hydrogen ion activity in 2013, compared with 2012. The pH decreased most in Toms River and at Little Egg Inlet.

Figure 23. (Left) differences in bottom water pH between July 2013 and 2012. (Right) Box and whisker plots enclose the middle half of the data. The box is bisected by a line at the value for the median. The vertical lines at the top and the bottom of the box (the whiskers) indicate the range of “typical” data values.





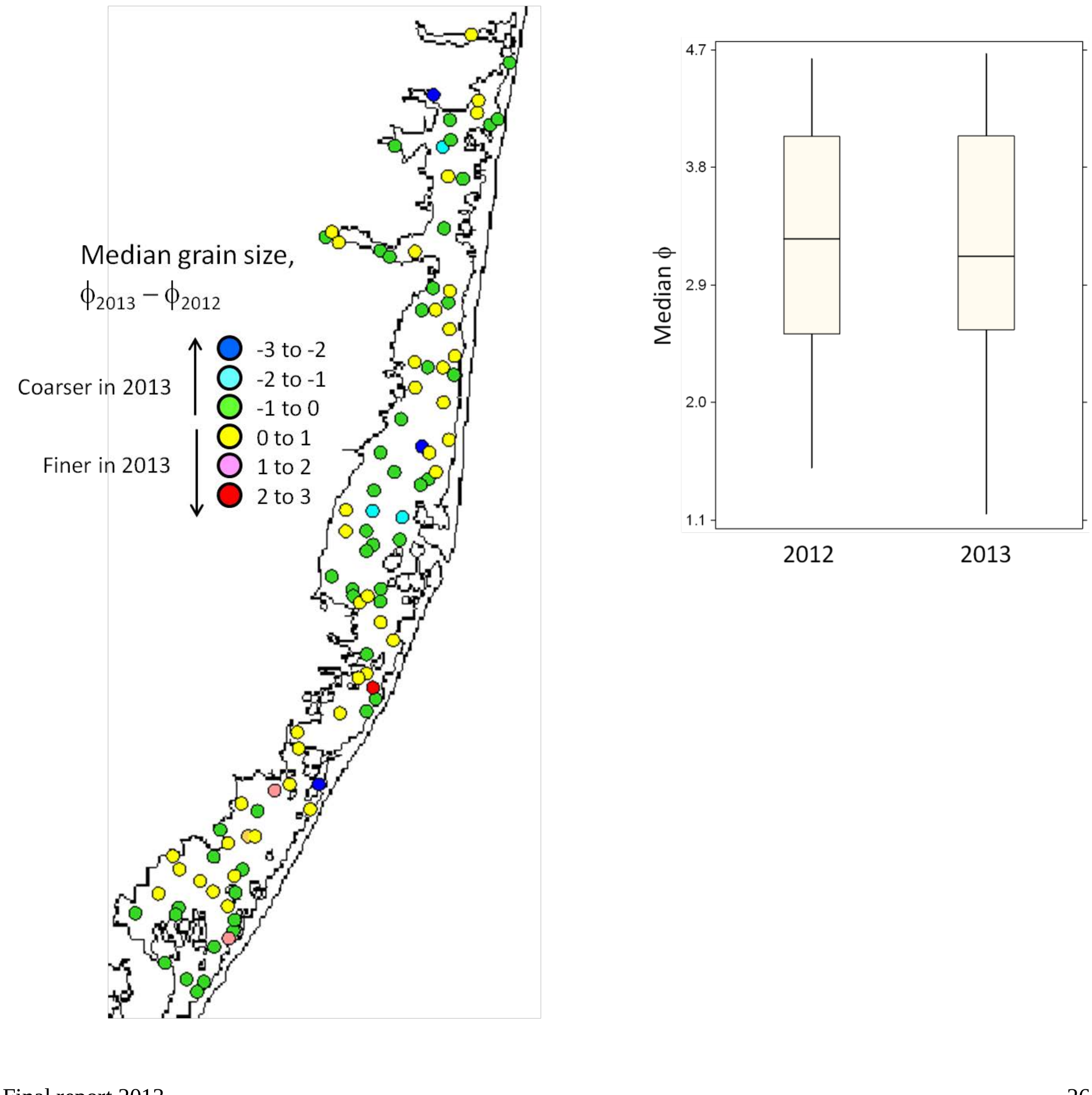
	2012	2013
Average pH	7.83	7.76
95% confidence interval	7.81 – 7.86	7.73 – 7.8

Comparison of sediment properties in 2013 with 2012

Sediment grain size

For all stations combined, median sediment grain sizes in 2013 (0.110 mm) and 2012 (0.108 mm) were essentially equal. At six stations the sediments were notably coarser in 2013, by 1 to 3 phi units, while at three stations sediments were notably finer (Figure 24). These stations did not group together, however. We conclude that there were no bay-wide changes in sediment sizes due to Hurricane Sandy. In many cases there were opposite trends in closely spaced stations.

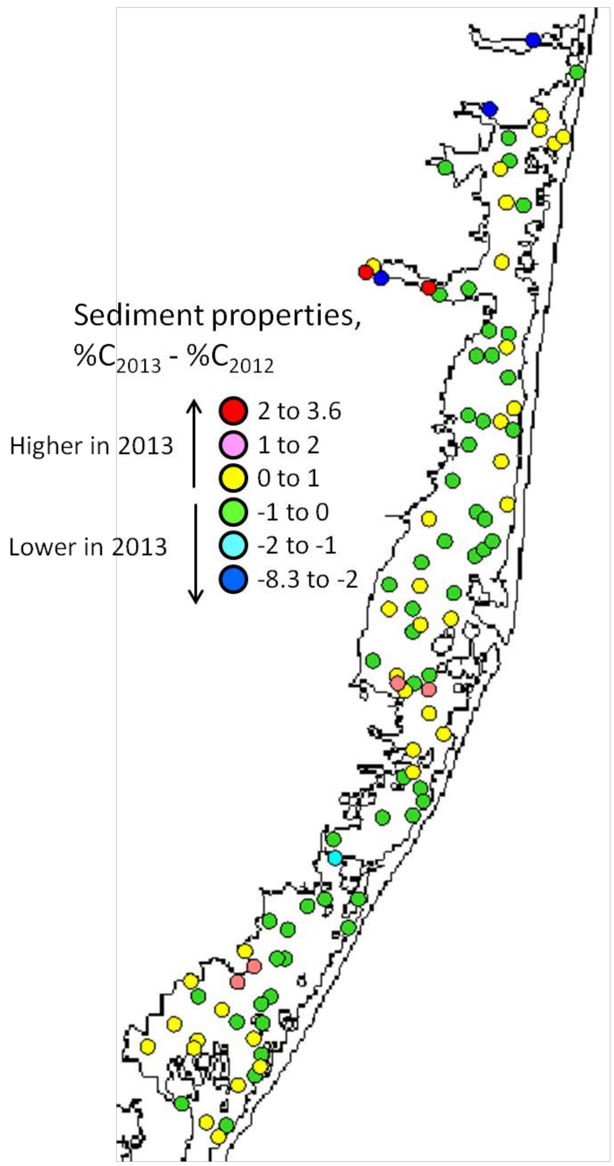
Figure 24. (Left) differences in median sediment grain size between July 2013 and 2012. (Right) Box and whisker plots enclose the middle half of the data. The box is bisected by a line at the value for the median. The vertical lines at the top and the bottom of the box (the whiskers) indicate the range of "typical" data values.

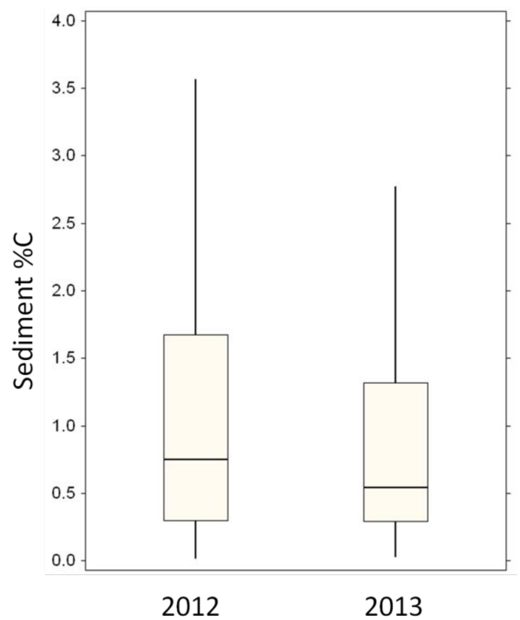


Sediment carbon, nitrogen, and phosphorus

Baywide, sediment total carbon concentrations were on average slightly lower in 2013 than in 2012, but the difference was not significant (Figure 25). At three stations in northern Barnegat Bay in the Metedoconk River, Kettle Creek, and Toms River carbon concentrations were lower by 2 to 8.3% in 2013, perhaps due to increased flushing during Hurricane Sandy. Complicating this interpretation, however, are two other stations in Toms River where carbon concentrations were 2 to 3.6% greater in 2013. We conclude that there were no bay-wide changes in sediment carbon concentration due to Hurricane Sandy.

Figure 25. (Left) differences in sediment %C between July 2013 and 2012. (Right) Box and whisker plots enclose the middle half of the data. The box is bisected by a line at the value for the median. The vertical lines at the top and the bottom of the box (the whiskers) indicate the range of “typical” data values.

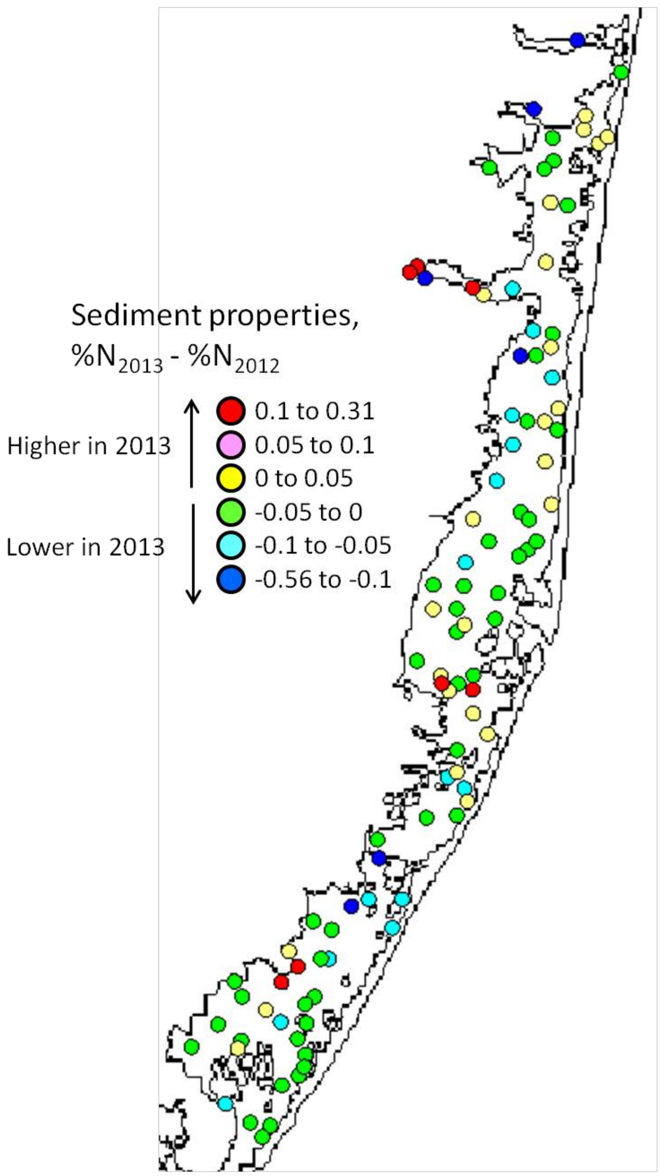


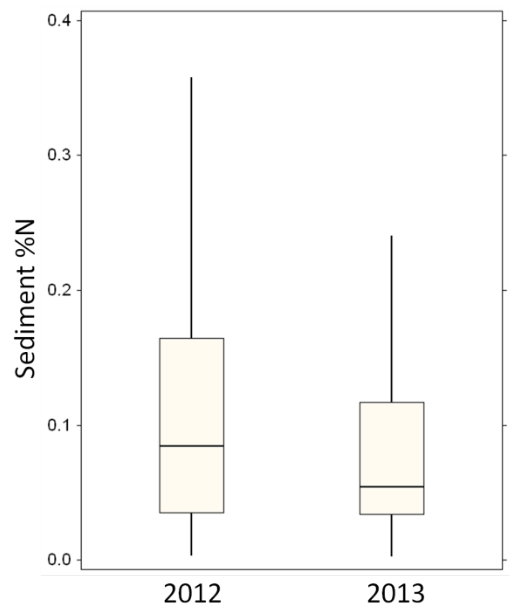


	2012	2013
Average %C	1.37	1.26
95% confidence interval	0.97 – 1.78	0.85 – 1.67

Baywide, sediment total nitrogen concentrations were on average slightly lower in 2013 than in 2012, but the difference was not significant (Figure 26). At three stations in northern Barnegat Bay in the Metedoconk River, Kettle Creek, and Toms River total nitrogen concentrations were lower by 0.1 to 0.56% in 2013, perhaps due to increased flushing during Hurricane Sandy. Complicating this interpretation, however, are three other stations in Toms River where nitrogen concentrations were 0.1 to 0.3% greater in 2013. We conclude that there were no bay-wide changes in sediment nitrogen concentration due to Hurricane Sandy.

Figure 26. (Left) differences in sediment %N between July 2013 and 2012. (Right) Box and whisker plots enclose the middle half of the data. The box is bisected by a line at the value for the median. The vertical lines at the top and the bottom of the box (the whiskers) indicate the range of "typical" data values.

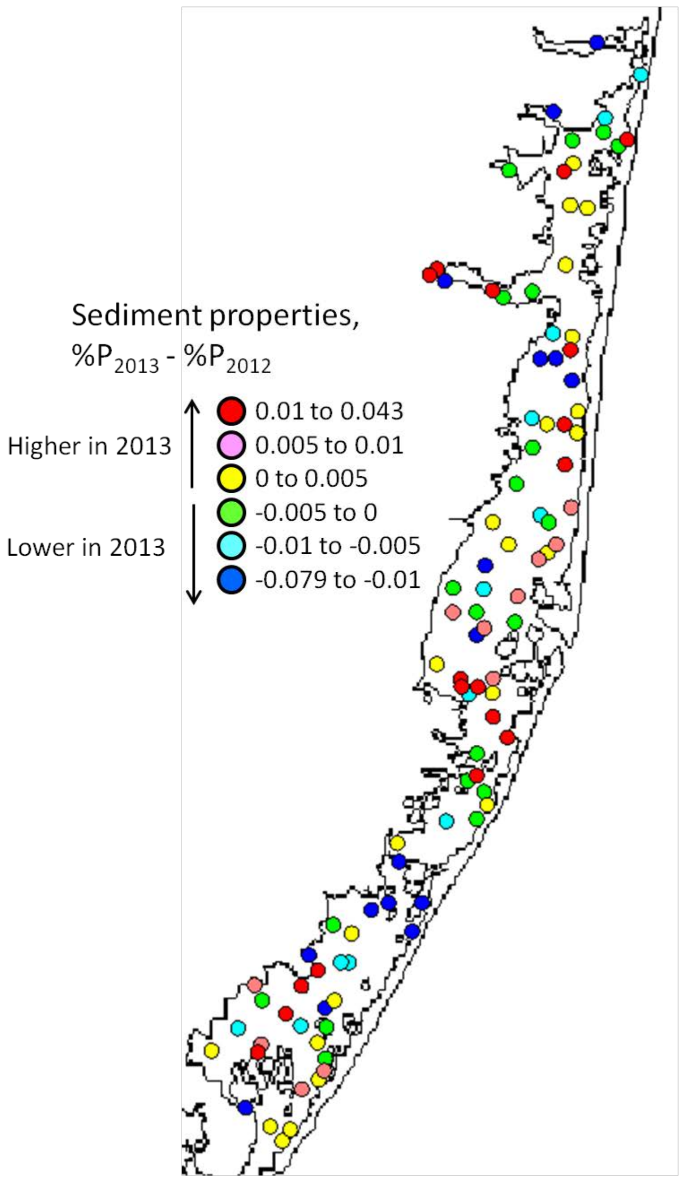


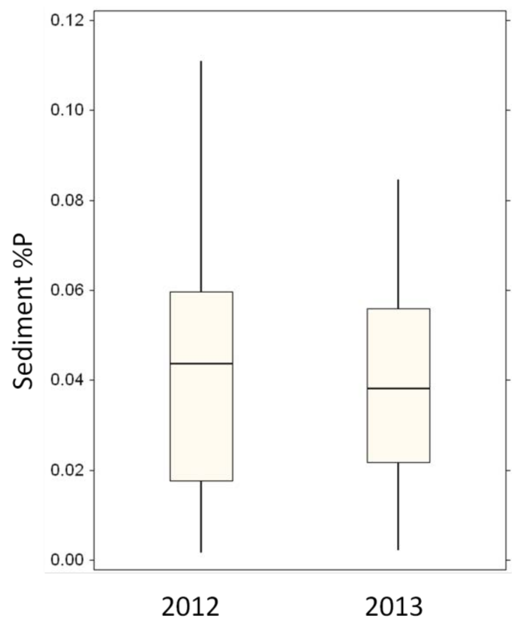


	2012	2013
Average %N	0.132	0.111
95% confidence interval	0.102 – 0.161	0.08 – 0.142

Baywide, sediment total phosphorus concentrations were the same in 2013 as in 2012 (Figure 27). At three stations in northern Barnegat Bay in the Metedoconk River, Kettle Creek, and Toms River total nitrogen concentrations were lower by 0.1 to 0.56% in 2013, perhaps due to increased flushing during Hurricane Sandy. Complicating this interpretation, however, are three other stations in Toms River where nitrogen concentrations were 0.1 to 0.3% greater in 2013. We conclude that there were no bay-wide changes in sediment nitrogen concentration due to Hurricane Sandy.

Figure 27. (Left) differences in sediment %P between July 2013 and 2012. (Right) Box and whisker plots enclose the middle half of the data. The box is bisected by a line at the value for the median. The vertical lines at the top and the bottom of the box (the whiskers) indicate the range of "typical" data values.





	2012	2013
Average %P	0.041	0.04
95% confidence interval	0.036 – 0.046	0.035 – 0.045

Benthic macroinvertebrate community composition

A total of 258 taxa were collected in 2013. A subset of 204 of these taxa was used for further analyses. Taxa were not included in analyses if they were epifaunal (for example, encrusting on *Zostera* or *Ruppia* blades), since such taxa are not indicative of conditions in sediments. We consulted the list of taxa omitted in calculations of the Chesapeake Bay Benthic Index of Biotic Integrity (see below and Table 1 in Llansó 2002) when making these decisions since the species lists in BB-LEH and the Chesapeake Bay are similar. We also omitted highly motile species since they are unlikely to be sampled quantitatively by a Van Veen grab. We omitted all taxonomic designations at the generic, familial, and higher taxonomic levels if there were two or more valid lower-level designations for that group (Gallagher and Grassle 1997). This usually occurred with unidentified specimens that were likely to belong to an already identified species. For consistency when comparing the values for the various indices (see below), omitted taxa were not used in calculations of any index. Most of the omitted taxa were rare or only occurred at a few stations, therefore we do not believe that our conclusions were materially affected by these omissions. Finally, we also omitted three stations at the head of Toms River (stations, 18, 19, 25) because they contained only 2, 3, and 1 individual, respectively.

As is common in estuarine environments, the benthic community in BB-LEH is dominated by relatively few species. Five taxa accounted for 50% of all individuals collected, and 45 taxa accounted for 90% of all individuals (Figure 28). The most abundant species, *Mediomastus ambiseta*, was present at 95 stations selected for further analyses and by itself accounted for 31% of all individuals (Table 1). At the other end of the spectrum, 70 taxa had 10 or fewer individuals.

Figure 28. Species rank (1 = most abundant) vs. cumulative abundance of all macroinvertebrates at all stations. Some taxa were tied in abundance.

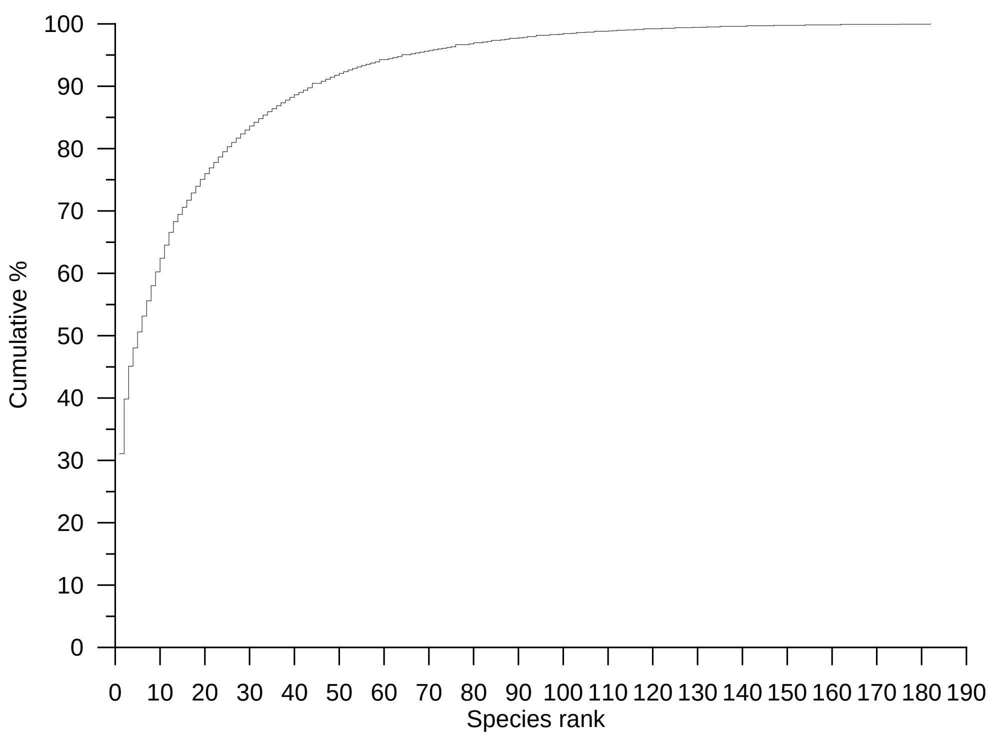
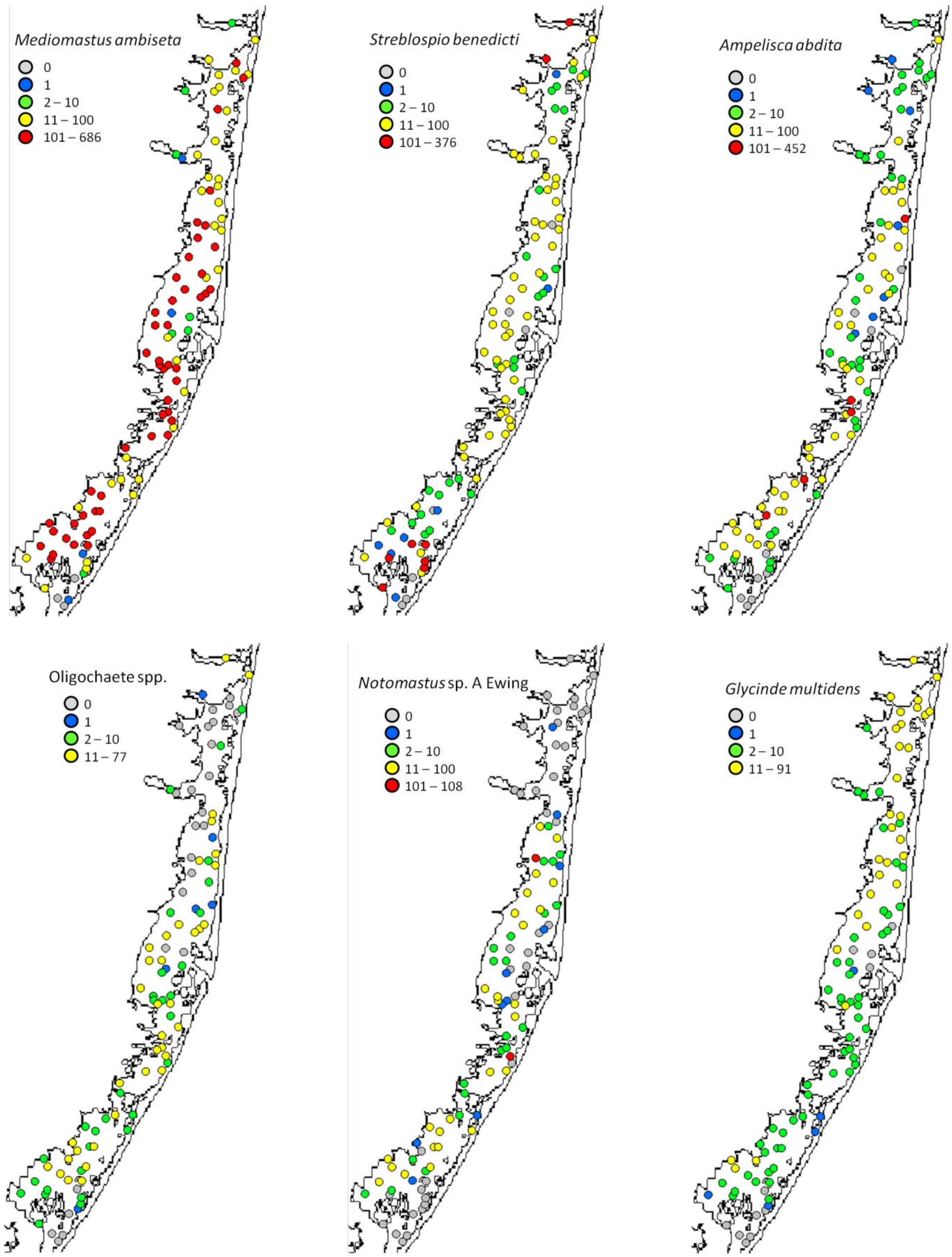


Table 1. Most abundant 45 taxa that made up 90% of all individuals collected.

Taxon	RANK	TOTAL	cumulative %
Mediomastus ambiseta	1	13845	29.91
Streblospio benedicti	2	3905	38.35
Ampelisca abdita	3	2356	43.44
Oligochaeta sp.	4	1298	46.25
Notomastus sp. A Ewing	5	1148	48.73
Glycinde multidens	6	1130	51.17
Leitoscoloplos robustus	7	1093	53.53
Ampelisca verrilli	8	1078	55.86
Heteromastus filiformis	9	988	57.99
Spiochaetopterus costarum oculatus	10	976	60.10
Clymenella zonalis	11	939	62.13
Tharyx sp. A (MWRA)	12	912	64.10
Clymenella torquata	13	762	65.75
Angulus agilis	14	585	67.01
Acteocina canaliculata	15	552	68.20
Polydora cornuta	16	516	69.32
Elasmopus levis	17	509	70.42
Sabaco elongatus	18	508	71.52
Turbonilla interrupta	19	506	72.61
Mulinia lateralis	20	504	73.70
Exogone (Exogone) dispar	21	486	74.75
Ampelisca vadorum	22	481	75.79
Leucon americanus	23	414	76.68
Rhepoxynius hudsoni	24	413	77.57
Microdeutopus gryllotalpa	25	393	78.42
Tubificoides sp.	26	387	79.26
Listriella barnardi	27	368	80.06
Haminoea solitaria	28	357	80.83
Solemya velum	29	355	81.59
Japonactaeon punctostriatus	30	317	82.28
Aricidea (Acmira) catherinae	31	307	82.94
Scolelepis (Parascolelepis) bousfieldi	32	299	83.59
Scoletoma tenuis	33	286	84.21
Oxyurostylis smithi	34	285	84.82
Paraprionospio alata	35	264	85.39
Saccoglossus kowalevskii	36	252	85.94
Alitta succinea	37	238	86.45
Glycera americana	38	211	86.91
Eumida sanguinea	39	205	87.35
Tagelus divisus	40	199	87.78
Hypereteone heteropoda	41	190	88.19
Melinna maculata	42	186	88.59
Pentamera pulcherrima	43	182	88.99
Nucula proxima	44	169	89.35
Pectinaria gouldii	45	163	89.70

Of the six most-abundant taxa, comprising over half of all individuals, five were annelids and one was a crustacean (Table 1). All six were consistently absent or in low abundances near Little Egg Inlet and Barnegat Inlet (Figure 29). *Mediomastus ambiseta*, the most abundant species in 2013, was most abundant in Little Egg Harbor and southern and central Barnegat Bay. *Streblospio benedicti*, second most abundant overall, reached maximum abundances in southern Little Egg Harbor and extreme northern Barnegat Bay. The amphipod *Ampelisca abdita* was third most abundant and, aside from low abundance near inlets, occurred throughout BB-LEH with no apparent pattern. Oligochaetes and *Notomastus* sp A Ewing were rare in northern Barnegat Bay, while *Glycinde multidens* was common there.

Figure 29. Summary maps of the distributions of the six most abundant taxa.



Univariate analyses of community structure: abundance of individual taxa

The most straightforward approach to relating community structure to environmental variables is to look for correlations of single variables with abundances of various taxa; a univariate approach. This must be tempered with the realization that correlation does not necessarily imply causation, that multiple environmental variables can be at work, and that relationships may not be linear. In fact, classic ecological theory posits that species responses to environmental factors are unimodal. Initially, therefore, we examined simple scatterplots of species abundances against environmental properties measured in this study.

An example is given for abundance of the numerical dominant, *Mediomastus ambiseta*, plotted against seven environmental properties (Figure 30). LOWESS smoothing of the data suggests a unimodal response of the abundance of this species to sediment C, N, and P, salinity, temperature, and median sediment phi size. The response to dissolved oxygen is less clear.

Assuming that sediment concentrations of total carbon, nitrogen, and phosphorus may be indicative of eutrophic conditions, we conducted similar univariate analyses for the ten most abundant taxa (Figures 31-33). An ideal 'indicator' species would show a monotonic increase with carbon, nitrogen, or phosphorus, or all. In most cases, LOWESS analysis indicated a unimodal model was appropriate. Normal curves were fit to the abundance data. Species abundances dropped off sharply with increased sediment carbon, nitrogen, and phosphorus concentrations.

Figure 30. Scatterplots of abundance of *Mediomastus ambiseta* vs. sediment %C, %N, %P, bottom water DO, salinity, temperature pH, and median particle size. Lines are LOWESS fits.

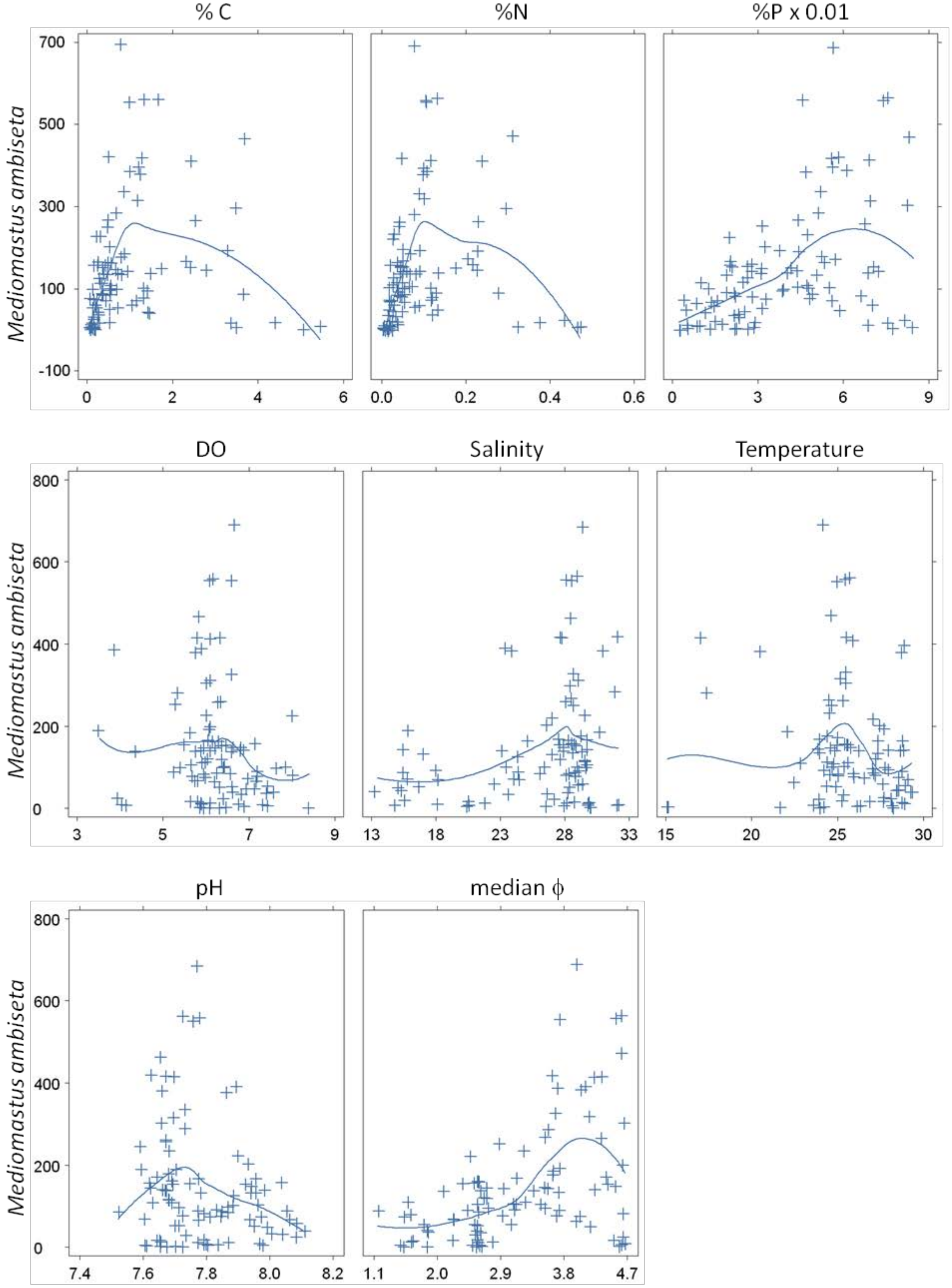


Figure 31. Unimodal curve fits to abundances of 10 most abundant taxa as a function of sediment %C.

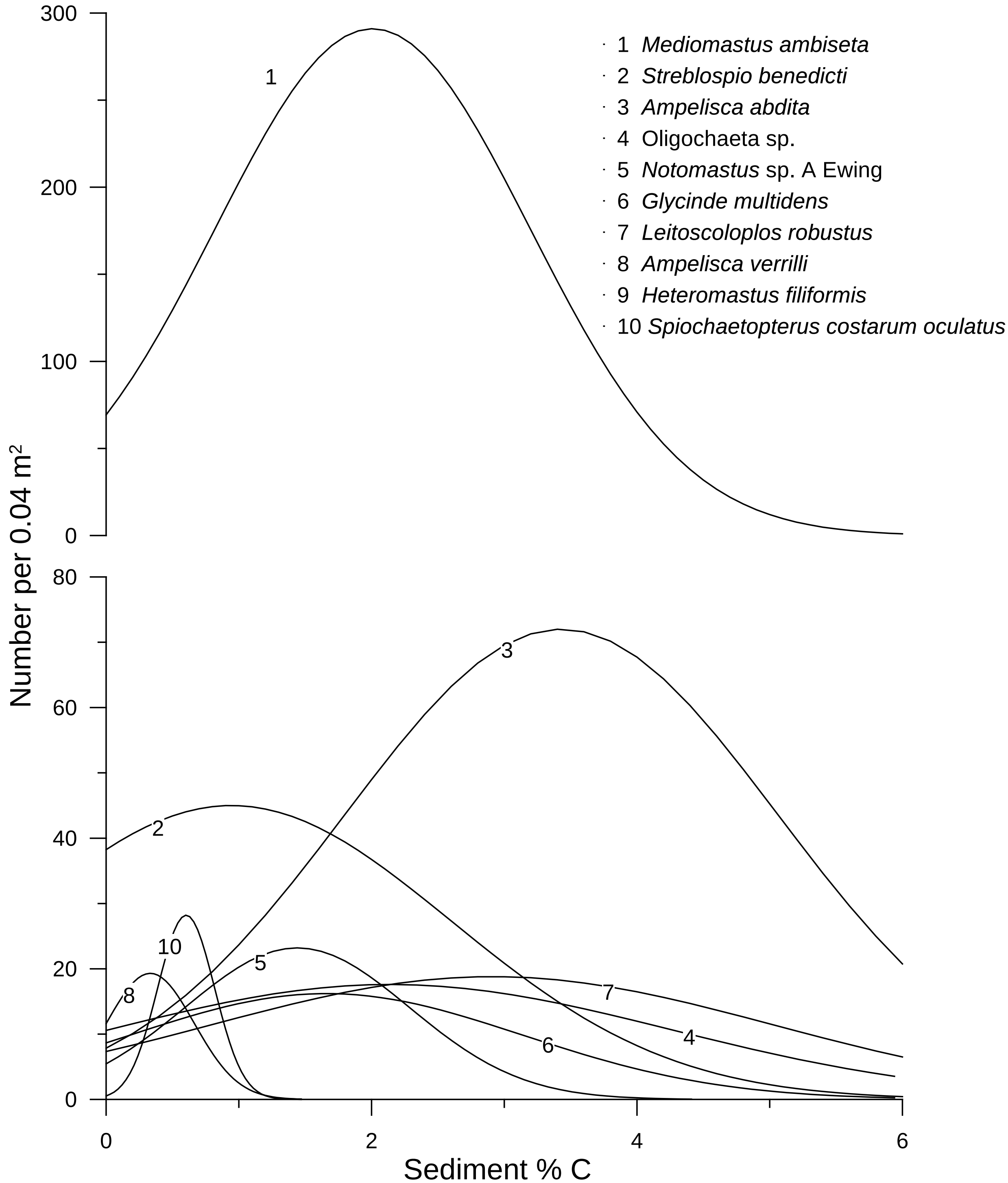


Figure 32. Unimodal curve fits to abundances of 10 most abundant taxa as a function of sediment %N.

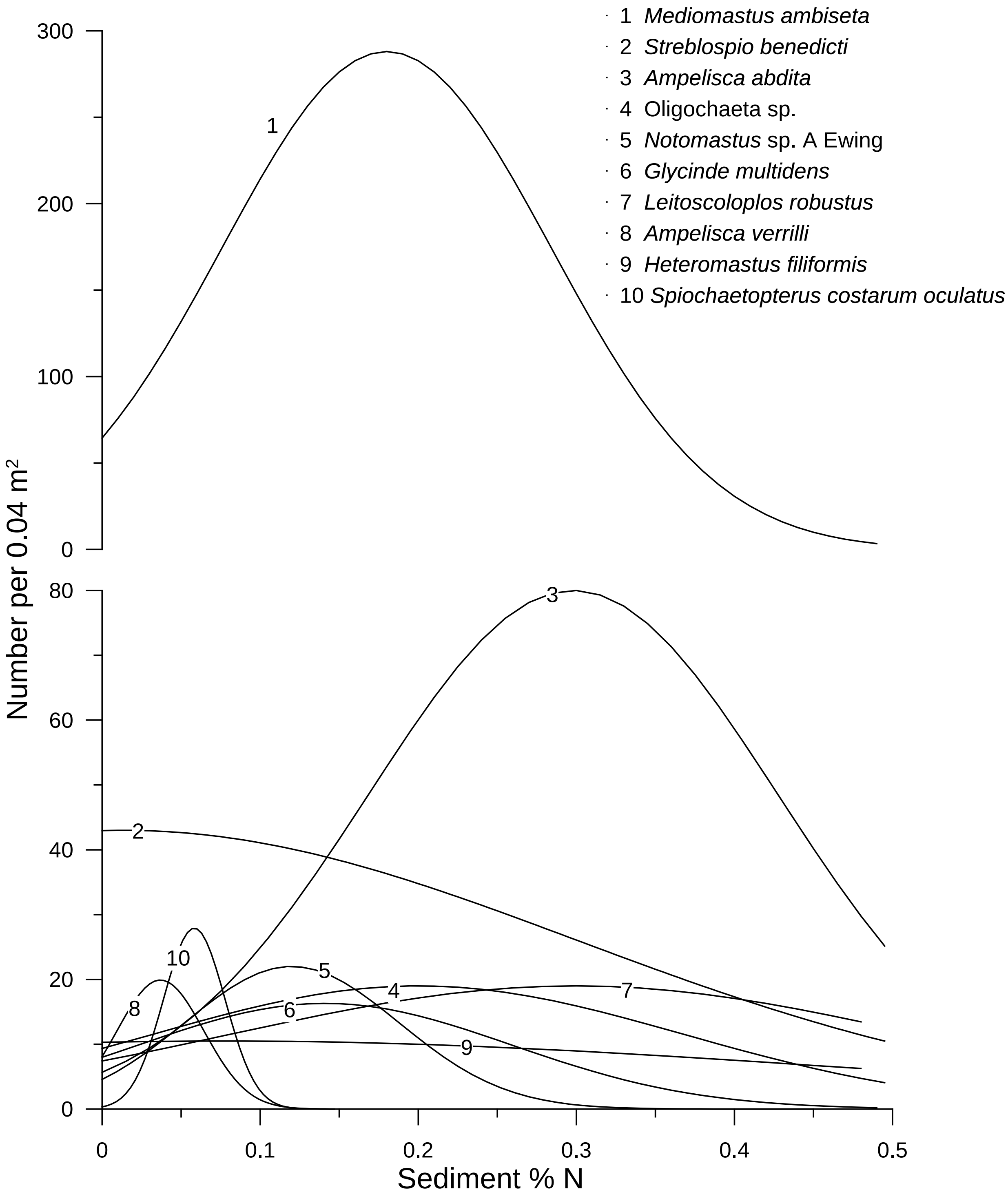
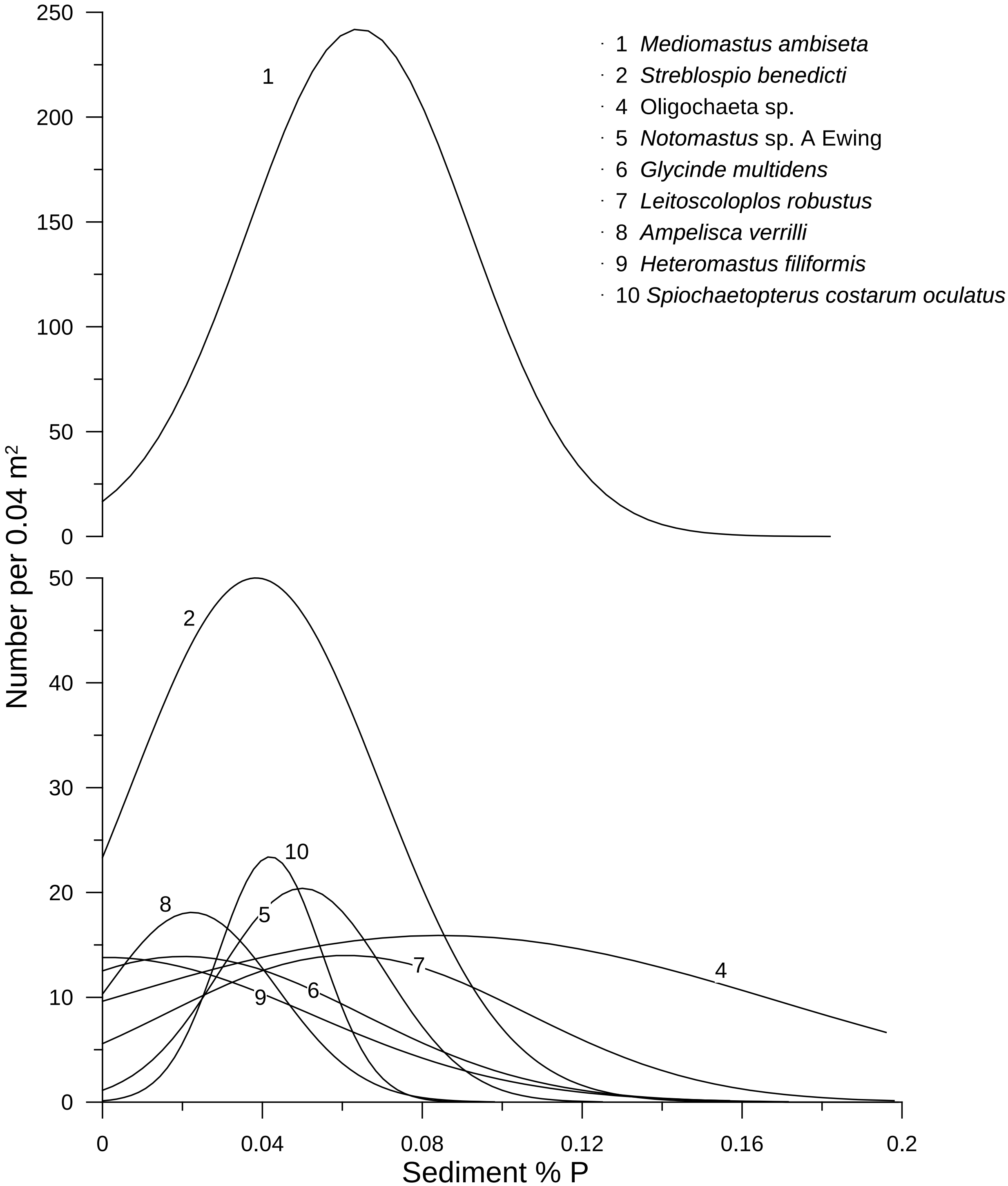


Figure 33. Unimodal curve fits to abundances of 10 most abundant taxa as a function of sediment %P.



Since abundances of these dominant species are usually low at both low and high sediment C, N, and P concentrations, a simple univariate approach will not suffice, at least if applied to the entire data set of stations throughout BB-LEH. An alternative approach is to subdivide BB-LEH into regions where the environmental gradients are not as ‘long,’ in order to determine if linear, rather than unimodal, patterns can be used. Estuarine habitats are commonly classified on the basis of salinity given that different taxa strongly respond to salinity differences (Gallagher and Grassle 1997) (Weisberg et al. 1997). In our final report for the year 2012 samples we separated stations into two groups, ‘low salinity stations’ with salinities ≤23 and ‘high salinity stations’ with salinities ≥24 because there was a clear separation of stations. In 2013 the separation was not as clear (Figure 34), so we have made the split at ≤25 for the low salinity stations and ≥26 for the high salinity stations. As in 2012, all of the low salinity stations in 2013 are also in northern Barnegat Bay (Figure 35).

Figure 34. Histogram of bottom water salinities during the period July 1 – July 10, 2013.

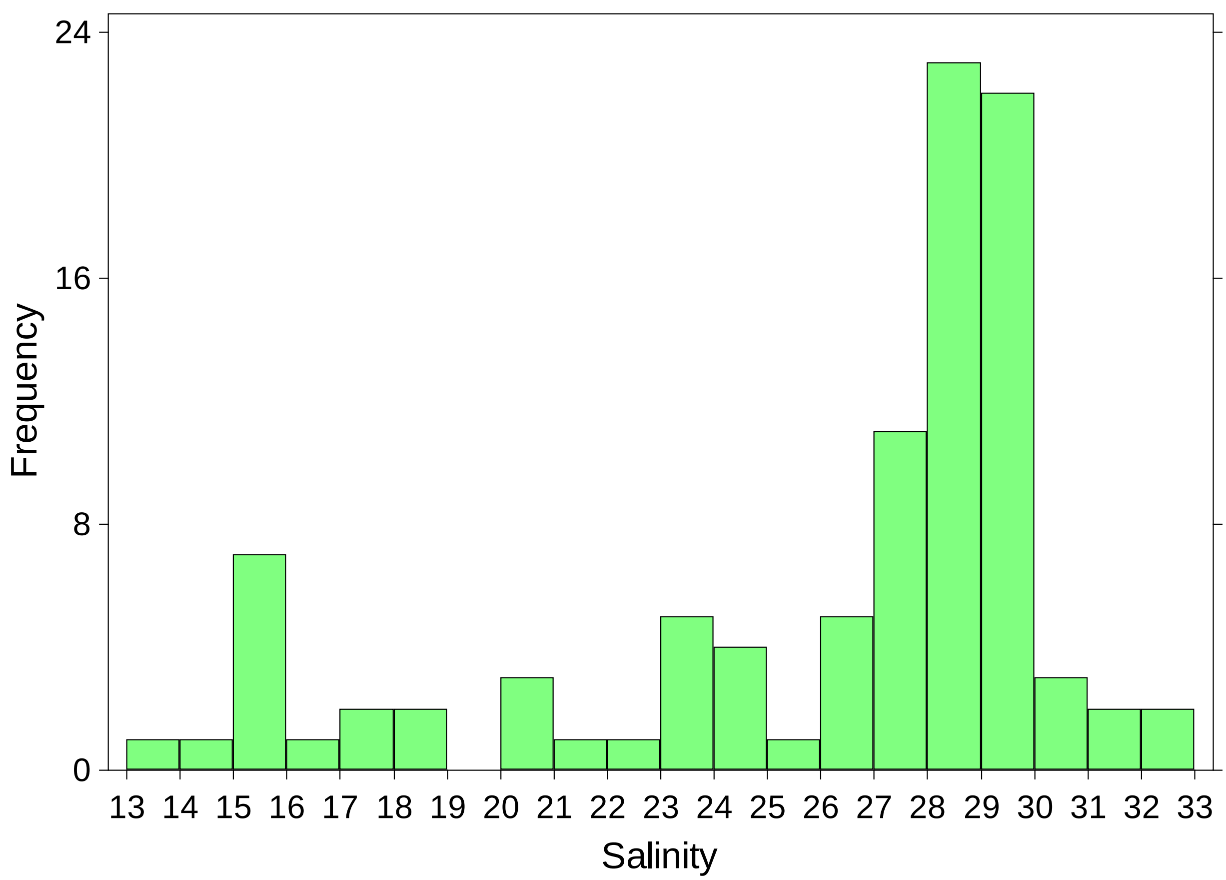
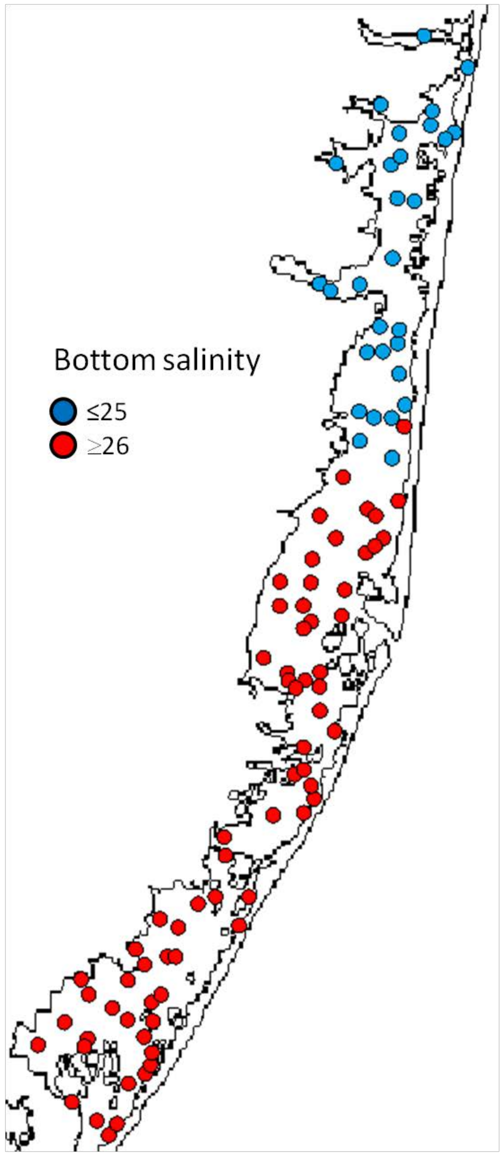


Figure 35. Distribution of stations with bottom water salinities ≤25 or ≥26 during the period July 1 – July 10, 2013.



Radar plots (Benyi et al. 2009) of the 20 most abundant taxa showed that 14 of them were more abundant than average at the high salinity stations, while six were more abundant than average at low salinity stations (Figure 36). Based on these shortened salinity gradients, we performed stepwise linear regressions to see if there were any correlations of abundance with measured environmental variables. As an example, the results for the top-ranked species, *Mediomastus ambiseta*, at the high salinity stations are given (Table 2). Running the model with unforced entry of variables, only median sediment phi size significantly correlates with abundance of *Mediomastus* (abundance increases in finer grained sediments), accounting for 40% of variation in abundance.

Table 2. Stepwise linear regression of abundance of *Mediomastus ambiseta* (as proportion of total individuals in the sample) against environmental variables.

Stepwise Linear Regression of prop_m_a

```
Unforced Variables: pctC_2013 pctN_2013 pctP_2013 bot_DO bot_temp bot_salin
Medan_phi bot_pH
  P to Enter 0.0500
  P to Exit  0.0500
```

Step	Variable	Coefficient	T	P	R^2	MSE
1	Constant	0.26857	11.84		0.0000	0.03500
2	Constant	-0.16884	-2.51		0.4076	0.02105
	Medan_phi	0.13561	6.74	0.0000		

Resulting Stepwise Model

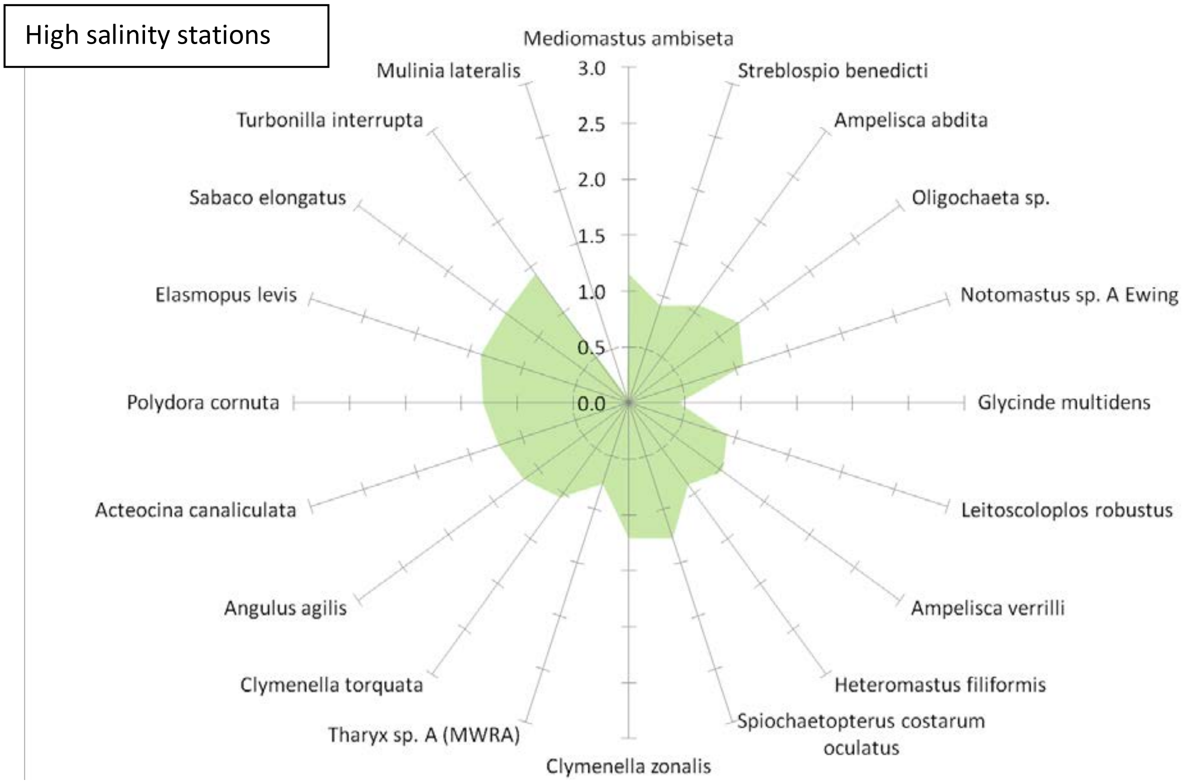
Variable	Coefficient	Std Error	T	P	VIF
Constant	-0.16884	0.06725	-2.51	0.0145	
Medan_phi	0.13561	0.02012	6.74	0.0000	1.0

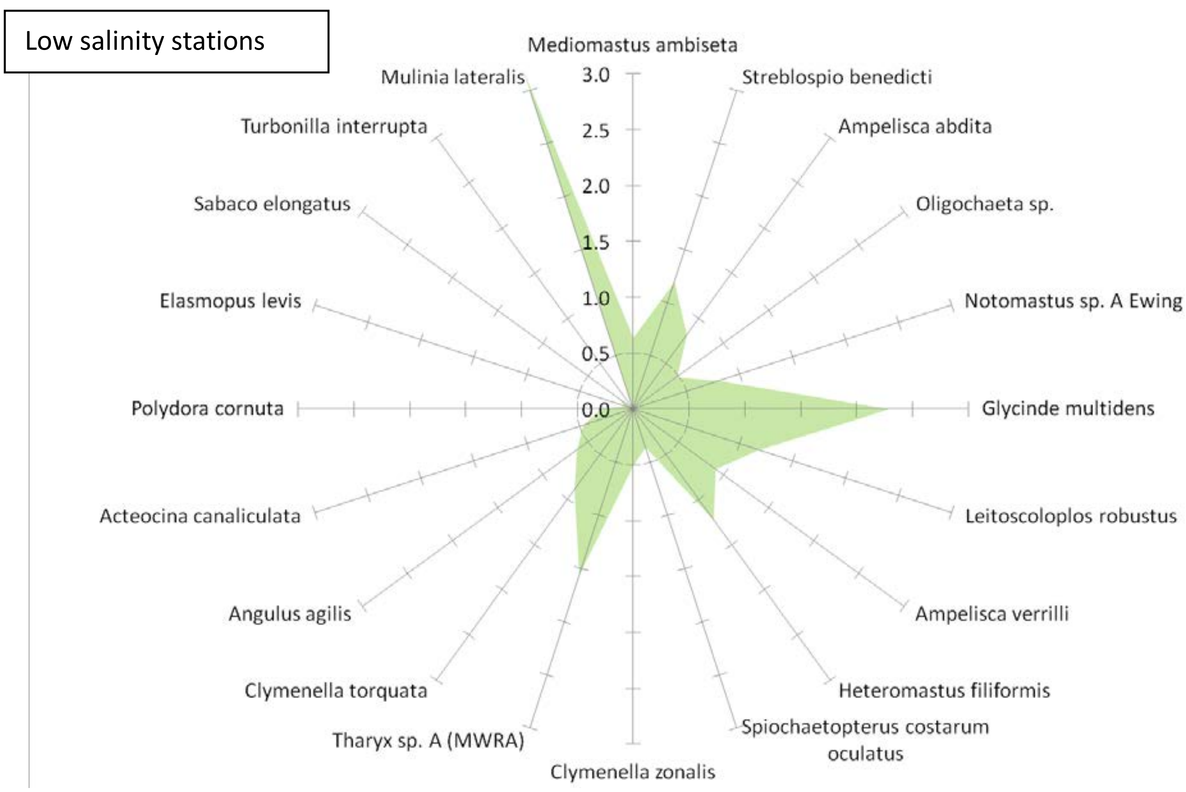
Cases Included	68	R^2	0.4076	MSE	0.02105
Missing Cases	0	Adjusted R^2	0.3986	SD	0.14508

Variables Not in the Model

	Correlations			
Variable	**Multiple**	**Partial**	**T**	**P**
pctC_2013	0.7846	-0.1805	-1.48	0.1439
pctN_2013	0.7731	-0.1817	-1.49	0.1411
pctP_2013	0.9280	0.0225	0.18	0.8565
bot_DO	0.2801	-0.1223	-0.99	0.3241
bot_temp	0.1209	0.0579	0.47	0.6418
bot_salin	0.1363	-0.0276	-0.22	0.8243
bot_pH	0.2826	0.0205	0.17	0.8690

Figure 36. Radar plots of average abundance of the 20 most abundant taxa at high salinity and low salinity stations, expressed as proportion of the average of each taxon for all stations.





A similar approach was used to evaluate the taxa that were disproportionately abundant at high salinity (Table 3) and low salinity (Table 4) stations. For a taxon to be a potentially useful indicator of eutrophic or degraded conditions, its abundance should be positively correlated with measures of organic enrichment such as C, N, P concentrations in sediment, or negatively correlated with water properties such as DO and pH. In addition, the environmental variables should account for a substantial amount of the variation in abundance, nominally 50% or more. With these criteria, no individual taxon is a useful indicator species at either high or low salinity sites.

Table 3. Results of stepwise linear regressions of abundances of highly ranked species at high salinity stations.

Taxon (abundance rank)	Variables in model	Conclusion
Mediomastus ambiseta (1)	Median ϕ	Not useful as indicator species of eutrophic conditions
Ampelisca abdita (3)	%C	Positively correlated, explains 25% of variation in abundance, potentially useful indicator species
Oligochaeta sp. (4)	%N	Positively correlated, explains 5% of variation in abundance, not useful indicator species
Notomastus sp. A Ewing (5)	DO	Negatively correlated, explains 6% of variation in abundance, not useful indicator species
Ampelisca verrilli (8)	%C	Negatively correlated, explains 10% of variation in abundance, not useful indicator species
Spiochaetopterus costarum oculatus (10)	Constant only	Abundance unaffected by any measured variable, not useful indicator species
Clymenella zonalis (11)	Median ϕ	Positively correlated, explains 20% of variation in abundance, not useful indicator species
Clymenella torquata (13)	Constant only	Abundance unaffected by any measured variable, not useful indicator species
Angulus agilis (14)	%C, DO, temperature	%C explains 16% of variation in abundance and is negatively correlated, not useful indicator species
Acteocina canaliculata (15)	%P	Positively correlated, explains 32% of variation in abundance, potentially useful indicator species
Polydora cornuta (16)	Salinity	Positively correlated, explains 8% of variation in abundance, not useful indicator species
Elasmopus levis (17)	pH	Positively correlated, explains 8% of variation in abundance, not useful indicator species
Sabaco elongates (18)	%N, %P	Positively correlated with %P but negatively with %N,variables explain 28% of variation in abundance, not useful indicator species
Turbonilla interrupta (19)	%N, %P	Positively correlated with %P but negatively with %N, variables explain 20% of variation in abundance, not useful indicator species

Table 4. Results of stepwise linear regressions of abundances of highly ranked species at low salinity stations.

Taxon (abundance rank)	Variables in model	Conclusion
Streblospio benedicti (2)	Constant only	Abundance unaffected by any measured variable, not useful as indicator species of eutrophic conditions
Glycinde multidens (6)	%N, salinity, pH	Negatively correlated with %N, not useful indicator species
Leitoscoloplos robustus (7)	Salinity	Not useful indicator species
Heteromastus filiformis (9)	Median ϕ, %N, pH	Positively correlated with %N, explains 11% of variation in abundance, not useful indicator species
Tharyx sp. A (MWRA) (12)	Constant only	Abundance unaffected by any measured variable, not useful indicator species
Mulinia lateralis (20)	Constant only	Abundance unaffected by any measured variable, not useful indicator species

Univariate analyses of community structure: species diversity

There are many indices for quantifying species diversity. A good index should be based on species richness (how many species are present) and equitability (how evenly individuals are distributed among species). We used Hurlbert's index, $E(S_n)$, which represents the expected number of species in a random subsample of *n* individuals from all those collected at a given station (Hurlbert 1971). A sample size of 50 individuals was chosen, common practice in studies attempting to relate benthic community structure to environmental stressors (Leonardsson et al. 2009, Rosenberg et al. 2004). $E(S_{50})$ ranged from 9 to 26 (Figure 37). The frequency distribution of $E(S_{50})$ values was well fit by a normal distribution with a mean of 17.3 (Shapiro-Wilk W = 0.988, p = 0.53 that the data are normally distributed).

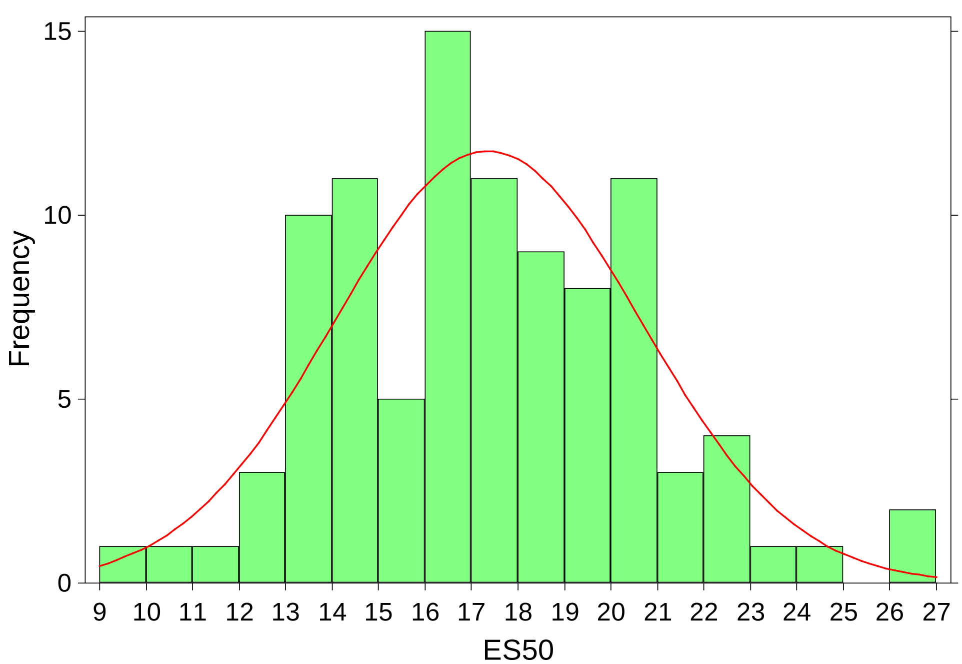
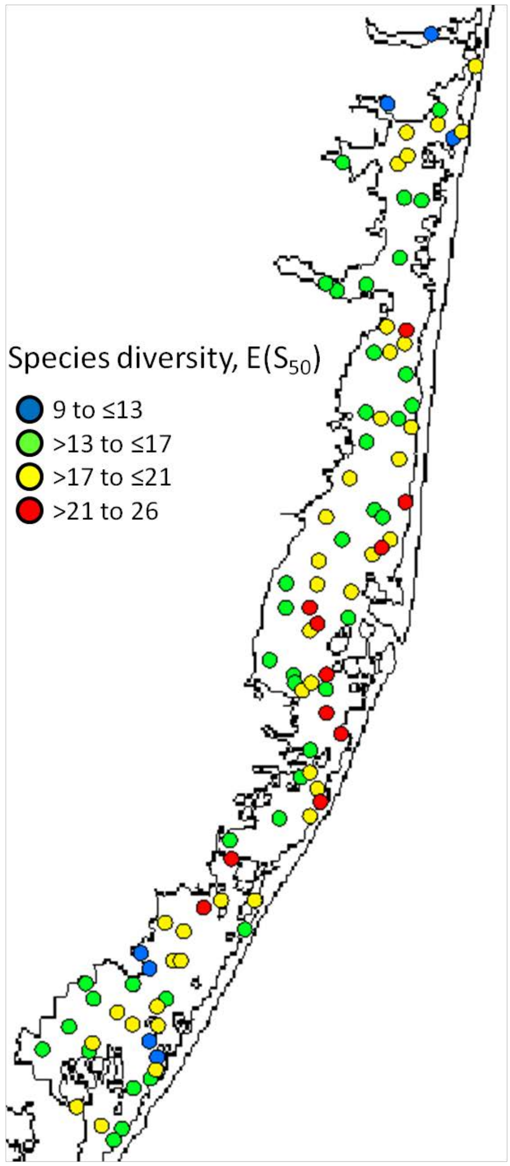


Figure 37. Frequency distribution of $E(S_{50})$ values. Red line is normal curve fit to the data. Three stations at head of Toms River omitted.

The sites with highest diversity were in central and southern Barnegat Bay, while the lowest diversity sites were in northern Barnegat Bay and Little Egg Harbor (Figure 38).

Figure 38. Distribution map of species diversity during the period July 1 – July 10, 2013.



Multivariate and multimetric analyses of community structure

We evaluated several multimetric and multivariate indices of benthic community condition in BB-LEH. There are many indices which have been developed by researchers all over the world. For example, Diaz et al. (2004) list 17 indices that attempt to relate estuarine or marine macrobenthos communities to some measure of environmental quality. A 'universal' index is unlikely to exist. Even indices developed for smaller regions may have limited utility to correctly classify habitats outside of the specific region for which they were calibrated (Pelletier et al. 2012). Therefore, our approach was to apply several of the most widely used indices to the 2013 data set from BB-LEH to determine if there was a general agreement among different indices.

<u>Benthic Index of Biotic Integrity (B-IBI)</u>

Weisberg et al. (1997) developed a multimetric benthic index of biotic integrity using data collected in Chesapeake Bay during sampling programs between 1972 and 1991. The B-IBI has been periodically updated since then as additional data becomes available (Llansó 2002). Depending on the salinity and percent sand of the site, the B-IBI uses different metrics, and different values for metrics, to score sites from a value of 1 to 5. Because the index was developed to track restoration efforts in Chesapeake Bay, a site score of ≤2 is considered "severely degraded," a score from 2.1 to 2.6 considered "degraded," from 2.7 to 2.9 considered "marginal," and ≥3 as "meets restoration goals." Metrics included in the calculation of the index include the Shannon index of species diversity, total abundance of individuals, abundance of pollution-indicative taxa, abundance of pollution-sensitive taxa, abundance of carnivorous and omnivorous taxa, and the abundance of deep deposit-feeding taxa. One of the pitfalls of using metrics based on sensitivity or tolerance to stressors such as pollution, or based on behavior, is that the classification of a given species is often based on expert opinion, and there may be no consensus among different experts. For example, the dominant species in BB-LEH in 2012 was *Mediomastus ambiseta*, which is classified in the B-IBI as pollution-sensitive (Weisberg et al. 1997). Other workers, however, classify this polychaete as pollution-tolerant (Pelletier et al. 2010). Most stations (76) were classified as "meets restoration goals" by the B-IBI (Figure 39).

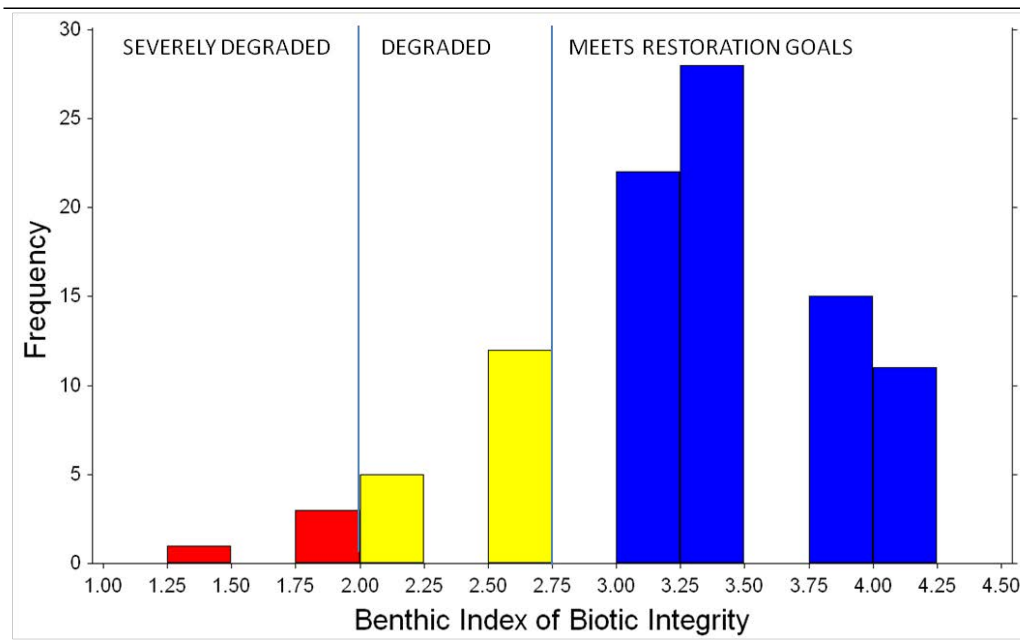
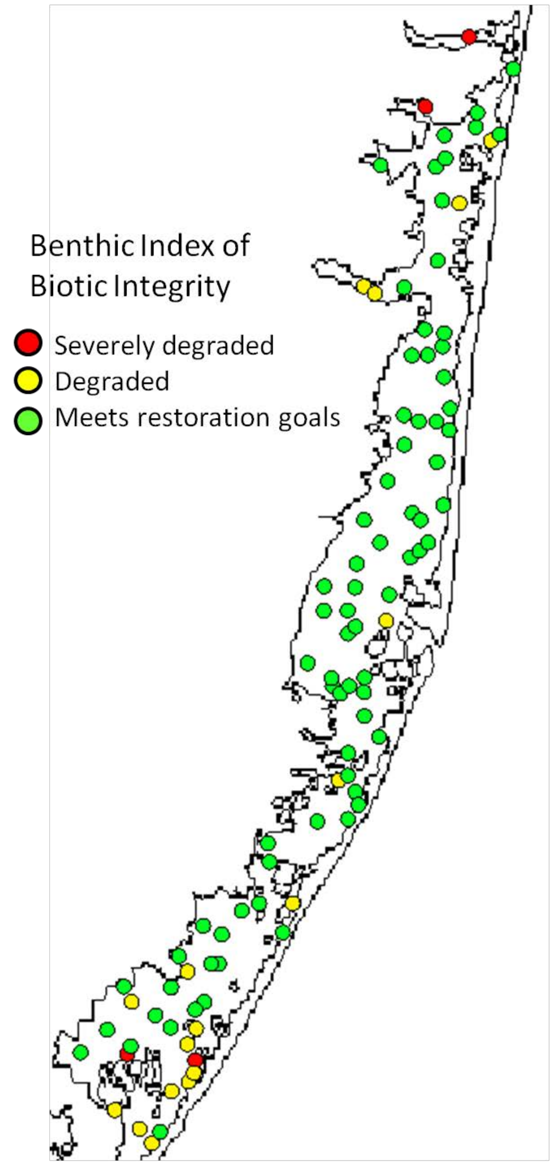


Figure 39. Histogram of frequency distribution of stations as classified by B-IBI.

Sites classified as “severely degraded” or “degraded” tended to occur at locations where freshwater enters the bay, and at Little Egg Inlet (Figure 40).

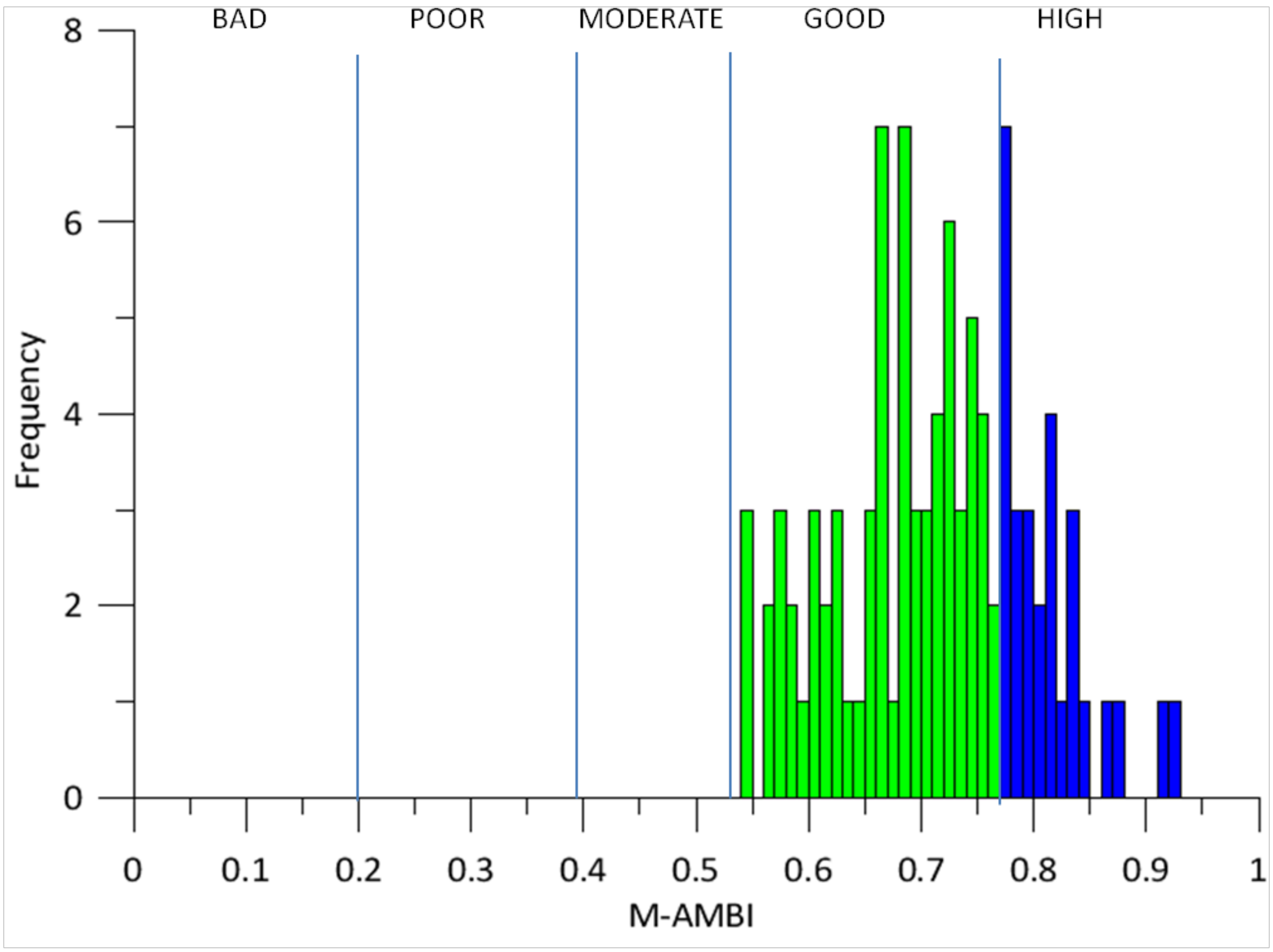
Figure 40. Distribution map for stations as classified by Benthic Index of Biotic Integrity.



AZTI's Marine Biotic Index (AMBI) and the Multivariate AMBI (M-AMBI)

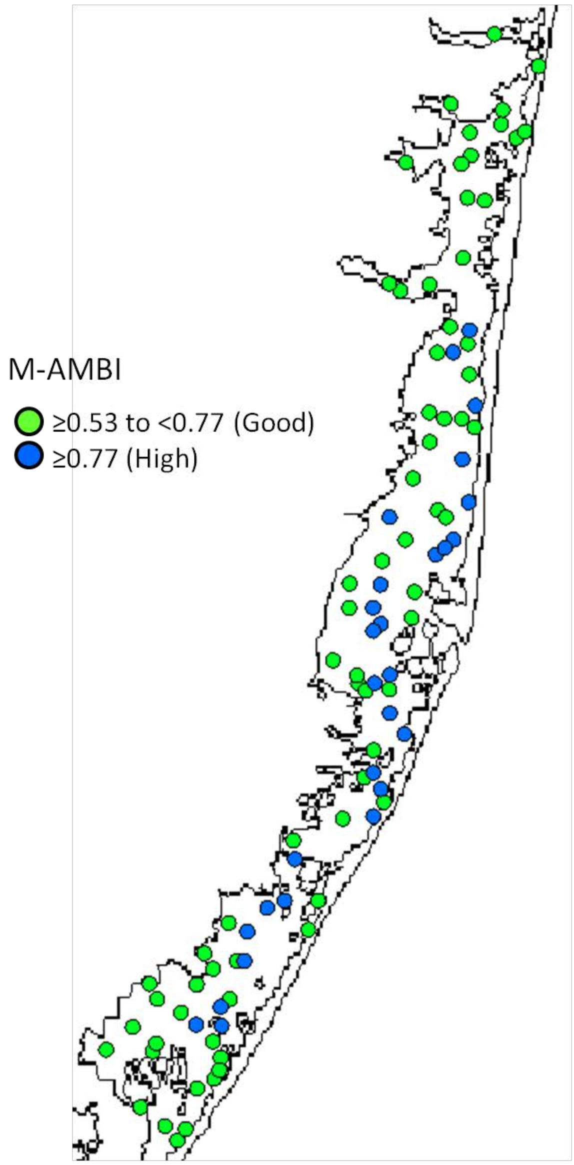
Borja et al. (2000) developed AMBI as an index of the habitat quality of European coastal zones. AMBI is based on the relative proportions of benthic macroinvertebrate that fall into each of five groups, based on their tolerance or response to organic enrichment: very sensitive, indifferent, tolerant, second-order opportunists, and first-order opportunists. As was the case for the B-IBI, there can be varying degrees of subjectivity in how species are assigned to the groups. AMBI values are used to place a site into one of five categories set by the European Union Water Framework Directive: bad, poor, moderate, good, or high. While originally developed for European waters, taxa from Chesapeake Bay have since been added to the database (Borja et al. 2008). A multivariate version, M-AMBI, added species richness and species diversity (Shannon index) to the index (Borja et al. 2012, Muxika et al. 2007), and that is the version we used here. The M-AMBI classified 69 of the stations in BB-LEH as "good" and 28 as "high" (Figure 41).

Figure 41. Histogram of frequency distribution of stations as classified by M-AMBI.



Stations classified as “high” by M-AMBI tended to be located in central and southern Barnegat Bay and in Little Egg Harbor (Figure 42).

Figure 42. Distribution map for stations as classified by M-AMBI.



Virginian Province Index (VPI)

Paul et al. (2001) developed a benthic index of estuarine condition for the Virginian Biogeographic Province, which extends from Cape Cod to the mouth of Chesapeake Bay. There are four components in this index: Gleason's D (a metric of species diversity), the abundance of tubificid oligochaetes, the abundance of polychaetes in the family Spionidae, and a constant to center the index on a value of 0. Gleason's D and the abundance of tubificids are adjusted for effects of low salinity, although for the 2012 data from BB-LEH the salinity adjustment is not needed. Gleason's D, while one of the earlier metrics of species diversity, is rarely used by benthic ecologists. Tubificids are a group often associated with organic pollution. Gallagher and Grassle (1997) critiqued the inclusion of all taxa in the family Spionidae, on the basis that it is species-rich family with many different feeding behaviors and a wide range of sensitivity to disturbance. Paul et al. (2001) define "degraded" sites as those with an index of ≤0 and "reference" sites as those with an index >0.

Ten stations in BB-LEH were classified as "degraded" and 87 were classified as "reference" by the VPI (Figure 43). Most of the "degraded" sites were near Little Egg Inlet (Figure 44).

Figure 43. Histogram of frequency distribution of stations as classified by the VPI.

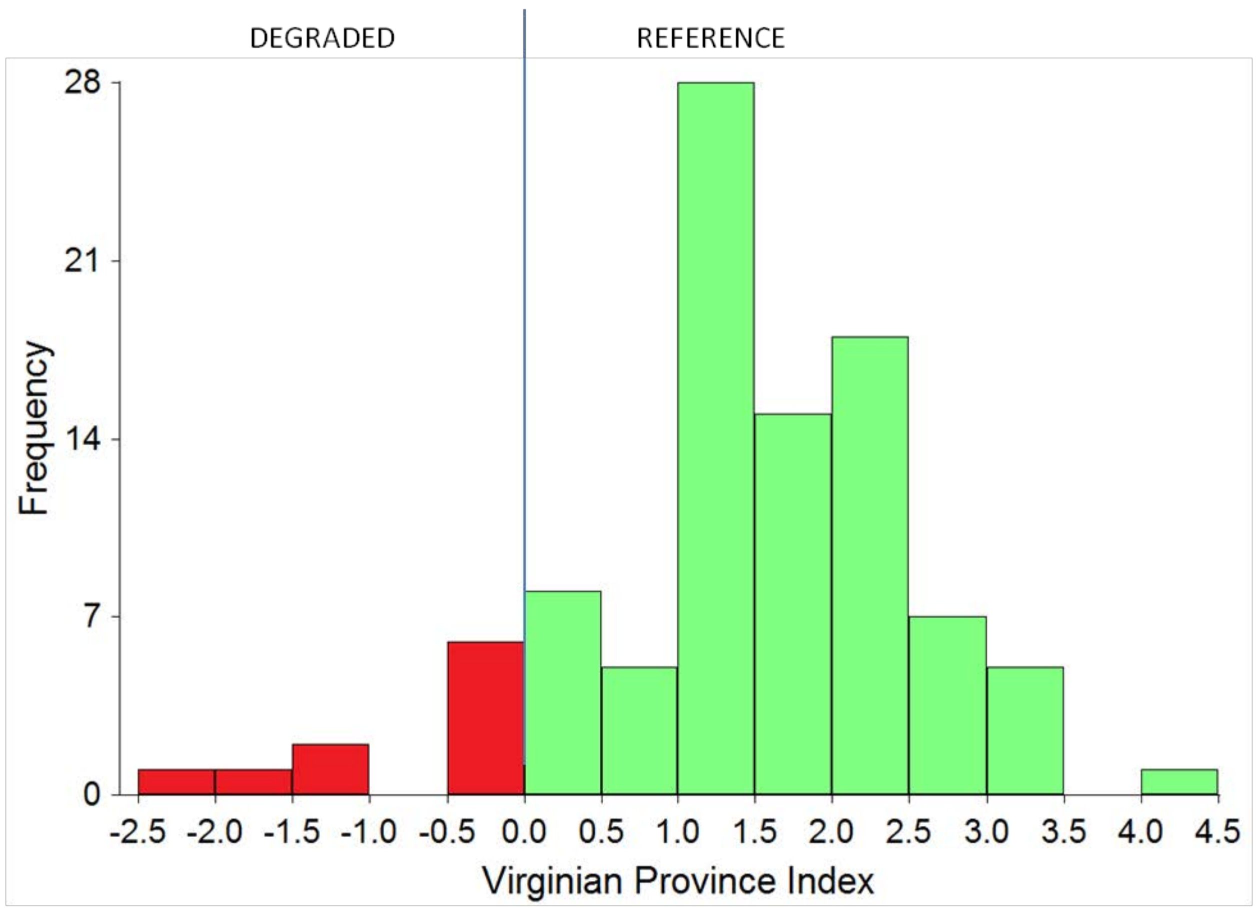
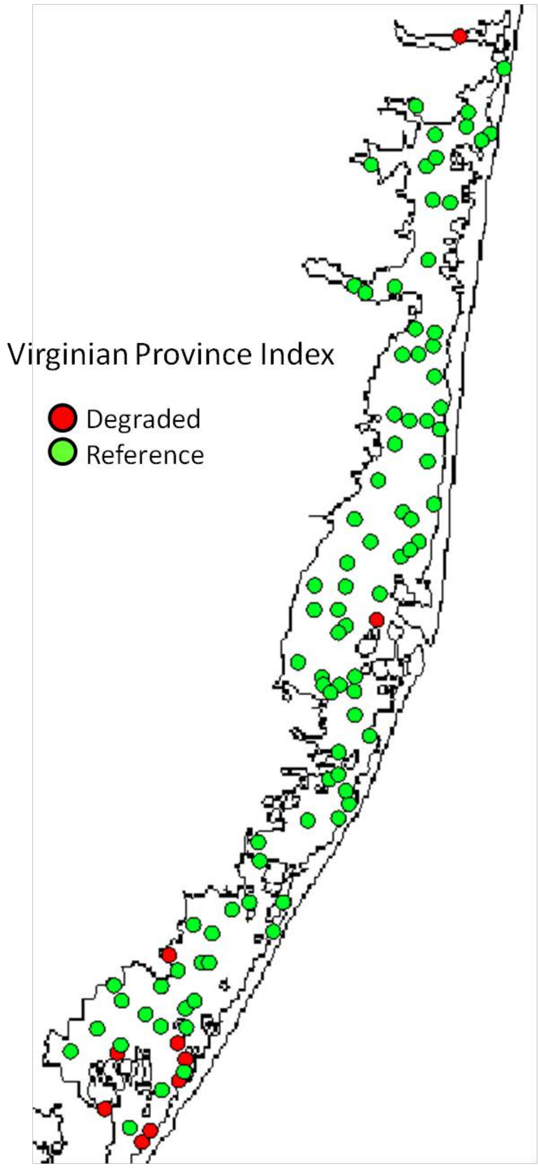


Figure 44. Distribution map for stations as classified by the Virginian Province Index.

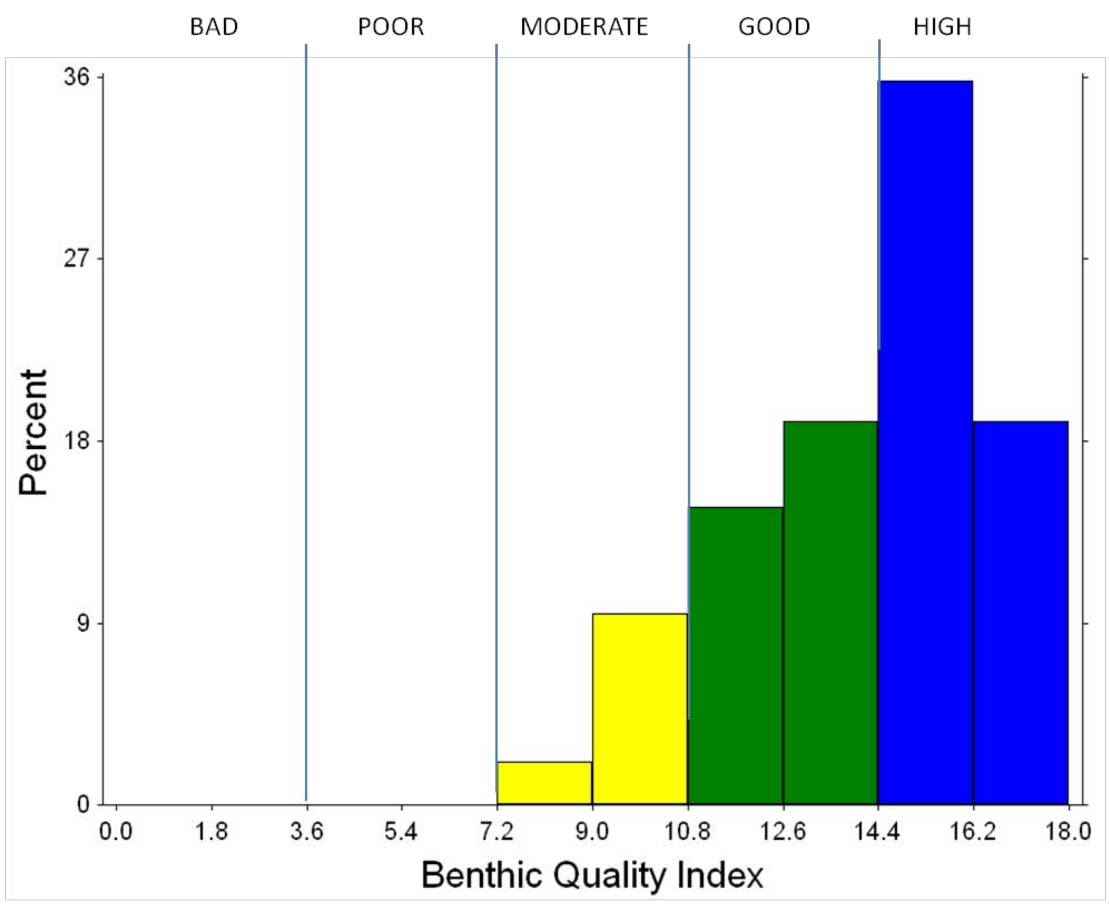


Benthic Quality Index (BQI)

Rosenberg et al. (2004) developed a benthic quality index (BQI) to classify habitat quality according to the European Union Water Framework. The BQI differs from other indices in that it does not include a metric based on classifying taxa into groups based on their (assumed) tolerance or sensitivity to pollution. While it is thus more objective than some indices, it is not without assumptions. At the heart of the BQI is calculating a tolerance value for each taxon in the area under study. Tolerance values are determined by plotting the cumulative abundance of each taxon against Hurlbert's species diversity index, $E(S_{50})$. The assumption is made that species diversity will be low in polluted environments, and hence a species that reaches high abundance in habitats with low diversity is tolerant to pollution or eutrophication. Rosenberg et al. (2004) chose the value of $E(S_{50})$ where a species reaches 5% of its cumulative abundance, designated $E(S_{50})_{0.05}$, as the tolerance value for that species.

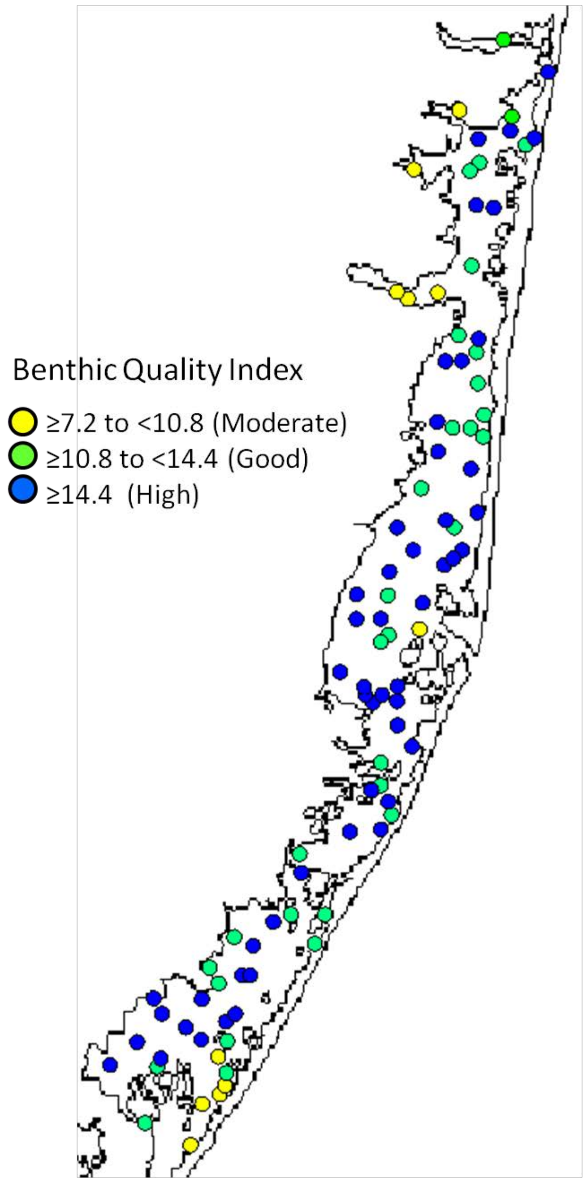
The BQI for a site is the summation of each species' tolerance value scaled by its relative abundance, with the final summation multiplied by the logarithm of the species richness (plus 1) (Rosenberg et al. 2004). The range of BQIs for all sites is divided into five equal intervals, as for M-AMBI, to correspond with the European Water Framework Directive's classifications of bad, poor, moderate, good, or high. Eleven stations were classified as "moderate," 32 as "good," and 52 as "high" by the BQI (Figure 45).

Figure 45. Histogram of frequency distribution of stations as classified by the BQI.



Stations classified as “moderate” were associated with locations where fresh water enters the northern section of BB-LEH, one was at Barnegat Inlet, and the others were near Little Egg Harbor Inlet (Figure 46). Stations classified as “good” or “high” were found throughout the bay.

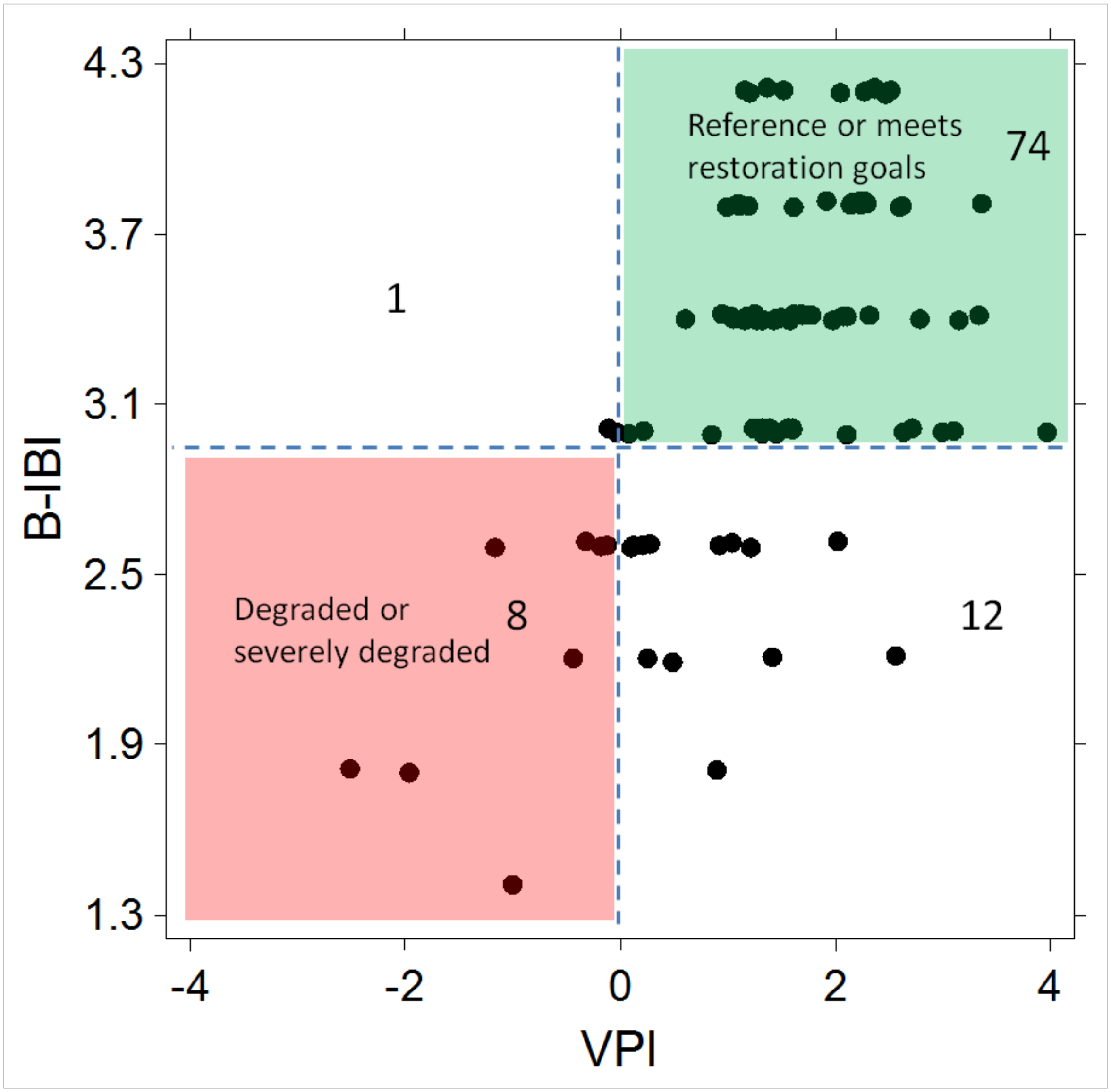
Figure 46. Distribution map for stations as classified by BQI.



Comparisons among multivariate and multimetric indices

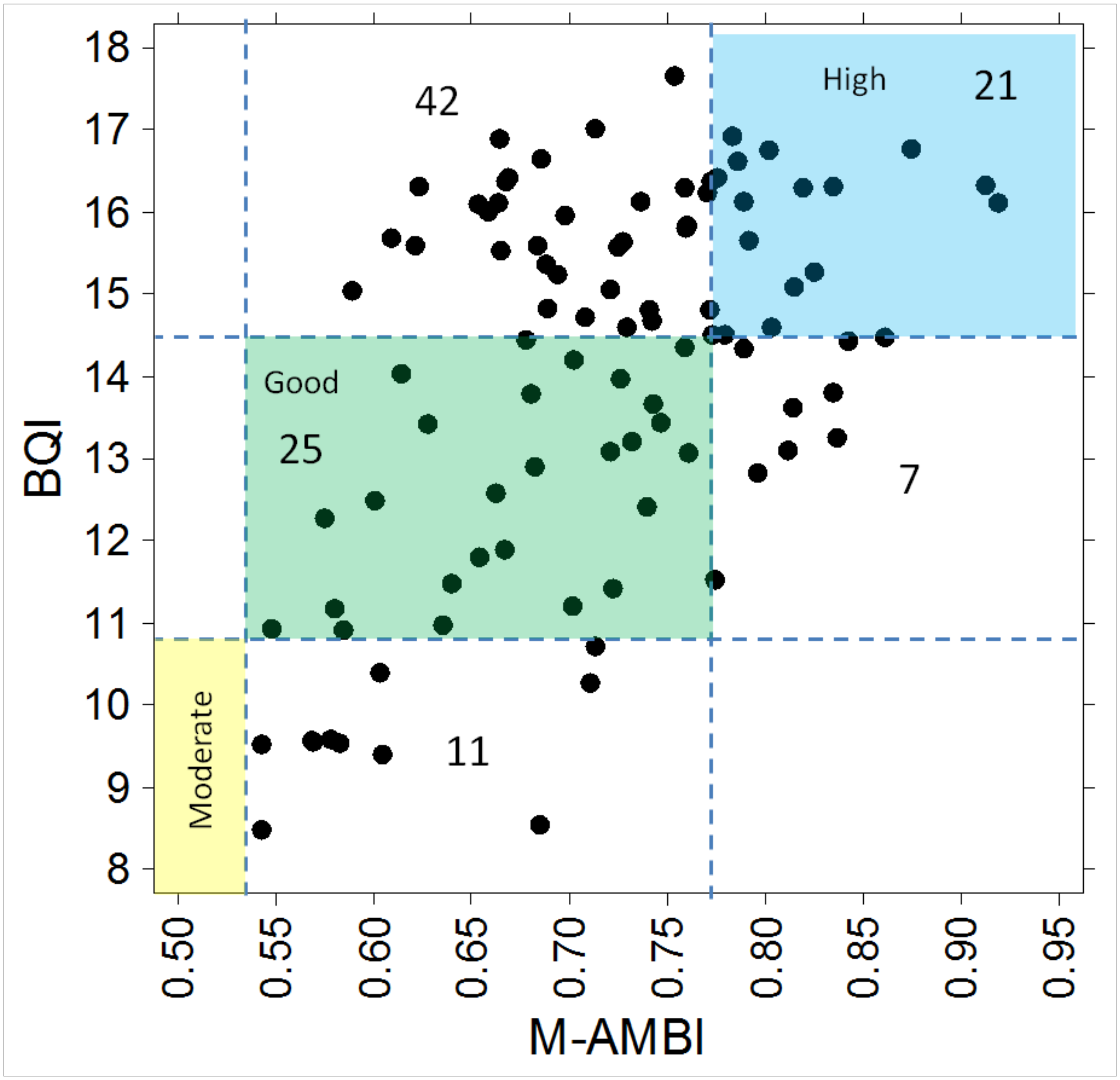
The B-IBI and VPI classifying sites into similar groups, either "reference/meets restoration goals" or "degraded/severely degraded." The indices agreed for 82 of the sites (Figure 47), 74 sites were jointly classified as reference/meets restoration goals while eight sites were jointly classified as degraded/severely degraded. Most of the disagreement between the indices arose from 12 sites classified as degraded by the B-IBI but as reference by the VPI.

Figure 47. Comparison of site classifications by the Benthic Index of Biotic Integrity and the Virginian Province Index. Sites in the green-shaded area are classified as reference sites (undegraded) by both indices, sites in the red-shaded area are classified as degraded by both indices. Numbers in each sections denote the number of sites.



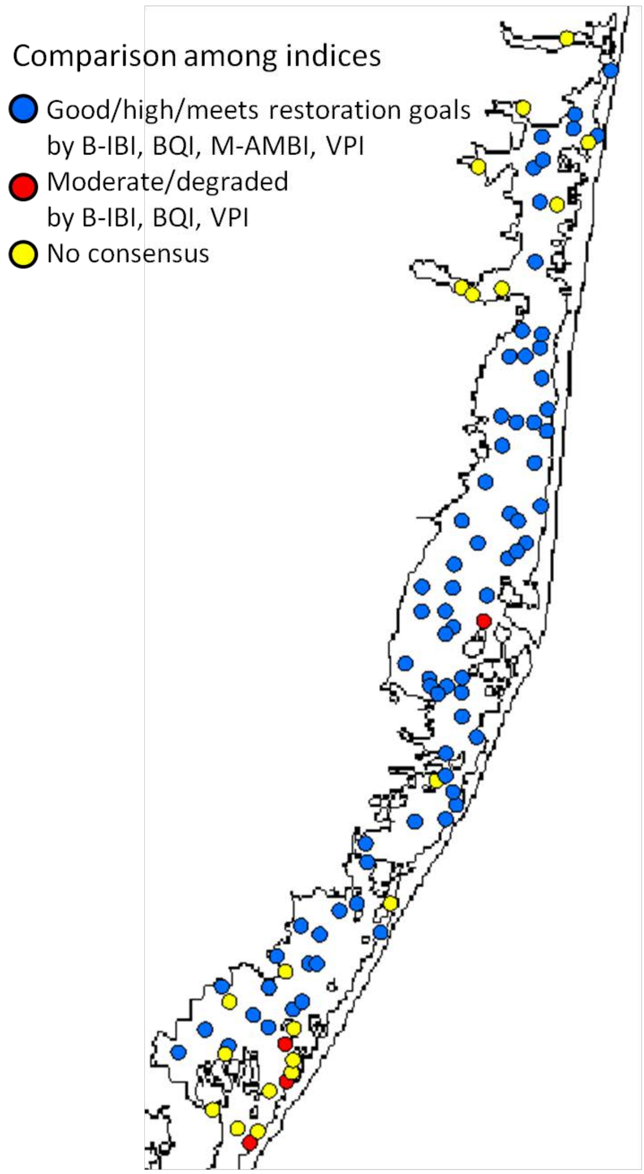
The Multivariate AMBI and the Benthic Quality Index both use the same five verbal descriptions of habitat quality. These indices agreed on classifications for 46 of the stations (Figure 48). Most of the disagreement (42 sites) was for sites classified as “good” by M-AMBI but as “high” by BQI.

Figure 48. Comparison of site classifications by the Multivariate AMBI and the Benthic Quality Index. Both indices agree on classifications for sites in the shaded areas. Numbers in sections denote the number of sites.



Comparison among all four indices is not straightforward, since the B-IBI and VPI are dichotomous, while the M-AMBI and BQI have five classification levels. We combined classification levels from the latter two indices to permit comparison. We consider all indices in agreement if a site was classified as good or high or reference or meets restoration goals; 73 sites were in this category and they were located throughout BB-LEH (Figure 49). All indices were also in agreement if a site was classified as moderate or degraded or severely degraded (this omits M-AMBI because no site was thus classified); 4 sites were in this category, near Barnegat Inlet and Little Egg Harbor Inlet. No consensus was reached for 20 sites, most of them in northern Barnegat Bay and in southern Little Egg Harbor.

Figure 49. Comparison of site classifications by the B-IBI, VPI, M-AMBI, and BQI.



Multivariate analyses of community structure and relation to environmental properties

Cluster analysis of the macrofauna data was performed to see if there were "natural groupings" of stations that could delineate different regions of BB-LEH. Only taxa that made up at least 3% of the total abundance at any one station were included (Field et al. 1982). Abundances were log transformed (log(n+1)) to scale down the scores of abundant species so that they did not overwhelm the data. Similarities were calculated with the Bray-Curtis measure. The resulting dendrogram was interpreted as four major groups of stations: three groups of stations with approximately 50% similarity within each group and a fourth group of stations with 35% similarity (Figure 50). Based on the majority of stations within each cluster, the groups were assigned to geographic regions corresponding to north Barnegat Bay, central and south Barnegat Bay, proximal to Barnegat and Little Egg Harbor inlets, and distal to the inlets.

Non-metric multidimensional scaling was next conducted to see if there was a consistent relationship among stations. As was the case when classification and ordination of the environmental data was performed, there was general agreement for the taxonomic data, but no clear separation of all groups (Figure 51). The "tightest" clusters of stations were the central/south bay and distal to inlets stations, while the proximal to inlets stations were least similar to each other. In many cases a station within a cluster based on the classification analysis was closer to a station in another cluster in the ordination.

Using the same color coding on the physical map of station locations confirmed that these clusters should only be thought of as general groupings and that boundaries are not absolute (Figure 52).

Figure 50. Dendrogram of stations by hierarchical cluster analysis with group average sorting, based on Bray-Curtis similarity matrix of log-transformed abundances of taxa that made up at least 3% of the total number of individuals at any station. Groupings are based on a similarity level among stations of roughly 50%.

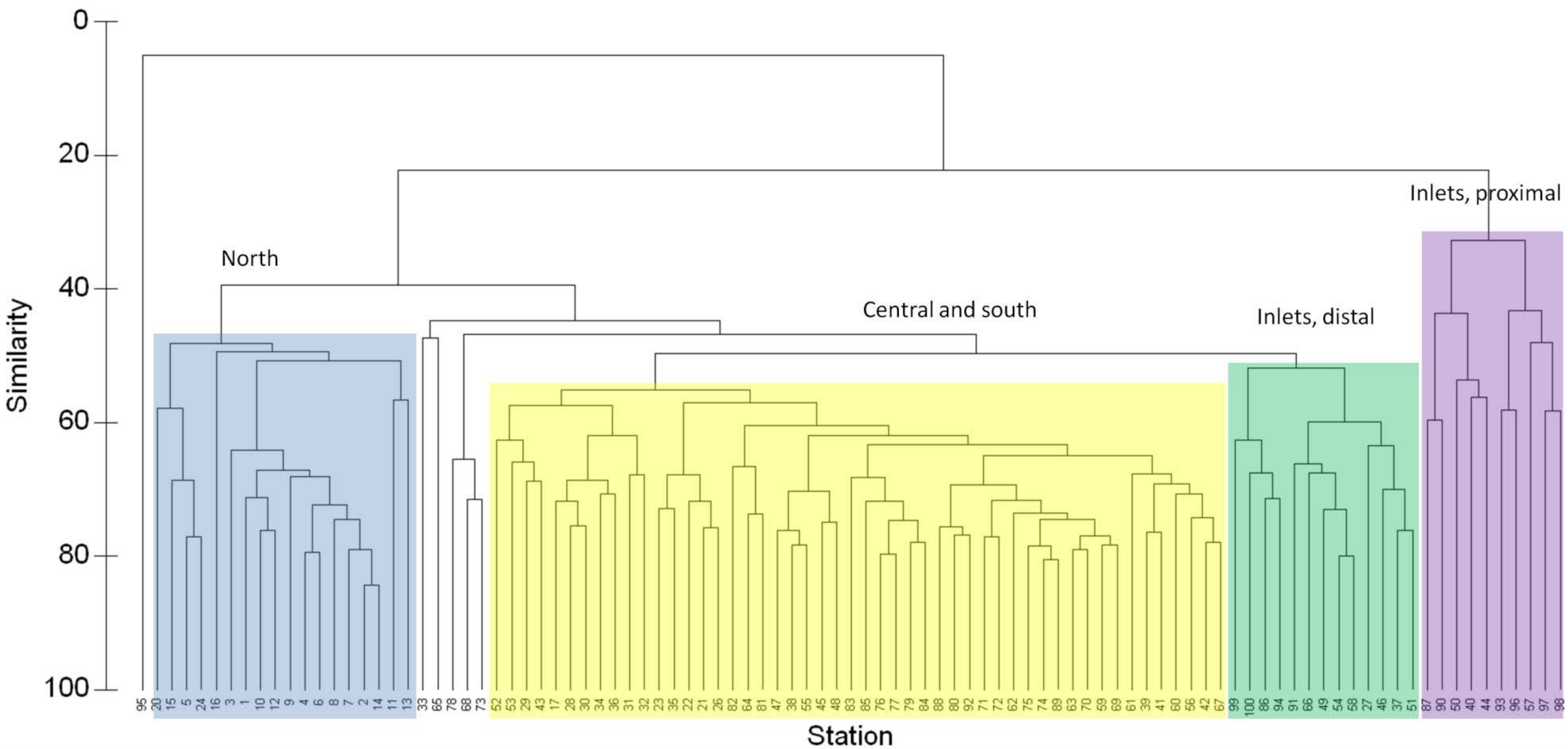
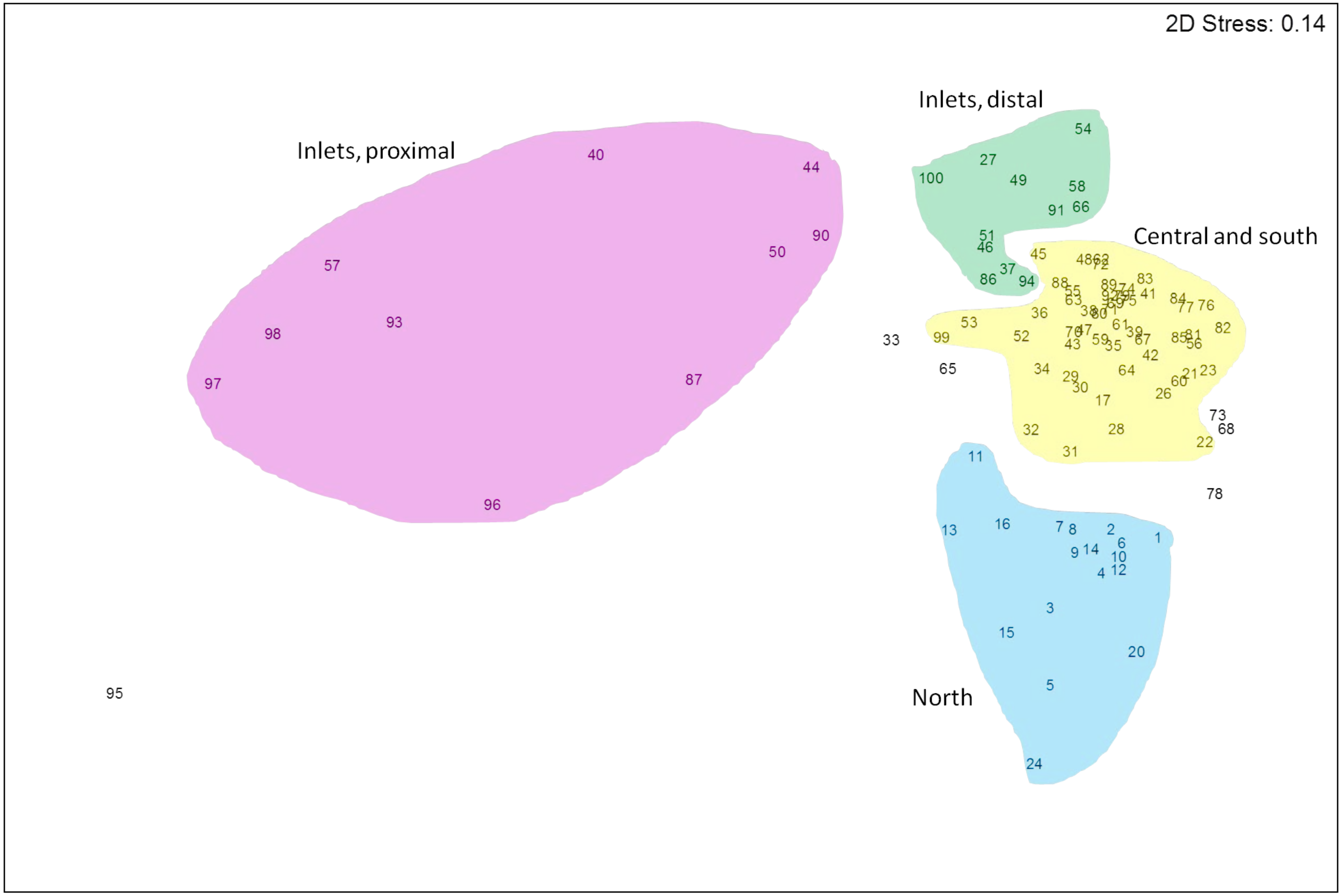
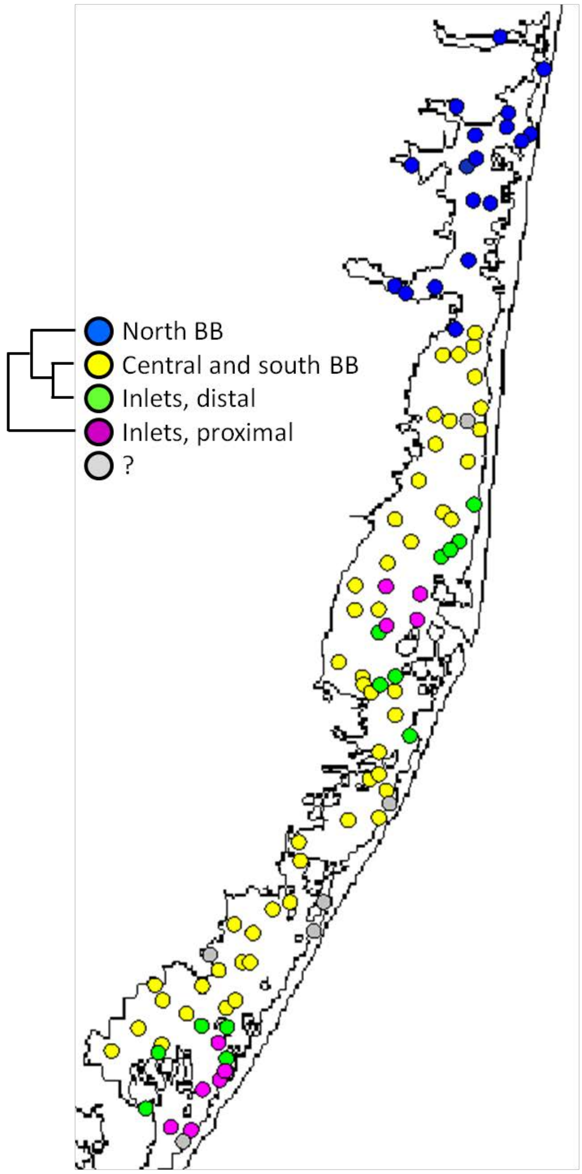


Figure 51. Ordination of stations by MDS, based on Bray-Curtis similarity matrix of log-transformed abundances of taxa that made up at least 3% of the total number of individuals at any station. Groupings and colors correspond to those in Figure 50.

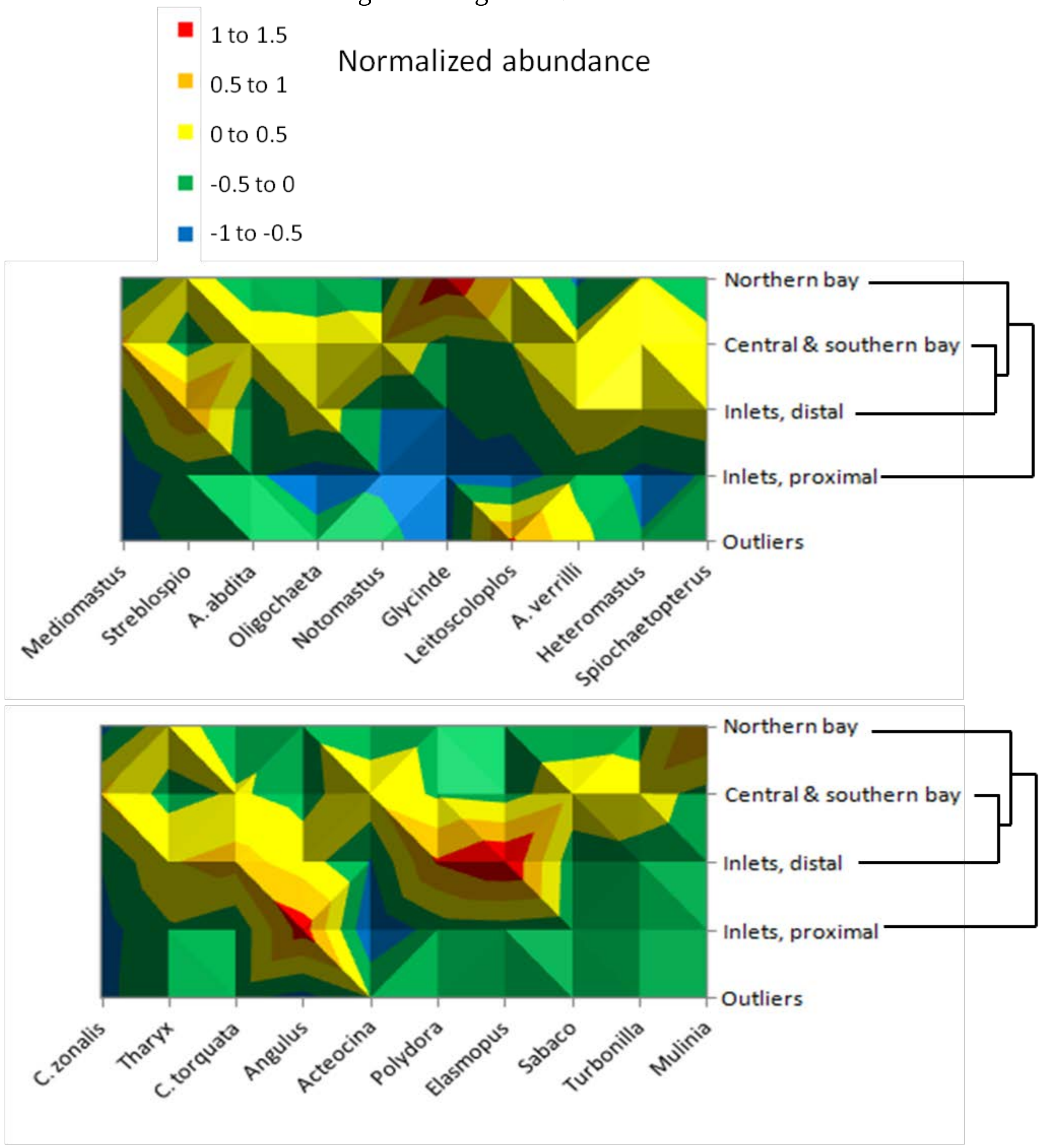


Fgure 52. Station clusters as identified by the dendrogram in Figure 50. The clustering of groups is also included for comparison.



Heat maps of the normalized abundances of the 20 most abundant taxa show differences in distribution that in some cases appear to reflect differences in environmental preferences (Figure 53). For example, the numerical dominant *Mediomastus ambiseta* is relatively rare in the northern bay where salinity is lower (see Figure 19), while *Glycinde multidens* and *Mulinia lateralis* reached their greatest abundances there. The polychaete *Streblospio benedicti* was the second most abundant species overall and reached highest numbers in stations distal to the inlets, sediment C, N, and P were higher than average and temperatures were coolest.

Figure 53. Heat map of the average normalized abundances of the 20 most abundant taxa at the station clusters from the dendrogram in Figure 50.



Comparison of benthic macroinvertebrate community composition in 2013 with 2012

Changes in abundance of numerically dominant taxa between 2012 and 2013

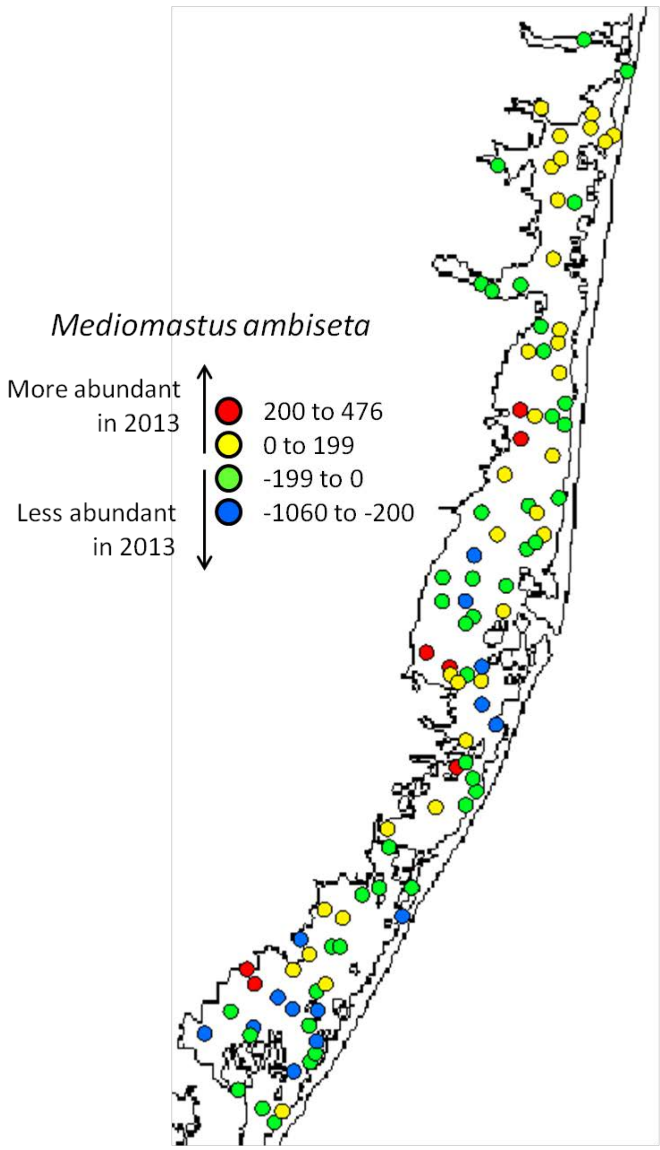
Most of the taxa that were numerical dominants in 2012 also were in 2013, with a few exceptions, but there were changes in their rankings (Table 4). The polychaete *Mediomastus ambiseta* continued to be the numerical dominant. The amphipod *Ampelisca abdita* moved up six spots, and the congener *A. verrilli* moved up from 22 to 8. The most dramatic increase in abundance was for the dwarf surfclam *Mulinia lateralis*, which moved from 83 in 2012 to the 20th most abundant taxon in 2013.

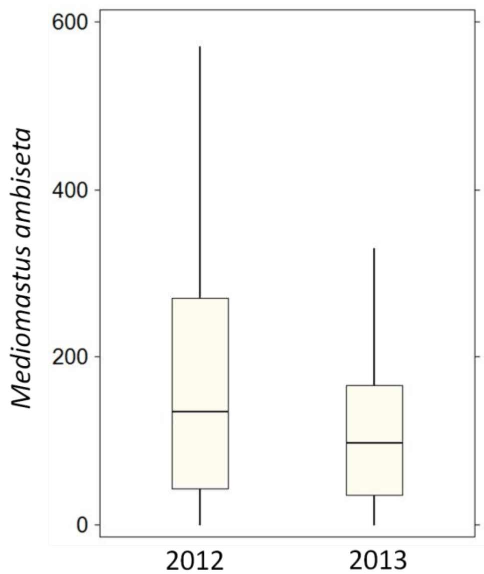
Table 4. The 20 most abundant taxa in 2013, with the change in their ranking from 2012. Positive change in rank means the taxon was relatively more abundant in 2013 than 2013, and vice versa.

Taxon	RANK 2013	Change in rank from 2012 to 2013
Mediomastus ambiseta	1	0
Streblospio benedicti	2	3
Ampelisca abdita	3	6
Oligochaeta spp.	4	-2
Notomastus sp. A Ewing	5	3
Glycinde multidens	6	7
Leitoscoloplos robustus	7	12
Ampelisca verrilli	8	14
Heteromastus filiformis	9	20
Spiochaetopterus costarum oculatus	10	6
Clymenella zonalis	11	0
Tharyx sp. A (MWRA)	12	-8
Clymenella torquata	13	-1
Angulus agilis	14	0
Acteocina canaliculata	15	5
Polydora cornuta	16	1
Elasmopus levis	17	-7
Sabaco elongatus	18	-3
Turbonilla interrupta	19	15
Mulinia lateralis	20	63

Mediomastus ambiseta, the most abundant species in 2013, was significantly less abundant in 2013 than 2012 (Wilcoxon signed rank test, p = 0.031). Stations with the greatest decrease in abundance were mainly in central Barnegat Bay and Little Egg Harbor (Figure 54).

Figure 54. (Left) differences in per grab abundance of *Mediomastus ambiseta* between July 2013 and 2012. (Right) Box and whisker plots enclose the middle half of the data. The box is bisected by a line at the value for the median. The vertical lines at the top and the bottom of the box (the whiskers) indicate the range of "typical" data values.

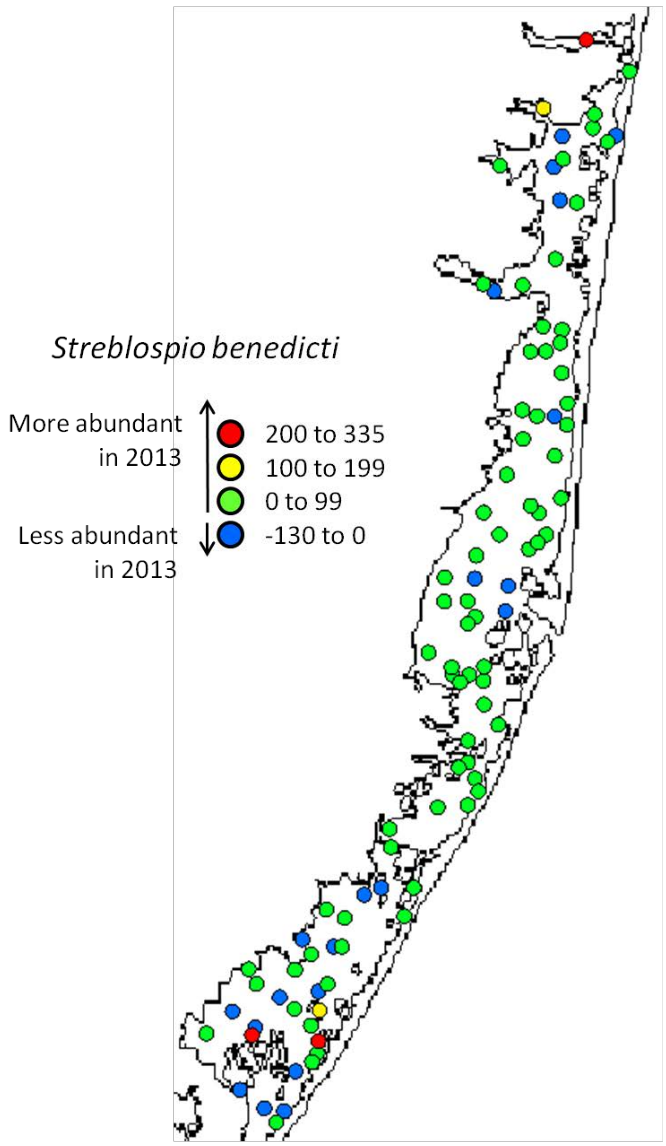


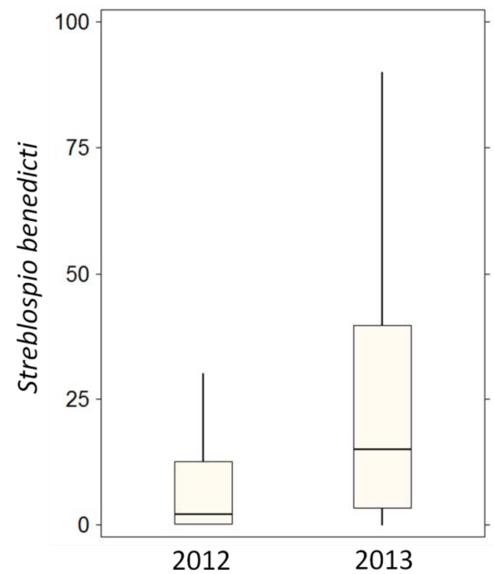


	2012	2013
Average abundance	182	138
95% confidence interval	145-219	109-167

Streblospio benedicti, the second most abundant species in 2013, was significantly more abundant in 2013 than 2012 (Wilcoxon signed rank test, $p < 0.0001$). There was no obvious pattern in the changes, with adjacent stations often showing opposite changes between years (Figure 55).

Figure 55. (Left) differences in per grab abundance of *Streblospio benedicti* between July 2013 and 2012. (Right) Box and whisker plots enclose the middle half of the data. The box is bisected by a line at the value for the median. The vertical lines at the top and the bottom of the box (the whiskers) indicate the range of "typical" data values.

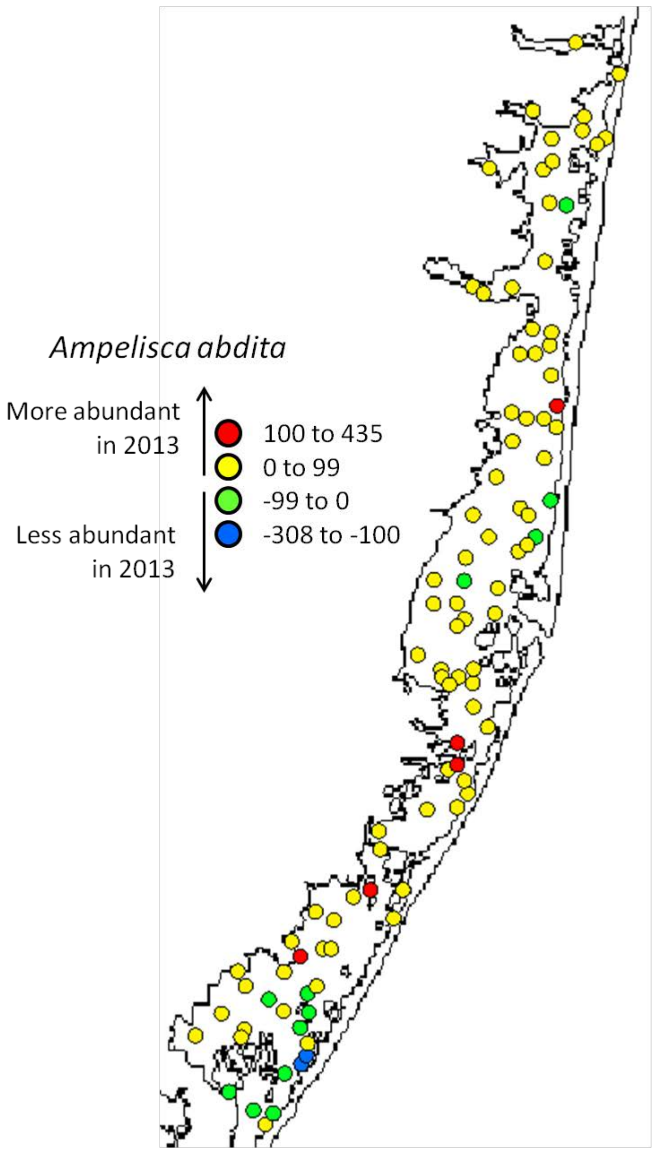


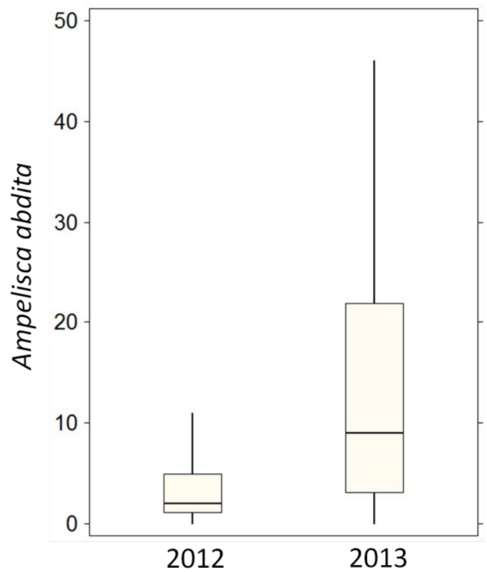


	2012	2013
Average abundance	13.9	39
95% confidence interval	7-20.8	24.9-53.2

Ampelisca abdita, the third most abundant species in 2013, was significantly more abundant in 2013 than 2012 (Wilcoxon signed rank test, $p < 0.0001$). *Ampelisca abdita* increased in abundance in stations throughout BB-LEH (Figure 56). Most stations where abundance decreased were concentrated in the southern half of Little Egg Harbor.

Figure 56. (Left) differences in per grab abundance of *Ampelisca abdita* between July 2013 and 2012. (Right) Box and whisker plots enclose the middle half of the data. The box is bisected by a line at the value for the median. The vertical lines at the top and the bottom of the box (the whiskers) indicate the range of "typical" data values.

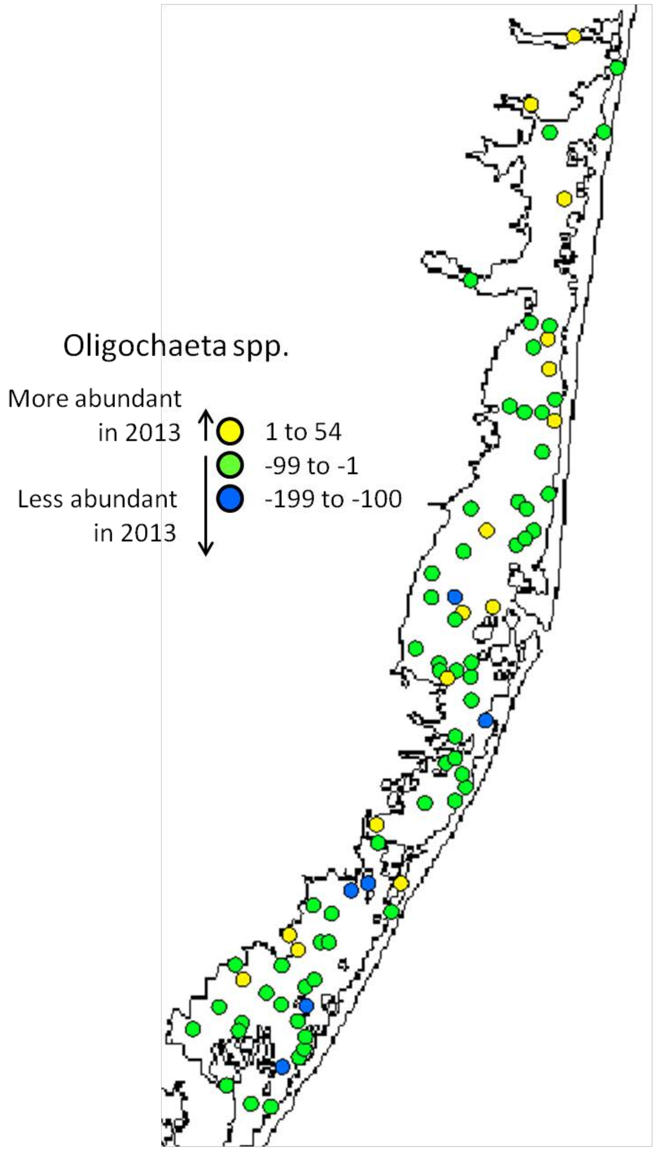


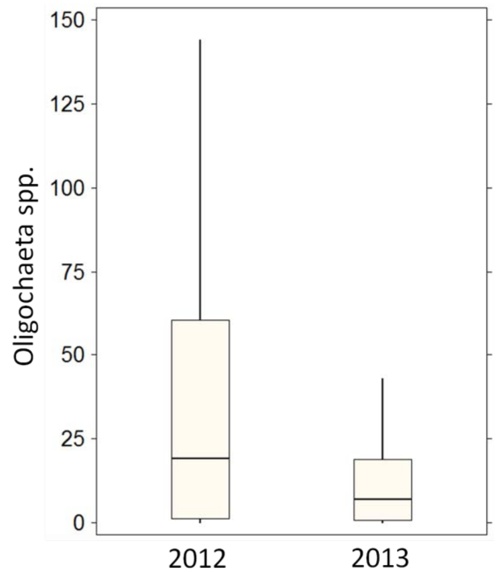


	2012	2013
Average abundance	9.2	23.6
95% confidence interval	2.3-16.1	13.1-34

Oligochaeta spp., the fourth most abundant taxon in 2013, were significantly less abundant in 2013 than 2012 (Wilcoxon signed rank test, $p < 0.0001$). Oligochaeta spp. decreased in abundance in stations throughout BB-LEH (Figure 57).

Figure 57. (Left) differences in per grab abundance of *Ampelisca abdita* between July 2013 and 2012. Stations where no oligochaetes were collected in either year are not mapped. (Right) Box and whisker plots enclose the middle half of the data. The box is bisected by a line at the value for the median. The vertical lines at the top and the bottom of the box (the whiskers) indicate the range of "typical" data values.

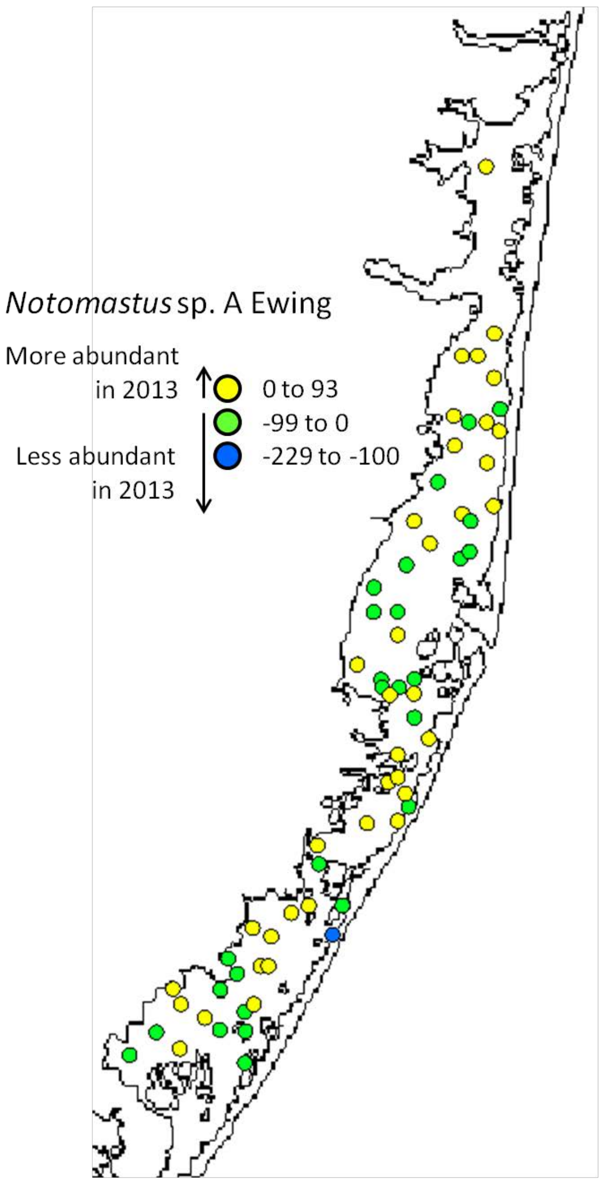


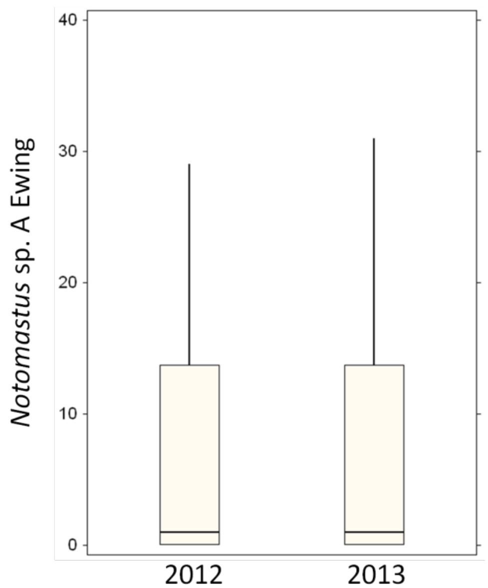


	2012	2013
Average abundance	37.9	13.4
95% confidence interval	28.5-47.4	9.8-16.9

The abundance of *Notomastus* sp. A Ewing, the fifth most abundant species in 2013, was not significantly different in 2013 than 2012 (Wilcoxon signed rank test, p = 0.062). Stations where *Notomastus* sp. A Ewing increased or decreased in abundance between years were randomly distributed throughout BB-LEH (Figure 58).

Figure 58. (Left) differences in per grab abundance of *Notomastus* sp. A Ewing between July 2013 and 2012. Stations where no worms were collected in either year are not mapped. (Right) Box and whisker plots enclose the middle half of the data. The box is bisected by a line at the value for the median. The vertical lines at the top and the bottom of the box (the whiskers) indicate the range of "typical" data values.

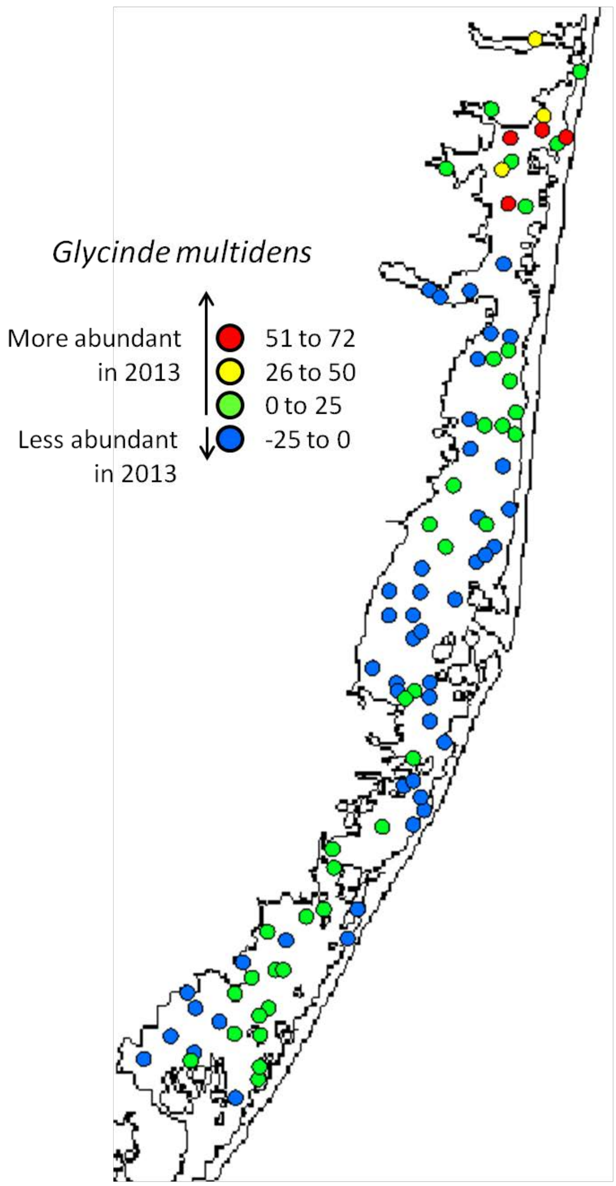


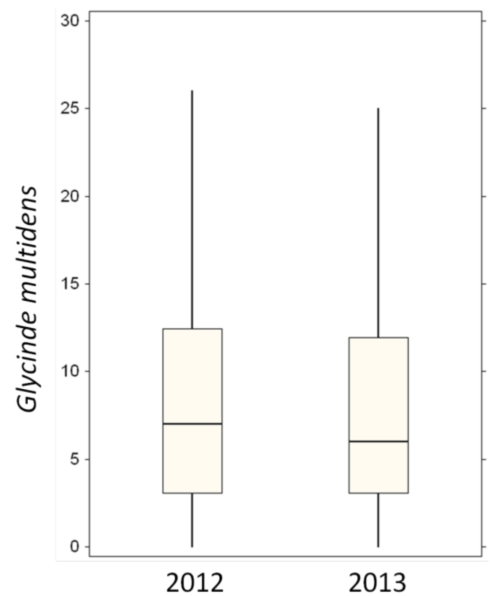


	2012	2013
Average abundance	9.7	11.5
95% confidence interval	4.6-14.8	7.2-15.8

The abundance of *Glycinde multidens*, the sixth most abundant species in 2013, was not significantly different in 2013 than 2012 (Wilcoxon signed rank test, p = 0.97). While the abundance was the same averaged over all stations, *Glycinde multidens* was more abundant at stations north of the Toms River and less abundant in the central part of the bay (Figure 59).

Figure 59. (Left) differences in per grab abundance of *Glycinde multidens* between July 2013 and 2012. Stations where no worms were collected in either year are not mapped. (Right) Box and whisker plots enclose the middle half of the data. The box is bisected by a line at the value for the median. The vertical lines at the top and the bottom of the box (the whiskers) indicate the range of "typical" data values.

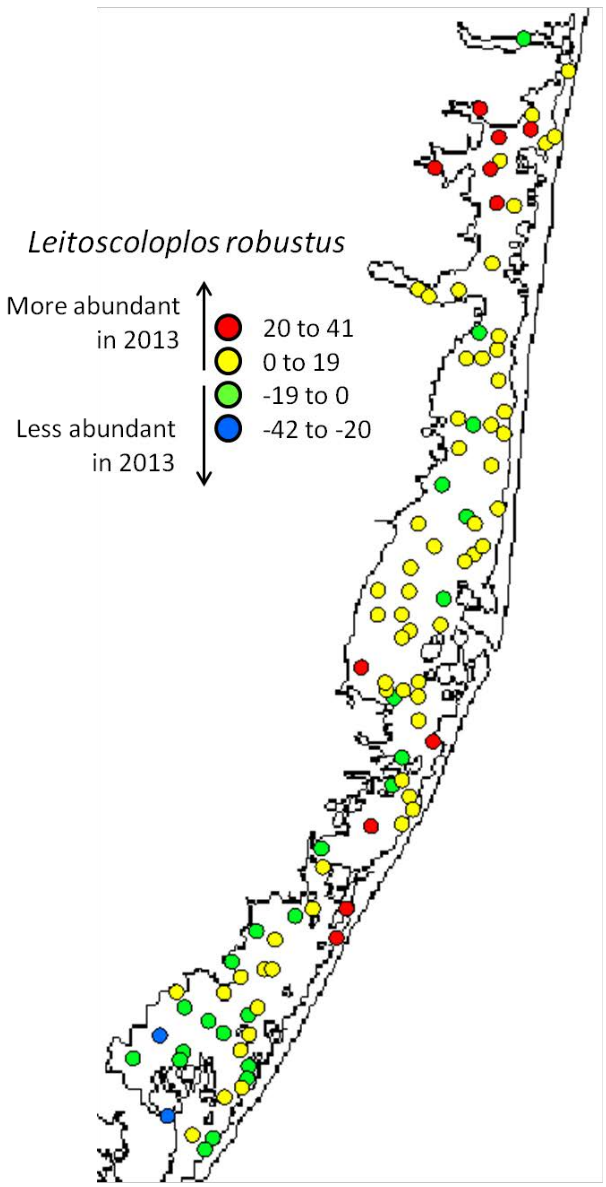


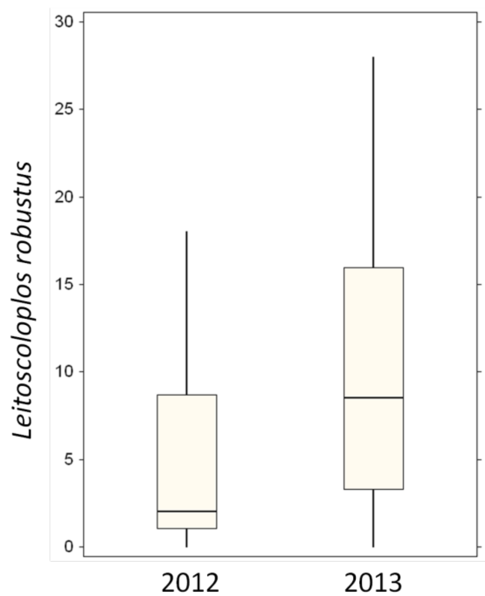


	2012	2013
Average abundance	9	11.6
95% confidence interval	7.5-10.4	8.3-15

Leitoscoloplos robustus, the seventh most abundant species in 2013, was significantly more abundant in 2013 than 2012 (Wilcoxon signed rank test, $p < 0.0001$). While *Leitoscoloplos robustus* increased in abundance in stations throughout BB-LEH, most stations where abundance increased were north of Barnegat Inlet (Figure 60).

Figure 60. (Left) differences in per grab abundance of *Leitoscoloplos robustus* between July 2013 and 2012. (Right) Box and whisker plots enclose the middle half of the data. The box is bisected by a line at the value for the median. The vertical lines at the top and the bottom of the box (the whiskers) indicate the range of "typical" data values.

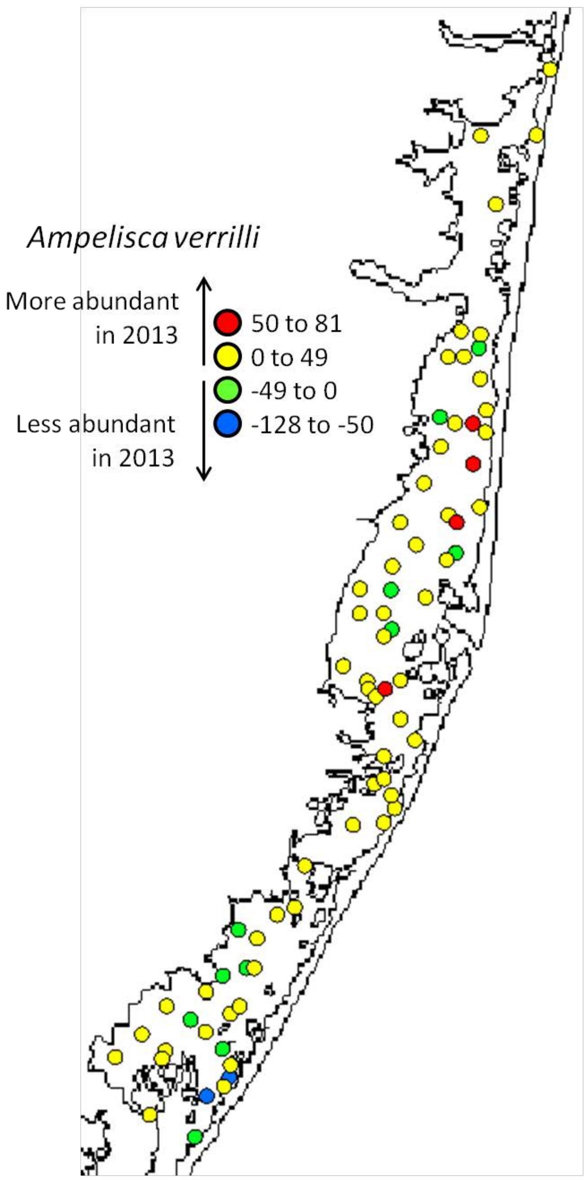


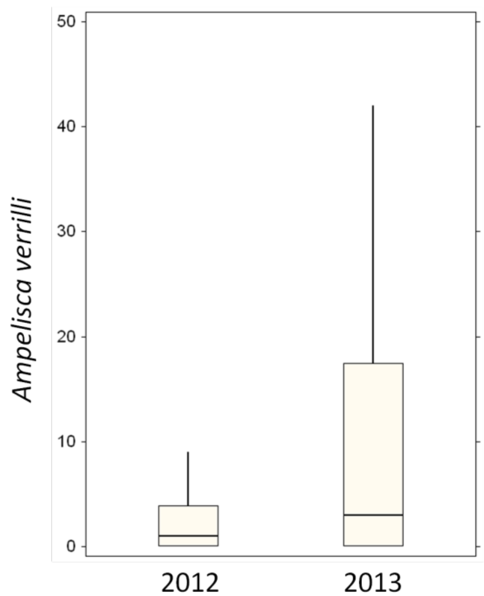


	2012	2013
Average abundance	6.2	11.3
95% confidence interval	4.5-7.8	9.4-13.1

Ampelisca verrilli, the eighth most abundant species in 2013, was more than twice as abundant in 2013 than in 2012 (Wilcoxon signed rank test, $p < 0.0001$). *Ampelisca verrilli* increased in abundance in stations throughout BB-LEH (Figure 61). The stations where its abundance decreased the most were near Little Egg Harbor Inlet.

Figure 61. (Left) differences in per grab abundance of *Ampelisca verrilli* between July 2013 and 2012. Stations where no amphipods were collected in either year are not mapped. (Right) Box and whisker plots enclose the middle half of the data. The box is bisected by a line at the value for the median. The vertical lines at the top and the bottom of the box (the whiskers) indicate the range of "typical" data values.

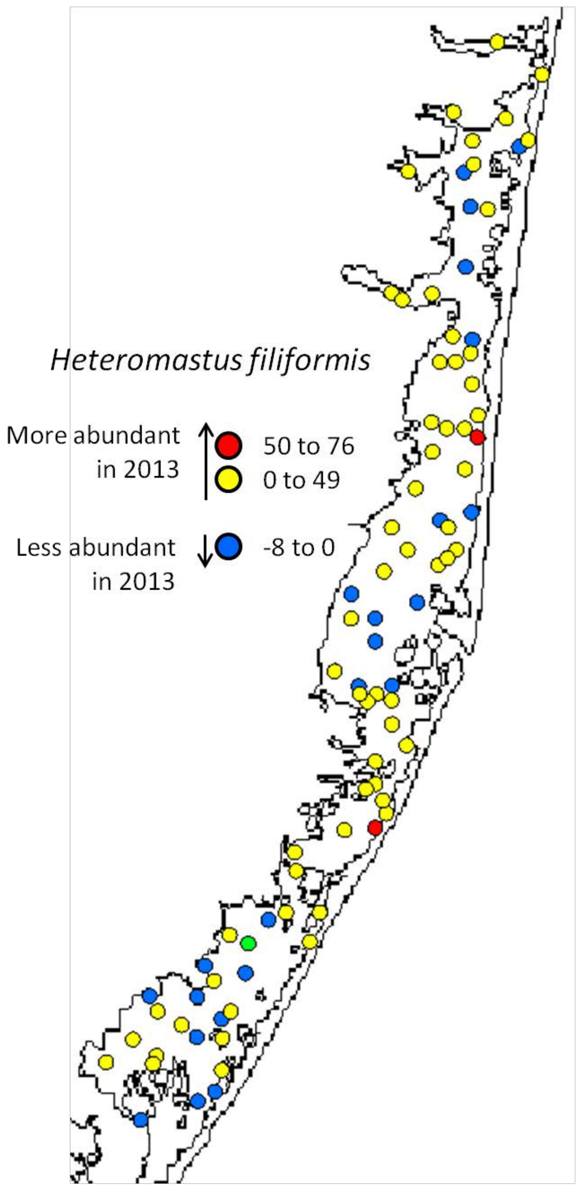


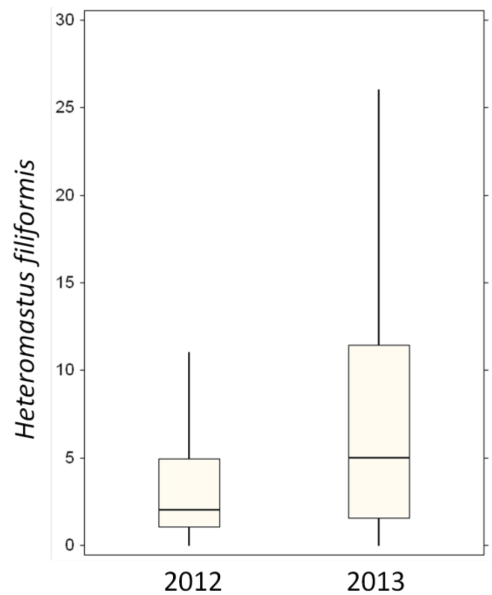


	2012	2013
Average abundance	5	11.1
95% confidence interval	1.4-8.6	7.6-14.6

Heteromastus filiformis, the ninth most abundant species in 2013, was also more than twice as abundant in 2013 than in 2012 (Wilcoxon signed rank test, $p < 0.0001$). *Heteromastus filiformis* both increased and decreased in abundance in stations spread throughout BB-LEH with no apparent pattern (Figure 62).

Figure 62. (Left) differences in per grab abundance of *Heteromastus filiformis* between July 2013 and 2012. Stations where no worms were collected in either year are not mapped. (Right) Box and whisker plots enclose the middle half of the data. The box is bisected by a line at the value for the median. The vertical lines at the top and the bottom of the box (the whiskers) indicate the range of "typical" data values.

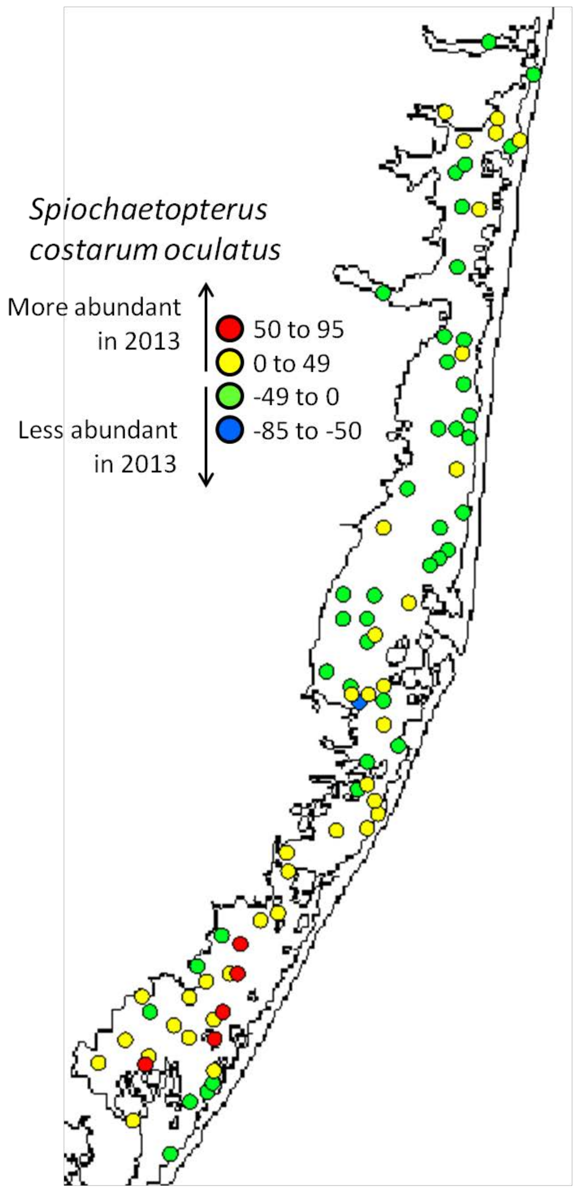


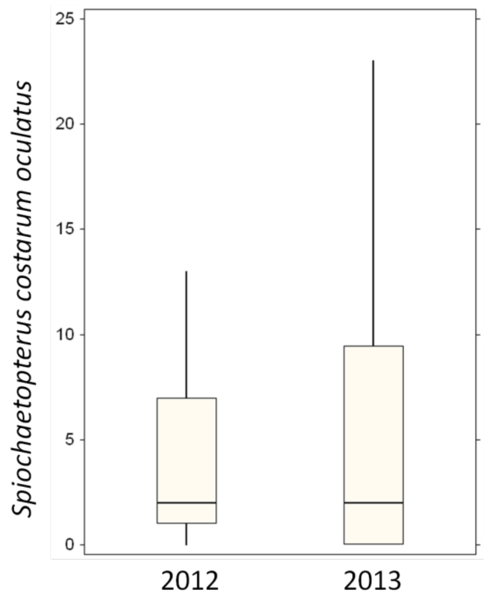


	2012	2013
Average abundance	3.5	10.2
95% confidence interval	2.6-4.5	7.2-13.2

The abundance of *Spiochaetopterus costarum oculatus,* the tenth most abundant species in 2013, was not significantly different in 2013 than 2012 (Wilcoxon signed rank test, p = 0.28). While the abundance was the same averaged over all stations, *Spiochaetopterus* tended to be less abundant in 2013 north of Barnegat Inlet and more abundant to the south (Figure 63).

Figure 63. (Left) differences in per grab abundance of *Spiochaetopterus costarum oculatus* between July 2013 and 2012. Stations where no worms were collected in either year are not mapped. (Right) Box and whisker plots enclose the middle half of the data. The box is bisected by a line at the value for the median. The vertical lines at the top and the bottom of the box (the whiskers) indicate the range of "typical" data values.



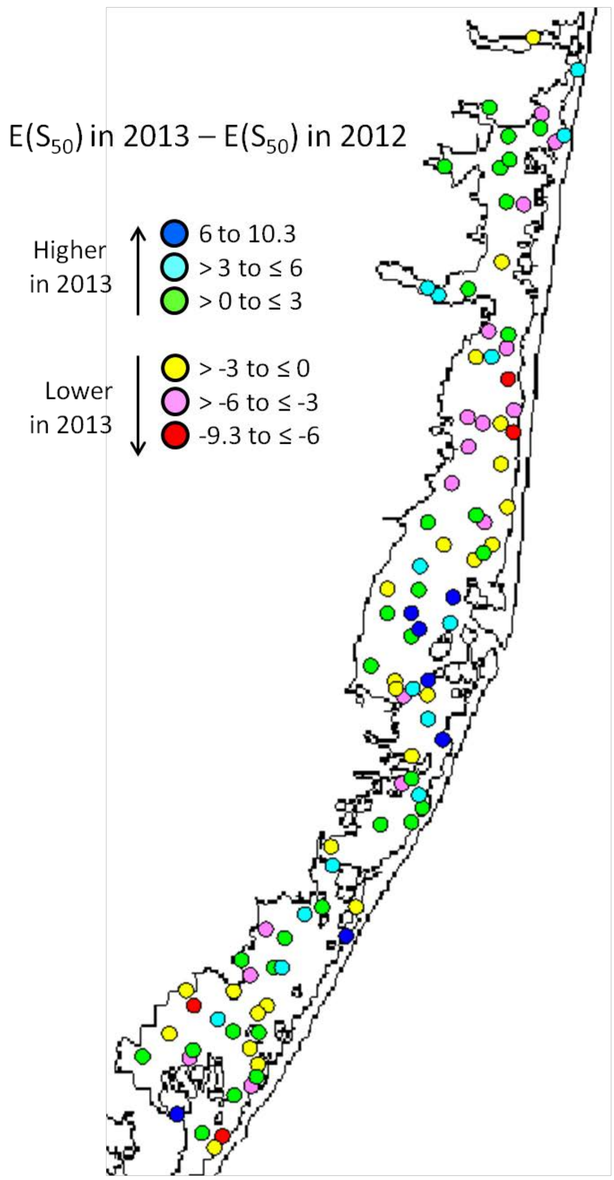


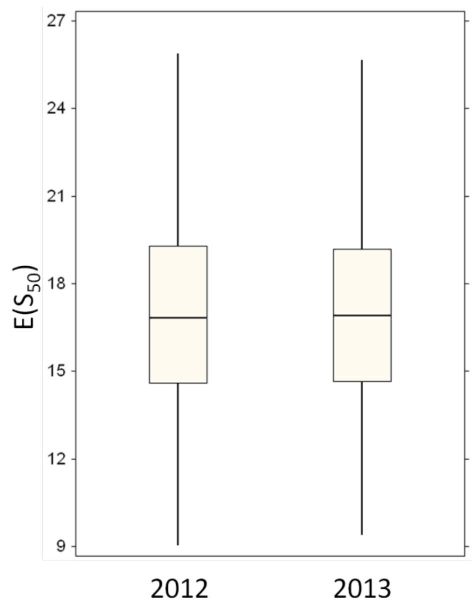
	2012	2013
Average abundance	6.8	10.1
95% confidence interval	4.3-9.2	6-14.1

Changes in species diversity between 2012 and 2013

Changes in species diversity from 2012 to 2013 were nearly symmetrical. Species diversity increased at 50 stations and decreased at 47 (three stations at head of the Toms River not included); the sharpest decline in $E(S_{50})$ was 9.3, the maximum increase was 10.3. No consistent spatial pattern of changes in diversity was apparent (Figure 64).

Figure 64. (Left) differences in species diversity (as measured by $E(S_{50})$ values) between July 2013 and 2012. (Right) Box and whisker plots enclose the middle half of the data. The box is bisected by a line at the value for the median. The vertical lines at the top and the bottom of the box (the whiskers) indicate the range of "typical" data values.





Changes in benthic indices between 2012 and 2013

The Benthic Index of Biotic Integrity decreased, numerically, at 45 stations in 2013 compared to 2012. Seventeen stations changed to lower classification categories (Figure 65). No stations were scored as "severely degraded" in 2012, while four were in 2013. Thirteen stations that were classified as "meets restoration goals" in 2012 were classified as "degraded" in 2013. On the other hand, the median value was 3.4 both years (Figure 66). Stations where the B-IBI decreased occurred throughout BB-LEH but were especially prevalent in the northern section and in southern Little Egg Harbor (Figure 66).

Figure 65. Scatterplot of values for the Benthic Index of Biotic Integrity for the same stations in July 2012 vs. July 2013. Multiple stations often plot at the same coordinates. Colored squares denote stations that fall into the same classification in both years.

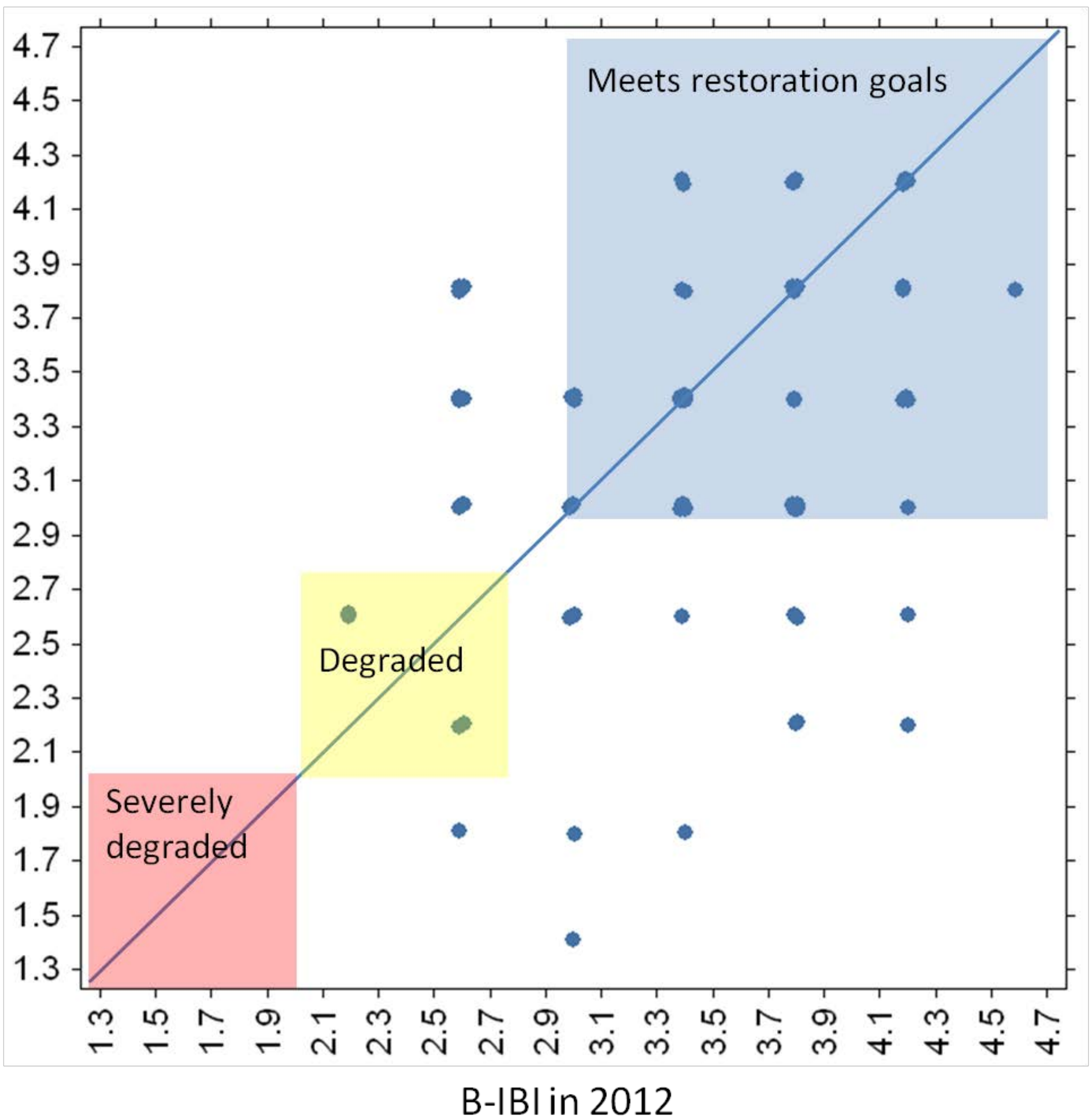
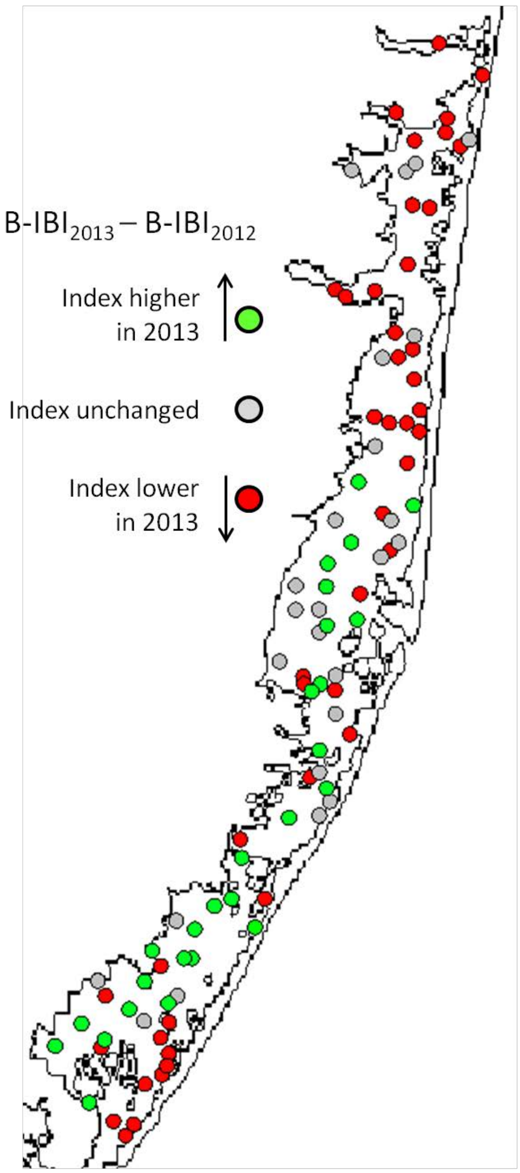
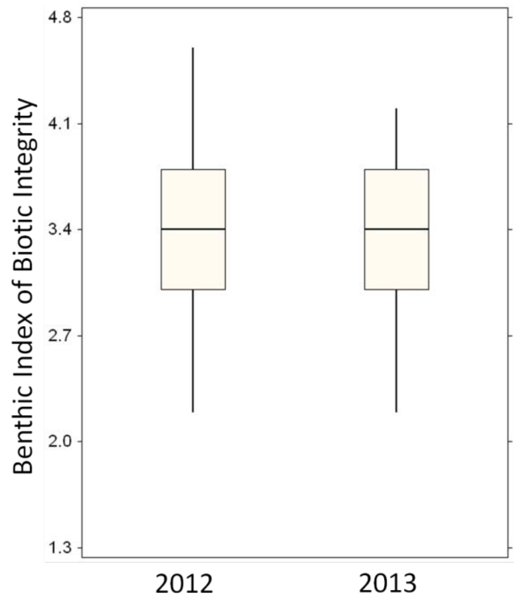


Figure 66. (Left) differences in the Benthic Index of Biotic Integrity between July 2013 and 2012. (Right) Box and whisker plots enclose the middle half of the data. The box is bisected by a line at the value for the median. The vertical lines at the top and the bottom of the box (the whiskers) indicate the range of “typical” data values.





The multimetric AMBI decreased, numerically at 51 stations in 2013 compared to 2012 but this was nearly balanced by 41 stations where the index increased (Figure 67). Five stations classified as “moderate” in 2012 moved up to “good” in 2013. Other stations switched from “good” to “high” and vice versa, with the net result being no change in the median value for the index of 0.72 for both years (Figure 68). Most stations where the M-AMBI decreased were between Barnegat Inlet and the mouth of the Toms River, and in southern Little Egg Harbor (Figure 68). M-AMBI increased in most of the stations in northern Barnegat Bay.

Figure 67. Scatterplot of values for the Multimetric AMBI for the same stations in July 2012 vs. July 2013. Colored squares denote stations that fall into the same classification in both years.

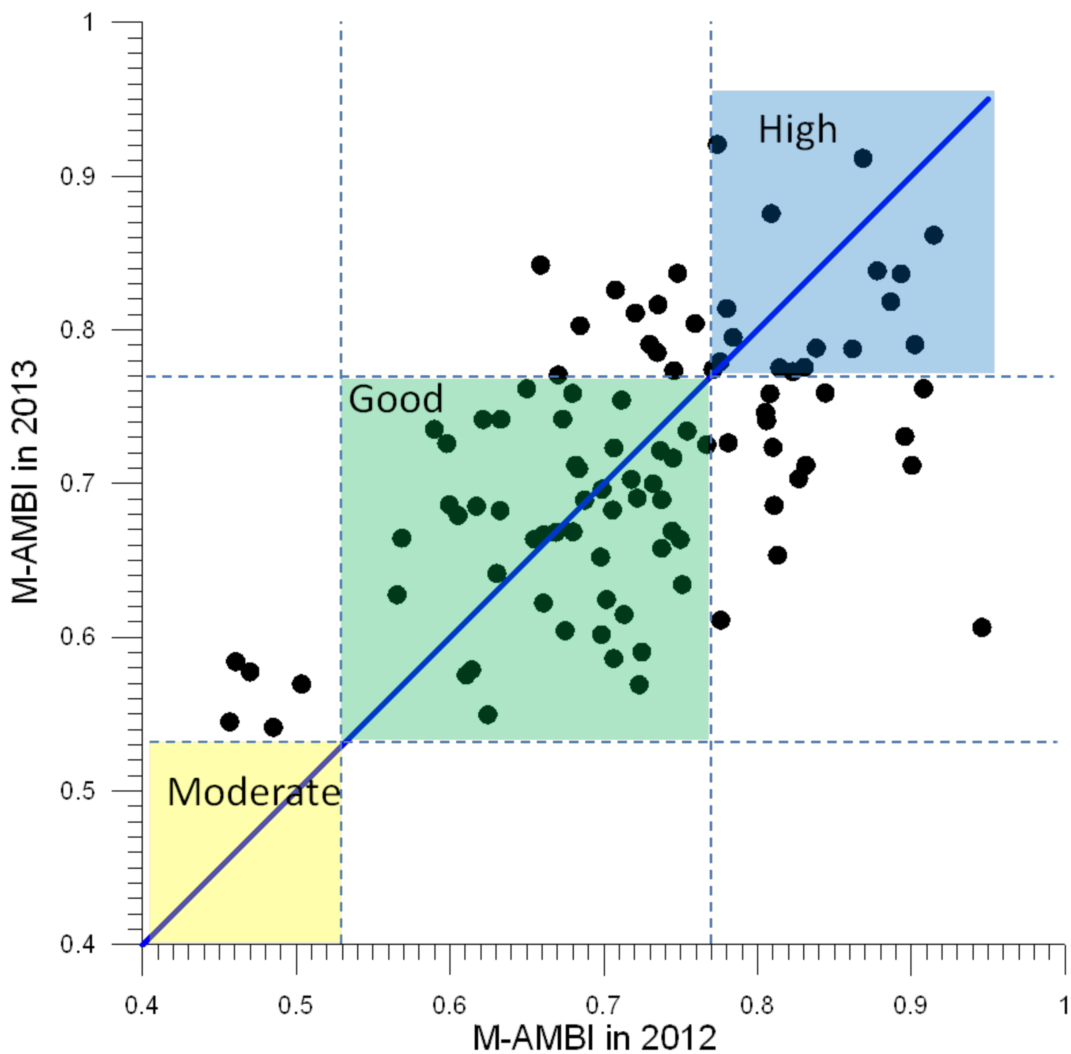
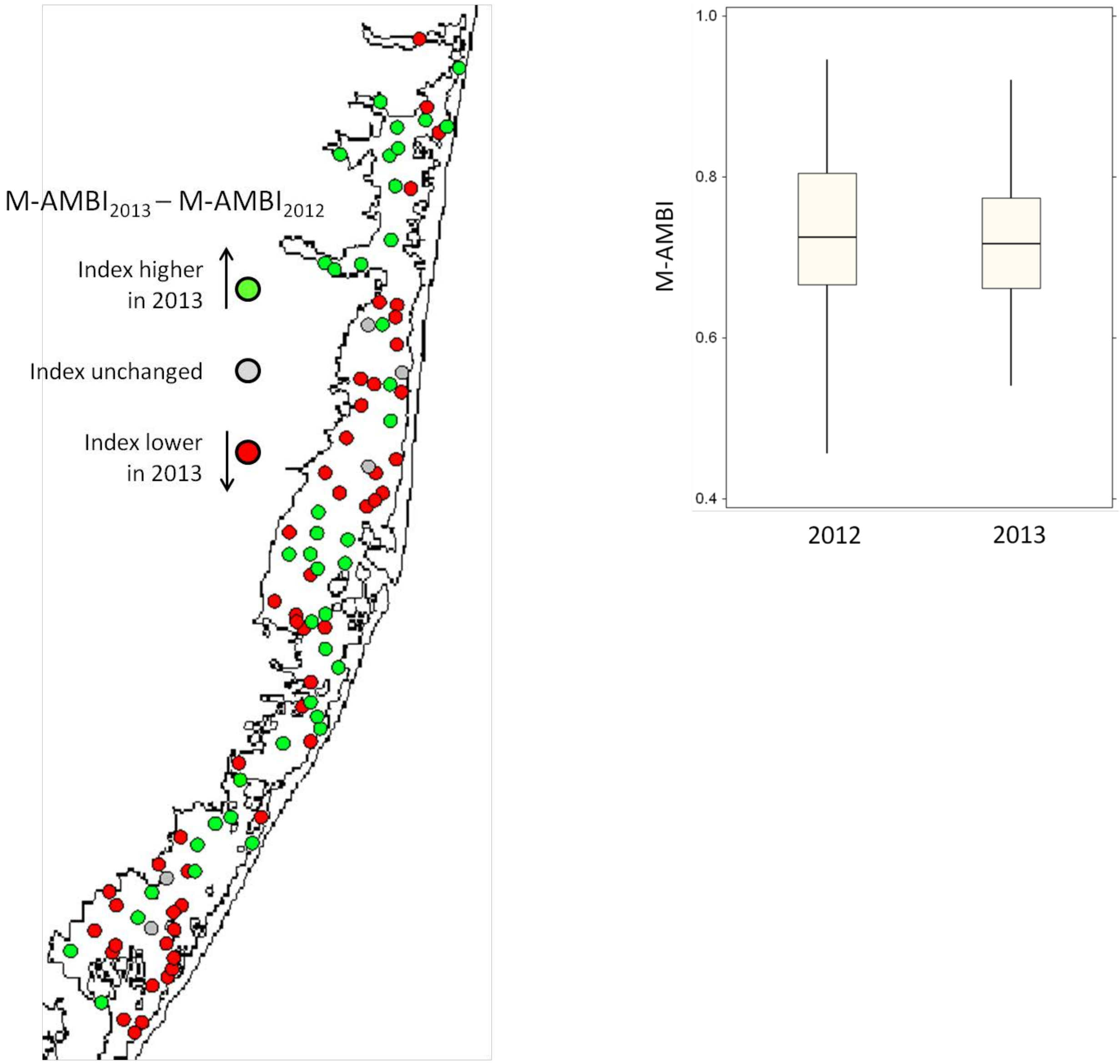


Figure 68. (Left) differences in the M-AMBI between July 2013 and 2012. (Right) Box and whisker plots enclose the middle half of the data. The box is bisected by a line at the value for the median. The vertical lines at the top and the bottom of the box (the whiskers) indicate the range of “typical” data values.



The Virginian Province Index decreased, numerically, at 49 stations and increased at 48 stations in 2013 compared to 2012 (Figure 69). Only 12 stations shifted classification, however: five classified as "degraded" in 2012 were classified as "reference" in 2013, and 7 stations changed classification the other way. The median VPI was 1.53 in 2012 and 1.42 in 2013 (Figure 70). The VPI increased in 2013 for most of the stations north of the Toms River and in the vicinity of Barnegat Inlet (Figure 70). The VPI decreased for many stations in central Barnegat Bay and in Little Egg Harbor.

Figure 69. Scatterplot of values for the Multimetric AMBI for the same stations in July 2012 vs. July 2013. Colored squares denote stations that fall into the same classification in both years.

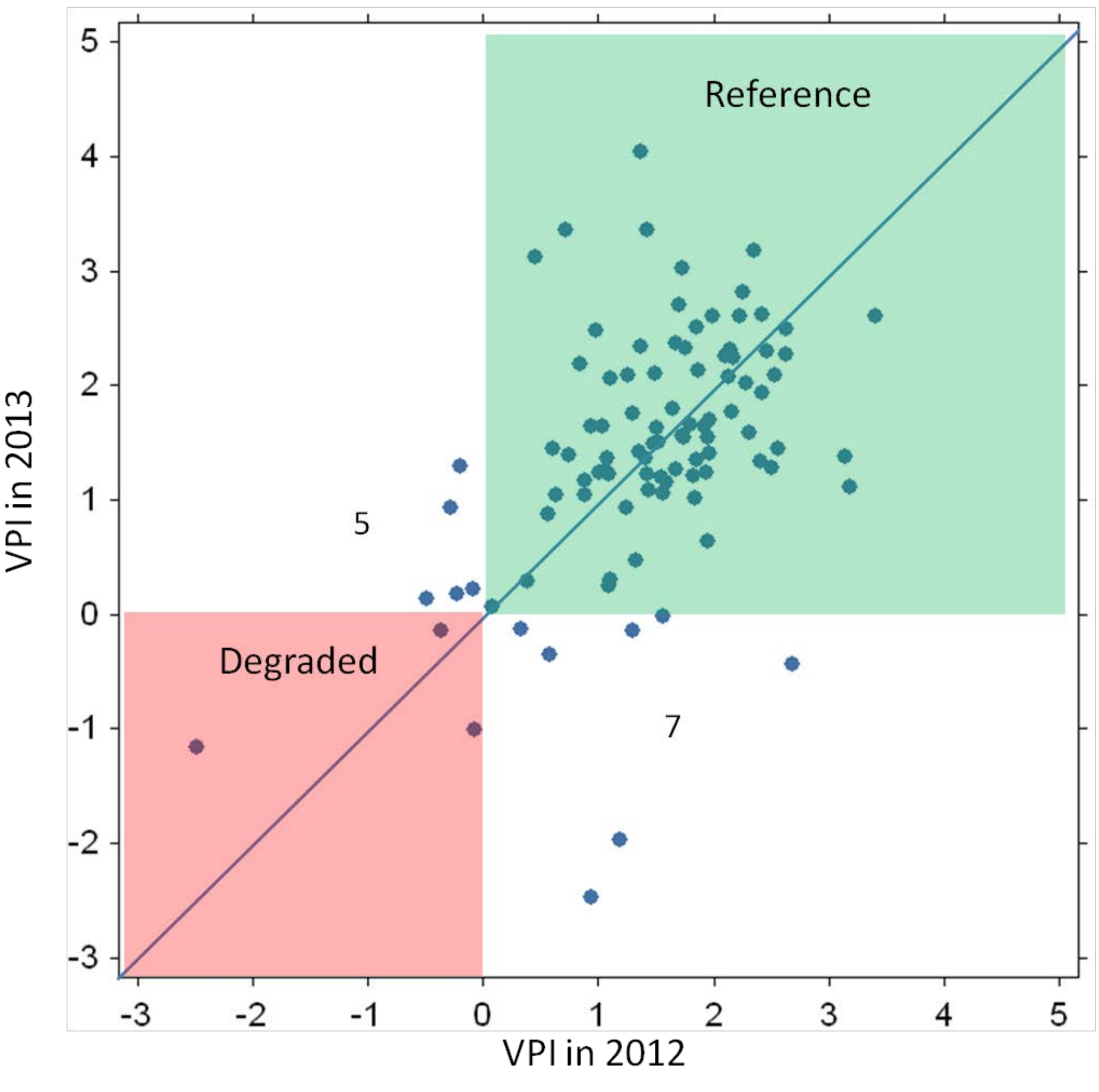
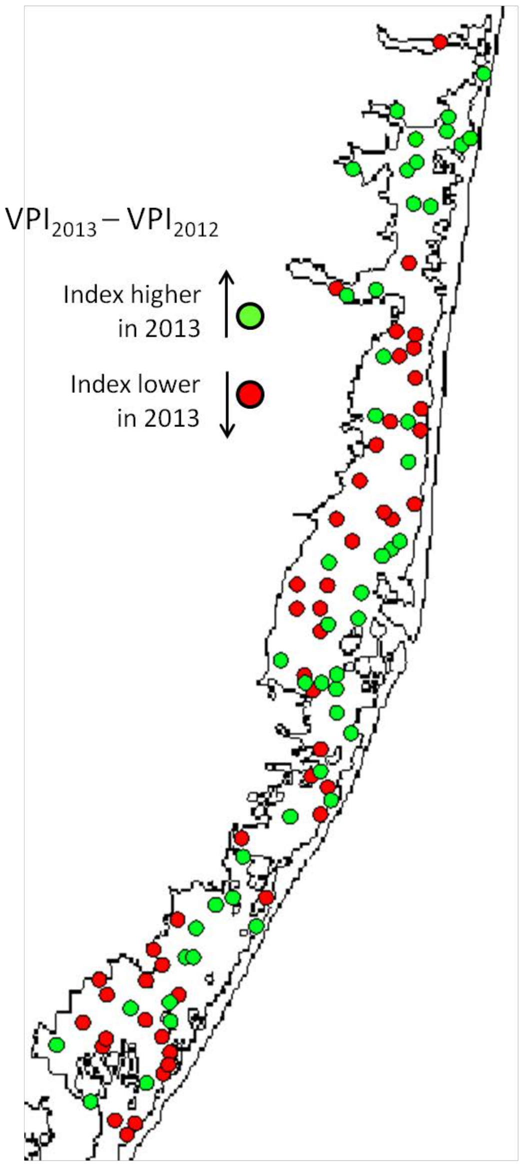
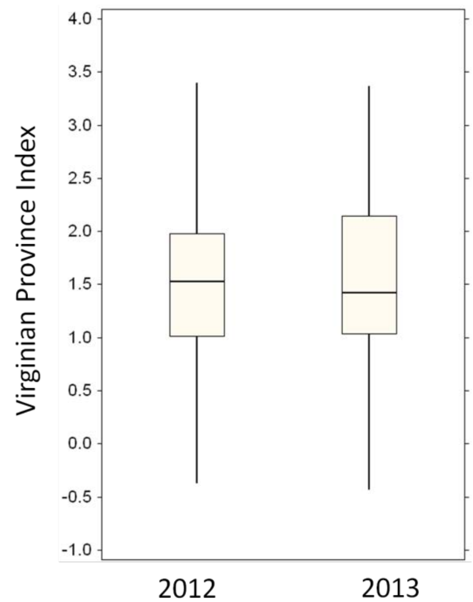


Figure 70. (Left) differences in the VPI between July 2013 and 2012. (Right) Box and whisker plots enclose the middle half of the data. The box is bisected by a line at the value for the median. The vertical lines at the top and the bottom of the box (the whiskers) indicate the range of “typical” data values.





Conclusions

All parameters measured at 100 locations throughout Barnegat Bay-Little Egg Harbor during the period July 1 through July 10, 2013 indicated that the benthic environment and macrofaunal communities were in good condition. For the most part, surface sediments had low concentrations of total organic carbon (the majority of stations <1%), total nitrogen (<0.1%), and total phosphorus (<0.06%). Exceptions were several stations in the northern section of the bay, especially sites near major sources of freshwater input, such as the Toms River. Although neither organic contaminants nor heavy metals were measured in this study, it would be surprising if there were elevated levels of these substances in the sediments given the generally low concentrations of organic carbon, except possibly in localized areas as noted above. Bottom water dissolved oxygen concentrations were above 5 mg/L at all sites during the sampling period, again except sor stations in the Toms River and several stations on the western side, central section of Barnegat Bay. Sediment TOC concentrations below 2% and bottom water dissolved oxygen concentrations above 5 mg/L are usually considered characteristics of reference, non-impacted habitats (Pelletier et al. 2012, Pelletier et al. 2010). Classification and ordination statistical techniques showed that the entire bay could be separated into seven clusters based on bottom water and sediment properties, although boundaries between the clusters were not sharp.

Benthic macroinvertebrates were abundant and diverse. Taxa typical of reference, non-impacted estuarine habitats in the Virginian Biogeographic Province dominated the fauna, again with a few exceptions as noted for sediment chemical properties. Salinity exerted a strong effect on the distribution and abundance of most taxa. Multivariate statistical analysis again revealed several clusters that appear to represent different communities that matched, in most cases, the environmental clusters.

Four multimetric or multivariate indices of habitat quality were evaluated using the benthic macroinvertebrate data. Two of these, the Virginian Province Index and the Benthic Index of Biotic Integrity, were developed specifically for coastal and estuarine habitats within the Virginian Biogeographic Province, in which Barnegat Bay is centrally located. A third, the Multivariate AZTI Marine Biotic Index was originally developed for coastal and estuarine benthic habitats in Europe but has been adapted to the Virginian Biogeographic Province. These three indices include both objective metrics, such as measures of species diversity and abundances of taxa, as well as more subjective metrics based on categorization of feeding behaviors or life history characteristics. A fourth index, the Benthic Quality Index, uses only objective metrics but has the explicit assumption that species diversity is inversely correlated with habitat quality. All of these indices characterized the substantial majority of the sites as not degraded, good, or high. On a site-by-site comparison, in the substantial majority of cases all indices agreed on the classification of the sites. Because each index emphasizes different metrics derived from the composition of benthic community, the agreement among indices can be taken as further evidence that the overall health of the Barnegat Bay-Little Egg Harbor benthic ecosystem was good in 2013.

We conducted extensive comparisons of the data collected in 2013 with the same variables measured at the same stations in 2012. In most cases there were only minor and statistically insignificant differences in sediment grain size and sediment carbon, nitrogen, and phosphorus concentrations. The same taxa dominated the benthos, although there were some shifts in their ranking. Although there were differences in species diversity and the indices of habitat quality on a station-by-station basis, taken as a whole throughout the bay these differences cancelled each other. We conclude that, from the perspective of physical, chemical, and biological properties, Barnegat Bay-Little Egg Harbor showed only minor differences between 2012 and 2013 and no effects that might be attributed to Hurricane Sandy were evident.

References

Benyi SJ, Hollister JW, Kiddon JA, Walker HA. 2009. A process for comparing and interpreting differences in two benthic indices in New York Harbor. Marine Pollution Bulletin 59:65-71.
Borja A, Dauer DM, Díaz R, Llansó RJ, Muxika I, Rodríguez JG, Schaffner L. 2008. Assessing estuarine benthic quality conditions in Chesapeake Bay: A comparison of three indices. Ecological Indicators 8:395-403.
Borja A, Franco J, Pérez V. 2000. A marine biotic index to establish the ecological quality of soft-bottom benthos within European estuarine and coastal environments. Marine Pollution Bulletin 40:1100-1114.
Borja A, Mader J, Muxika I. 2012. Instructions for the use of the AMBI index software (Version 5.0). Revista de Investigación Marina, AZTI-Tecnalia 19:71-82.
Clarke KR, Gorley RN. 2006. PRIMER v6: User manual/tutorial. Plymouth: PRIMER-E.
Cleveland WS. 1979. Robust locally weighted regression and smoothing scatterplots. Journal of the American Statistical Association 74:829-836.
Diaz RJ, Solan M, Valente RM. 2004. A review of approaches for classifying benthic habitats and evaluating habitat quality. Journal of Environmental Management 73:165-181.
Field JG, Clarke KR, Warwick RM. 1982. A practical strategy for analysing multispecies distribution patterns. Marine Ecology Progress Series 8:37-52.
Gallagher ED, Grassle JF. 1997. Virginian Province macroinfaunal community structure: PCA-H analyses and an assessment of pollution degradation indices. Final Report to Environmental Protection Agency, Atlantic Ecology Division, Narragansett, Rhode Island. Report no.
Gill AE. 1982. Atmosphere-Ocean Dynamics. Academic Press.
Hurlbert SH. 1971. The nonconcept of species diversity: a critique and alternative parameters. Ecology 52:577-586.
Leonardsson K, Blomqvist M, Rosenberg R. 2009. Theoretical and practical aspects on benthic quality assessment according to the EU-Water Framework Directive – Examples from Swedish waters. Marine Pollution Bulletin 58:1286-1296.
Llansó RJ. 2002. Methods for calculating the Chesapeake Bay benthic index of biotic integrity. Report no.
Muxika I, Borja Á, Bald J. 2007. Using historical data, expert judgement and multivariate analysis in assessing reference conditions and benthic ecological status, according to the European Water Framework Directive. Marine Pollution Bulletin 55:16-29.
Paul JF, Scott KJ, Campbell DE, Gentile JH, Strobel CS, Valente RM, Weisberg SB, Holland AF, Ranasinghe JA. 2001. Developing and applying a benthic index of estuarine condition for the Virginian Biogeographic Province. Ecological Indicators 1:83-99.
Pelletier MC, Gold AJ, Gonzalez L, Oviatt C. 2012. Application of multiple index development approaches to benthic invertebrate data from the Virginian Biogeographic Province, USA. Ecological Indicators 23:176-188.
Pelletier MC, Gold AJ, Heltshe JF, Buffum HW. 2010. A method to identify estuarine macroinvertebrate pollution indicator species in the Virginian Biogeographic Province. Ecological Indicators 10:1037-1048.
Poppe LJ, Eliason AH, Hastings ME. 2004. A Visual Basic program to generate sediment grain-size statistics and to extrapolate particle distributions. Computers & Geosciences 30:791-795.
Rosenberg R, Blomqvist M, C Nilsson H, Cederwall H, Dimming A. 2004. Marine quality assessment by use of benthic species-abundance distributions: a proposed new protocol within the European Union Water Framework Directive. Marine Pollution Bulletin 49:728-739.

US EPA. 1992. Methods for the Determination of Chemical Substances in Marine and Estuarine Environmental Sample. United States Environmental Protection Agency, Office of Research and Development, Washington DC. EPA/600/R-92/121. Report no.
---. 1995. Environmental Monitoring and Assessment Program (EMAP): Laboratory Methods Manual - Estuaries, Volume 1: Biological and Physical Analyses. United States Environmental Protection Agency, Office of Research and Development, Narragansett, RI. EPA/620/R-95/008. Report no.
---. 2001. National Coastal Assessment: Field Operations Manual. United States Environmental Protection Agency, Office of Research and Development, National Health and Environmental Effects Research Laboratory, Gulf Ecology Division, Gulf Breeze, FL. EPA 620/R-01/003. Report no.
---. 2010. Sampling and Analytical Procedures for GLNPO's Open Lake Water Quality Survey of the Great Lakes. United States Environmental Protection Agency, Great Lakes National Program Office, Chicago, IL. EPA 905-R-05-001. Report no.
Weisberg SB, Ranasinghe JA, Schaffner LC, Diaz RJ, Dauer DM, Frithsen JB. 1997. An estuarine benthic index of biotic integrity (B-IBI) for Chesapeake Bay. Estuaries 20:149-158.