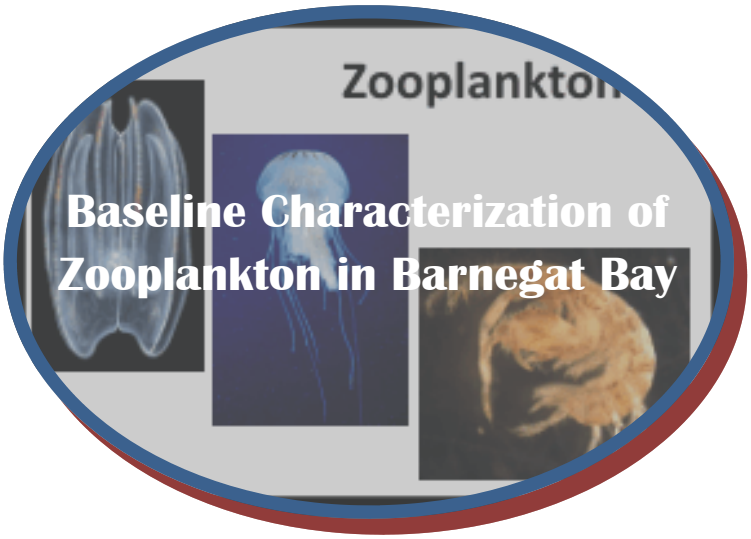
Barnegat Bay—Year 3



James Nickels and Ursula Howson, Monmouth University, Principal Investigators

Thomas Noji and Jennifer Samson, NOAA Fisheries, Co-Investigators

Project Manager:
Bob Hazen, Division of Science, Research and Environmental Health

Thomas Belton, Barnegat Bay Research Coordinator

Dr. Gary Buchanan, Director—Division of Science, Research & Environmental Health

Bob Martin, Commissioner, NJDEP

Chris Christie, Governor

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BASELINE SURVEY OF ZOOPLANKTON OF BARNEGAT BAY

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Monmouth University
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Final Project Report
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Principal Investigators
James Nickels and Ursula Howson
Monmouth University

Prepared by Ursula Howson

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1.0 EXECUTIVE SUMMARY

The goal of this three year project was to gather information on the status of zooplankton populations in Barnegat Bay and to determine the distribution, abundance, and species composition of important plankters. This project was a cooperative venture between Monmouth University and the NOAA James J. Howard Marine Sciences Laboratory at Sandy Hook, NJ (SHL) in the first two years of the project, and then conducted solely by Monmouth University during the third year.

Zooplankton, along with phytoplankton, form the base of the food web in estuarine ecosystems. Zooplankton species include those that remain their entire lives in the plankton and act as important food resources for larger invertebrates and fishes, as well as the larvae of commercially and recreationally important fishery stocks. Populations are subject to seasonal and annual changes due to natural and anthropogenic induced variations in environmental conditions. That is, biological conditions such as predation and competition, physical conditions such as salinity and depth and environmental degradation in estuaries such as nutrient pollution and the presence of oil and toxic chemicals can exert control over the composition, abundance, and distribution of the zooplankton. As a result zooplankters must adapt to varying stressors associated with changing conditions. According to the Barnegat Bay National Estuary Program's (BBNEP) Characterization Report, this back-bay ecosystem has been affected by an array of human impacts that potentially threaten its ecological integrity including nutrient enrichment, algal blooms, alterations of freshwater inputs, and extensive development around the bay and its watershed (BBNEP 2001, 2005).

Assessing current zooplankton populations in Barnegat Bay will provide updated information on the status of this important component of the bay's living resources which could then serve as an indicator for trends analysis.

Zooplankton samples were collected from the upper meter of the water column with horizontal surface net tows using bongo plankton nets. Samples were conducted monthly during the winter, and twice a month during spring, summer, and fall. Sites were located along a longitudinal transect in the bay, and corresponded with NJDEP water quality testing sites. Data were collected on the zooplankton community in the bay, including ichthyoplankton, gelatinous macrozooplankton, and important groups such as copepods, decapods, and bivalves. Results and recommendations for future work are presented in this report.

The zooplankton community in Barnegat Bay is characterized by strong spatial, seasonal and interannual trends in abundance and diversity. Spatial variability is most apparent between the northern and southern sections of the bay, with a characteristic suite of taxa and water quality parameters associated with each area. The northern bay (BB02, BB05a) was characterized by higher nitrogen and chlorophyll a, high abundances of copepods, ctenophores, and barnacle larvae, and the lowest species diversity of zooplankton and ichthyoplankton in the bay. Lower

water quality in the northern bay is likely due to increased urbanization coupled with poor flushing/water turnover in the upper bay. This has led to an increase in a few dominant species at the expense of species diversity in the northern bay. Alkalinity and phosphorus were higher in the southern bay (BB07a, BB10, BB12), as was species diversity of both zooplankton and ichthyoplankton. This was a typical pattern for the study, and remained stable even between seasons.

It is apparent that direct and/or indirect effects of weather patterns affect zooplankton abundance in Barnegat Bay. Density-indendent factors (e.g. temperature) strongly contribute to interannual variability in biological systems. This effect may serve to render the zooplankton community (and thus the food web) highly vulnerable to secondary, sublethal factors, resulting in potentially catastrophic conditions, e.g. a zooplankton community with low abundance or diversity as a result of several extreme winters is then subjected to a sublethal anthropogenic factor such as a pollutant. Additionally, such sensitivity to changes in weather patterns has the potential to cause long-term shifts in the zooplankton community as a result of climate change.

2.0 INTRODUCTION/PROBLEM STATEMENT

Plankton are comprised of plant-like organisms (phytoplankton) and animals (zooplankton) that live floating or suspended in marine and estuarine waters. Plankton range in size from very small microbes less than 0.05 mm to jellyfish and other gelatinous species that can exceed 1 m in diameter and have tentacles extending over 10 m (Kingsford and Battershill 2000). Phytoplankton include microscopic unicellular, colonial, or filamentous forms of algae, and as primary producers, are at the base of the food web in marine and estuarine ecosystems. Zooplankton include both unicellular and multicellular animals; many species are herbivorous and consume phytoplankton, while others consume smaller zooplankton. Zooplankton are typically categorized by life style and size. Zooplankton that spend their entire lives as plankton are known as holoplankton. Others, such as the larval stages of many benthic invertebrates, only spend part of their lives as plankton. These species are known as meroplankton (Johnson and Allen 2005, Kingsford and Battershill 2000).

In terms of classifying zooplankton by size, three categories are generally described – microzooplankton, mesozooplankton, and macrozooplankton. Microzooplankton are organisms that are classified as approximately 20 to 202 μm in length, being at the smaller end of the size spectrum for zooplankton. The predominant microzooplankton include ciliate, flagellate, and amoeboid protozoa which float passively in the water column due to their limited abilities to move. Difficulty in sampling and analyzing microzooplankton precluded this size group from the current study. This affects our understanding of the complete food chain and ecological processing of nutrients into biomass, but was unavoidable. Zooplankton in the 0.2 to 2.0 mm size range dominate the group known as mesozooplankton. Copepods are typically the most commonly encountered mesozooplankton. Other common mesozooplankton include rotifers,

larval barnacles, crab zoeae, and mollusk veligers. The largest zooplankton are classified as macrozooplankton. Macrozooplankton include shrimps, larval fishes, and other large, mobile planktonic animals as well as ctenophores and jellyfish (Johnson and Allen 2005).

As the main herbivorous component of marine ecosystems, zooplankton play an important role in estuarine food webs. Macrozooplankton are particularly important because they are intermediaries in estuarine food chains, forming a link between smaller zooplankton and higher trophic levels, including many commercially and recreationally valuable fishes (Gewant and Bollens 2005). However, despite their importance in filling this niche, little is known about the distribution, abundance, and ecology of macrozooplankton in many coastal regions (Wilson et al. 2003).

This is the case in the Barnegat Bay ecosystem. As noted by Kennish (2001), there has not been a detailed survey of zooplankton in the Barnegat Bay estuary since the 1970s. Furthermore, the most detailed of those studies (Tatham et al. 1977, 1978) were conducted for ecological assessments of Oyster Creek Nuclear Generating Station, so were focused on the central bay from Cedar Creek (Lanoka Harbor) south to Double Creek (Barnegat). Information from these studies in the 1970s, as summarized by Sandine (1984) and Kennish (2001), were examined in comparison to the current study. Methods differed somewhat from the present study, with 80 µ and 500 µ mesh nets being employed, and without fractioning of the 500 micron sample. Although direct comparisons with the current study are not appropriate, trends from that study indicate that, in general, macrozooplankton abundance peaks in the spring and summer months in response to phytoplankton food supply. In terms of species composition, common macrozooplankton found in the bay in the 1970s include hydromedusae (*Rathkea octopunctata*), shrimps (*Neomysis americana*, *Crangon septemspinosa*), larval crabs (*Neopanope texana*, *Panopeus herbstii*, *Rhithropanopeus harrisii*), amphipods (*Jassa falcata*), arrowworms (*Sagitta* spp.) and hydroids (*Sarsia* spp.). Ctenophores (*Mnemiopsis leidyi* and *Beroe* sp.) are also sometimes common, especially from summer to fall.

Typically, in Mid-Atlantic and northeastern estuaries, short but intense blooms of ctenophores, primarily *Mnemiopsis leidyi*, occur in late summer and early fall (Kremer 1994); however, several recent studies have documented an expansion in ctenophore abundance and seasonal distribution to include spring and early summer blooms. This shift appears to be related to increasing average water temperatures (Sullivan et al. 2001, McNamara et al. 2010). If such a shift in the seasonal pattern and abundance of ctenophores is occurring in Barnegat Bay, it could have an impact on the abundance of other planktonic assemblages, as ctenophores are voracious predators on a variety of zooplankton, including bivalve veligers, copepods, and nauplii (Sullivan et al. 2001, McNamara et al. 2010).

Sea nettles (*Chrysaora quinquecirrha*) are becoming more abundant in mid-Atlantic estuaries including Barnegat Bay, reaching peak numbers in mid- to late summer. This phenomenon has apparently resulted from warmer summer water temperatures and increased eutrophication,

although increase in anthropogenic habitat, e.g. hard untreated surfaces on bulkheads and docks, may play an equally important role in their recent proliferation (Bologna et al., 2015). Due to their severe sting, sea nettles are a nuisance and pose a hazard to recreational users of the bay. In Barnegat Bay, high summer concentrations of sea nettles have been observed north of the Toms River, which is included in the study area for this project, for several summers (BBNEP 2006). Although salinity and temperature requirements typically restrict them to the northern section of Barnegat Bay, documentation of the seasonal patterns of sea nettle distribution and abundance could also serve as an indicator of the overall health of the bay.

Updated information on ctenophore and sea nettle distribution and abundance may also assist scientists attempting to understand fishery declines in the bay since sea nettles, as well as some species of ctenophores such as *Mnemiopsis leidyi*, are known to prey on fish eggs and larval fishes (Purcell undated, Mianzan et al. 2009).

3.0 PROJECT DESIGN AND METHODS

One sample tow set was collected at each of three sites, BB02, BB05a, and BB12, from May 2012 to September 2012. Two sites, BB07a and BB10, were then added, so that all subsequent regular sampling events through April 2015 were conducted at the five sites, 2, 5a, 7a, 10, and 12 (Figure 1). A sample tow was defined as a replicate pair of 500 µm and a replicate pair of 202 µm plankton samples collected at a site, accompanied by the abiotic parameters water temperature, salinity, conductivity, dissolved oxygen (DO) mg/l, DO % saturation (% sat), pH, Secchi depth, and water depth. A sampling event was the collection of sample tows at all sites, typically over a one- or two-day period. Sampling events occurred twice monthly during March – September, and once monthly during October – January. Samples were not collected during February 2014 nor February 2015 due to weather and vessel mechanical issues. Four 24 hr sampling events were conducted at BB05a over the three-year project, in July 2012, October 2012, October 2013, and April 2014.

Table 1. Barnegat Bay site locations and coordinates.

Name	Latitude	Longitude	Location
BB02	39 58.6572 N	074 5.9082 W	Barnegat Bay between Silver Bay and Goose Creek
BB05a	39 54.946584 N	074 6.565422 W	Barnegat Bay below Good Luck Point
BB07a	39 48.077166 N	074 9.427031 W	Barnegat Bay below Oyster Creek and above Barnegat Inlet
BB10	39 39.657 N	074 12.3918 W	Barnegat Bay by Route 72 Bridge
BB12	39 34.8906 N	074 16.125 W	Barnegat Bay in Little Egg Harbor

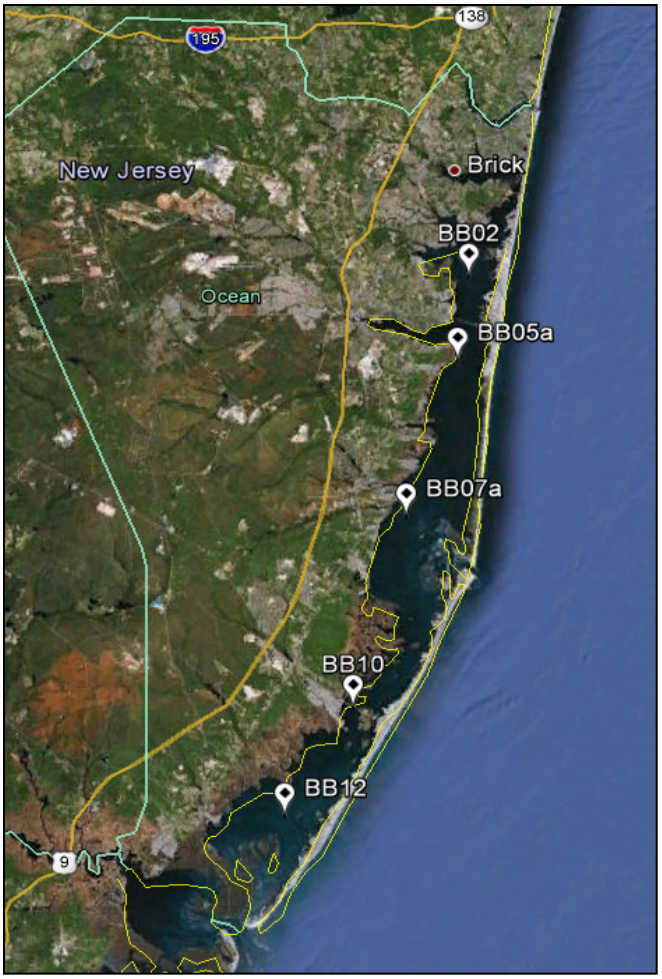


Figure 1. Barnegat Bay sampling site locations, BB02, BB05a, BB07a, BB10, and BB12. BB07a and BB12 were added in September 2012.

Zooplankton were collected from the upper meter of the water column with horizontal surface net tows using bongo plankton nets, with one 500 µ and one 202 µ paired sample. Nets were rigged with a flow meter to determine the volume of flow in order to calculate catch per unit effort (CPUE). Abiotic parameters were collected using a YSI meter and Secchi disc. Gelatinous macrozooplankton disintegrate when stored in a fixative, so they were processed fresh in the laboratory. Ichthyoplankton were removed before the zooplankton sample was preserved, and stored in 95% ethanol. Ichthyoplankton were retained at Monmouth University, and were identified with the assistance of the ichthyoplankton laboratory at Rutgers University Marine Field Station, Tuckerton, NJ. The remaining zooplankton were preserved in 5% formalin. The 202 µ samples were separated in the laboratory with a 500 µ and a 202 µ sieve to produce a 200 – 500 µ fraction. This was designated the "200 µ" sample. One each of a 500 µ and 200 µ sample for each site at each sampling event was selected randomly for transport to a sorting laboratory, Morski Instytut Rybacki - Państwowy Instytut Badawczyi (MIR), Zakład Sortowania i Oznaczania Planktonu (ZSIOP) in Poland. This laboratory has sorted plankton as a NOAA contractor for almost 40 years.

Data collected on the ctenophores *Mnemiopsis leidyi* and *Beroe ovata* included total volume per tow, total count per tow, and lengths of 20 haphazardly selected individuals from each sample. Catch per unit effort (CPUE) was calculated by incorporating volume of flow collected from the flow meters attached to the plankton nets. Length of the bell was measured longitudinally from apex to the top of the lobes; length was not measured to the bottom of the lobes as the lobes may break off during collection and handling. Data collected on sea nettle *Chrysaora quinquecirrha* included total volume per tow, total count per tow, and bell width.

4.0 QUALITY ASSURANCE

A Quality Assurance Project Plan was developed and approved by NJDEP for this study including lab certification of YSI meter and key field equipment along with field audits. Sub-samples totaling 10% of the total number of processed biotic samples were randomly selected (using a random number generator), single-blinded, then sent to ZSIOP for reprocessing as QA/QC samples (Appendix 1).

5.0 RESULTS

A total of 17 regular sampling events were conducted during June 2014 - April 2015, with 158 samples collected and sent to ZSIOP for processing. For the entire three year study, 54 regular sampling events were conducted during May 2012 – April 2015, with 501 samples collected and sent for processing. To look at possible diurnal (across the day) variation in spring, summer and fall, four intensive 24 hr. sampling events were conducted at Site 5a in July 2012, October 2012, October 2013, and April 2014. Samples were collected every six hours for the July 2012 event,

then every four hours for the three subsequent events. Abiotic data were collected during all regular and intensive sampling events. Mesozooplankton were collected during all regular and intensive sampling events and were subsequently processed for shipment to ZSIOP. Targeted gelatinous macrozooplankton were collected at all regular events and all intensive sampling events except July 2012, and processed at Monmouth University.

Data from the first two years of the study, May 2012 – May 2014, were already presented and discussed in those studies' final reports. However, those data are included in all figures in the current report so interannual trends may be better visualized.

5.1 Water Quality Data

Water temperature during the June 2014 – April 2015 study period followed trends expected with seasonal changes. Water temperature trends were similar across all five stations (Fig 2a), although it was slightly cooler in the summer of 2014 than in previous summers. The winters of 2013-2014 and 2014-2015 were abnormally cold in New Jersey; this was reflected in the low water temperatures observed in December 2013 - January 2014 and again in December 2014 - January 2015. In fact, sampling could not be conducted in February and most of March because Barnegat Bay was partially or fully frozen over. Salinity remained higher at BB7a, 10, and 12 throughout the sampling period, although there was a slight increase at Site 5a in March 2015, probably related to tidal flow. Salinity is lower in the northern bay (Sites 2 and 5a) due to riverine input (Fig 2b). Dissolved oxygen (DO) levels were greatest in winter 2014-2015, but were also comparably high in the two previous winters of the study (Fig 2c). It is likely that the high DO levels are due to the decrease in temperature, as cold water holds more oxygen than warm water. However, a decrease in DO seen in December 2012 is not repeated in December 2013. Secchi transparency (water clarity) is inversely related to turbidity, which is often due to particulates in the water column. Wind may mix particulate organic matter (POM) in the water column, or biological factors such as phytoplankton or zooplankton blooms may increase turbidity. Water clarity was variable over much of this study period, but was high in October 2014 at Site 10 (Fig 2d).

Abiotic parameters were sampled during all 24 hr intensive sampling events. Temperature changed only slightly over each 24 hr period (Fig 3a). As expected, temperature was highest during the July sampling event. The water was considerably warmer (+6-7°C) in October 2012 than in October 2013, even though the latter sampling event was only two weeks later in the year. All intensive sampling events except for October 2013 exhibited a change in salinity indicative of tidal flow (Fig 3b). Unexpectedly, DO was lowest in October 2012, not when water was warmest in July. Low DO during this period is likely due to the intense zooplankton bloom that occurred at this time (see Section 5.2 Zooplankton).

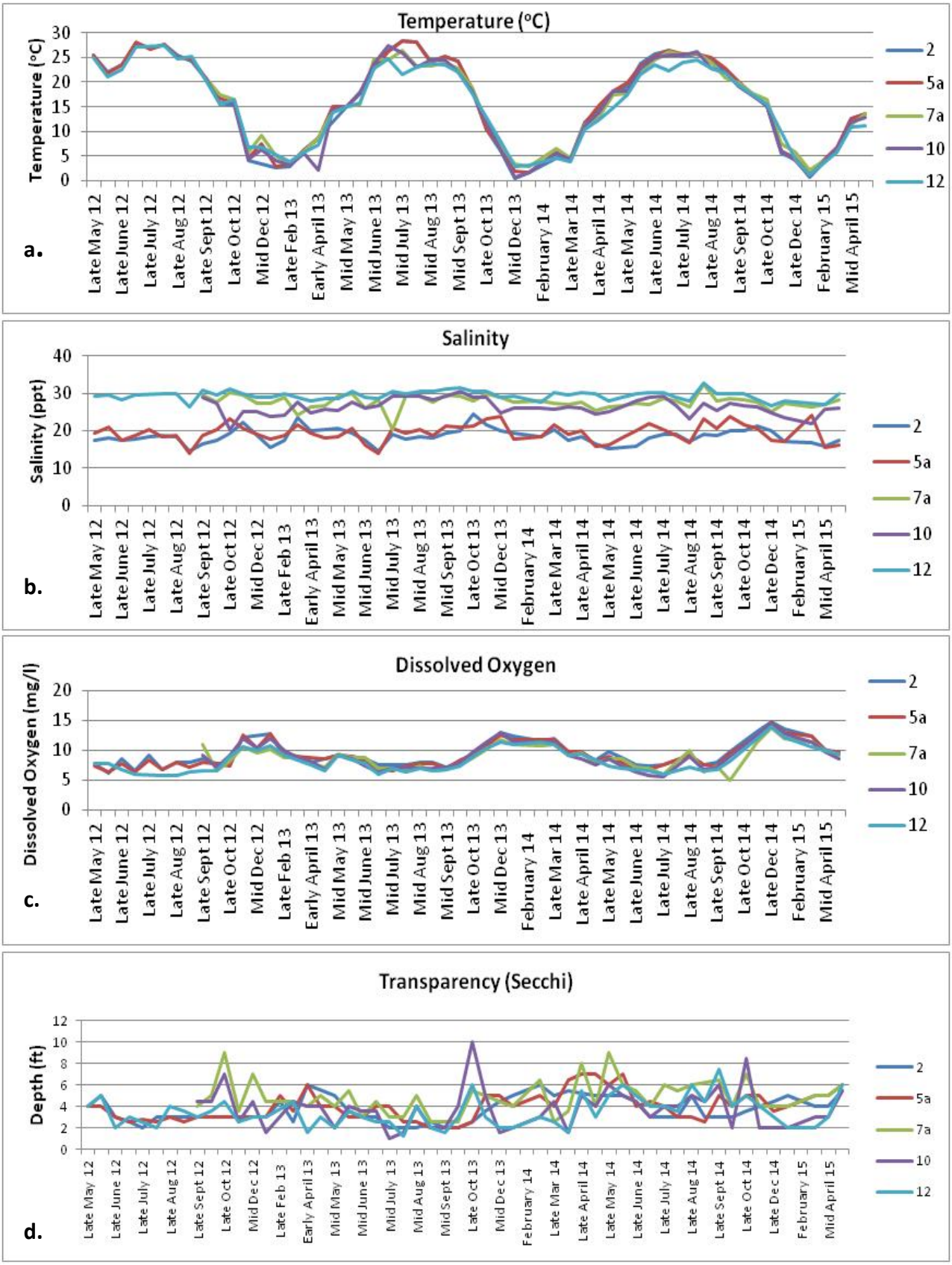


Figure 2. Abiotic data collected at Sites BB2, BB5a, BB7a, BB10, and BB12 in May 2012 – April 2015. **a**) temperature (°C); **b**) salinity (ppt); **c**) dissolved oxygen (mg/l); **d**) Secchi transparency (ft). Sites 7a and 10 were added in late September 2012.

Normalized abiotic data for the entire study were plotted with principal components analysis (PCA) (Fig 3). Parameters included temperature, salinity, transparency (Secchi), DO % saturation, pH and water depth. Trends in the data varied with site and season. PC1 accounted for 28.5% of the variability, while for PC2 that value was 22.4%. The most important parameters in PC1 were salinity and water depth, with transparency somewhat less important. Variability in PC2 was due to temperature, pH, and DO % saturation. Factors most important in distinguishing among sites (Fig 3a) included salinity, transparency, and water depth. Sites 7a, 10, and 12 are characterized by higher salinity, greater water depth, and greater transparency; Site 7a is located close to Barnegat Inlet and is exposed to more oceanic water, while Sites 10 and 12 are near the southern end of the bay and closer to oceanic influence from Little Egg Harbor. Sites 2 and 5a, in the northern bay, are characterized by lower salinity due to riverine input, as well as shallower, more turbid water. Seasonal trends are not as obvious as those for location. Summer and winter regimes are more defined than those for spring and fall. Temperature is the most obvious parameter driving the differences in water characteristics, and DO % saturation, as expected, is negatively correlated with temperature. However, pH is also negatively correlated with temperature.

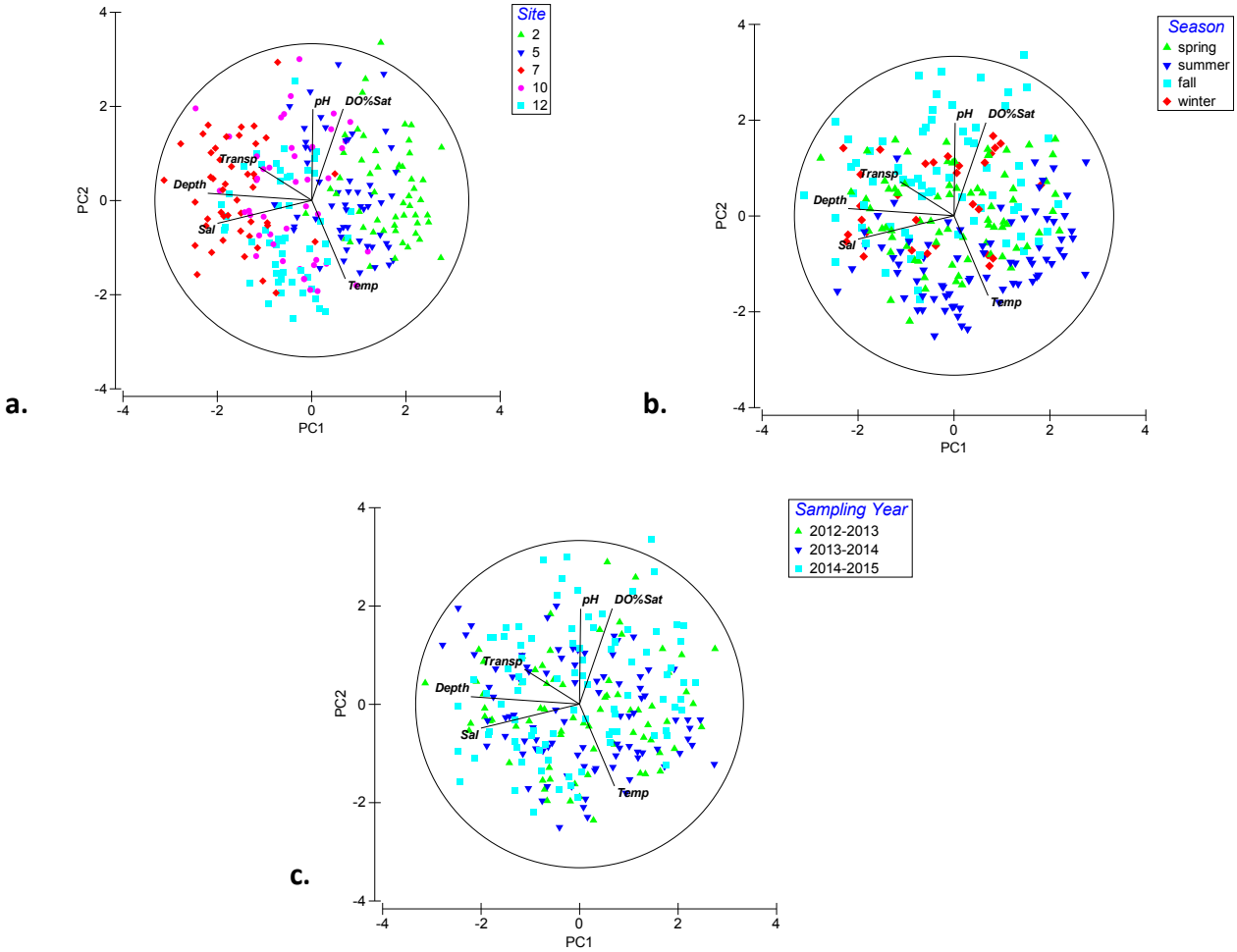


Figure 3. PCA of abiotic water quality data by **a**) site, **b**) season and **c**) sampling year. Abiotic data were collected for all sampling events. PC 1 = 28.5%, PC2 = 22.4%.

Nutrient data sets were taken from the NJDEP water quality database. Data for approximately 20% of the current study's sampling events were not available, most notably from winters 2013-2014 and 2014-2015. For several sampling events, data for a specific site from the current study were not available, so data from a neighboring station were used instead. All available nutrient data were normalized and plotted onto a PCA (Fig 4). PCA for the nutrient water quality data described the variability in the data better than that for the abiotic water quality data. PC1 accounted for 41% of the variability in the data, with alkalinity, phosphorus, and total suspended solids the most important parameters. PC 2 accounted for 35% of the variability in the data; important factors included nitrogen and chlorophyll a. Alkalinity, and to some extent nitrogen and chlorophyll a, drove the separation of sampling sites, with southern sites exhibiting higher alkalinity, while northern sites had higher nitrogen and chlorophyll a (Fig 4). The nutrient regime in spring was markedly different from that of the other three seasons, and was characterized by low nitrogen and chlorophyll a (Fig. 4 b); although nitrogen may be closely coupled with productivity when blooms occur, it is surprising that chlorophyll a is low during this time period. This may be due to the delayed blooms seen in several of the sampling years, which often did not occur until late June.

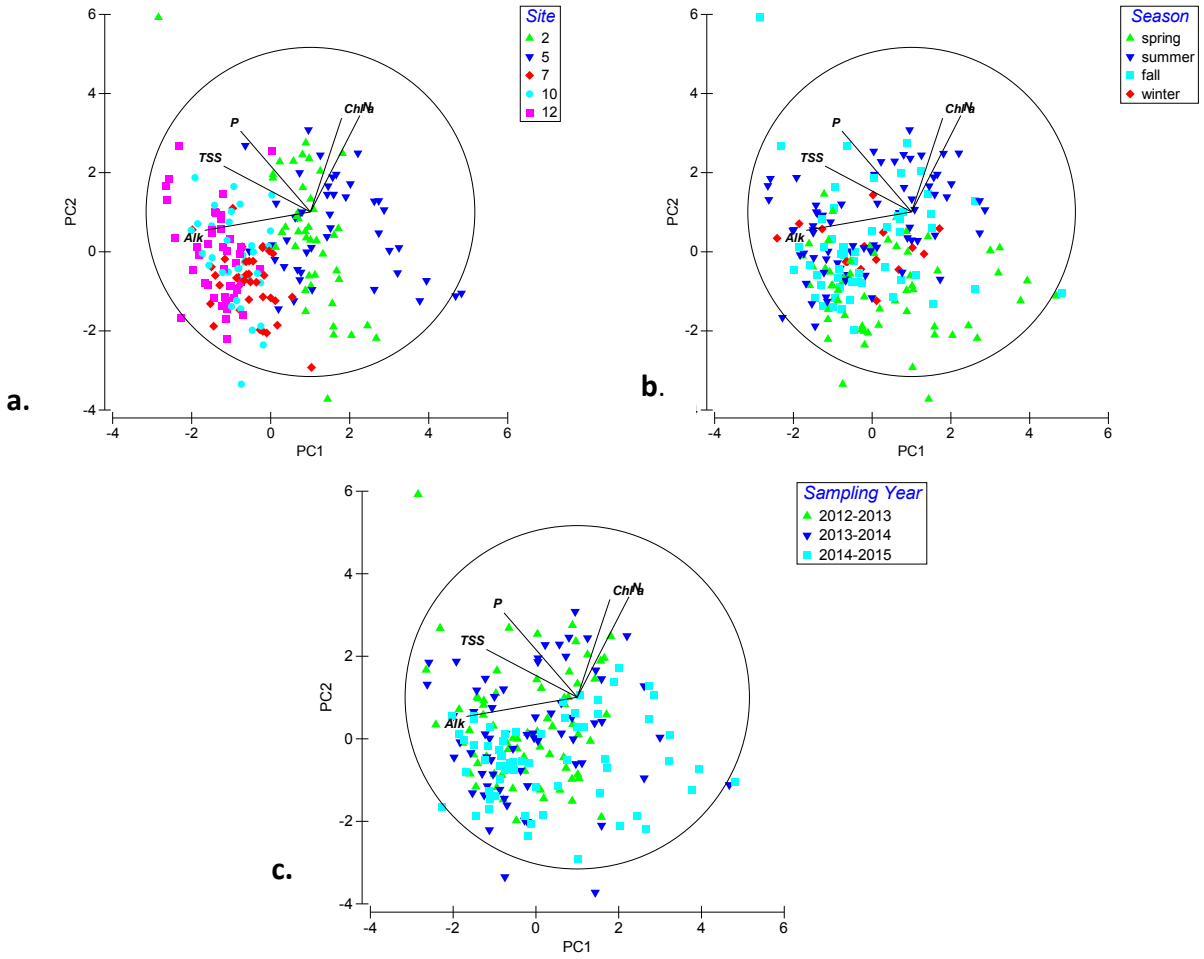


Figure 4 . PCA of nutrient water quality data by **a**) site, **b**) season, and **c**) sampling year. Nutrient data were collected for Alk = alkalinity, Chl a = chlorophyll a, N = total nitrogen, P = total phosphorus, TSS = total suspended solids. PC 1 = 41.0%, PC2 = 35.5%.

Abiotic and nutrient water quality data were normalized and combined into one PCA (Fig 5). However, resolution for the abiotic samples was decreased by 20% to match the data available for the nutrient parameters. Sampling site groups (Fig 5a) were separated along PC1, which accounted for 36.7% of the total variation, with alkalinity and salinity the primary parameters driving the differences seen between the northern bay (sites 2 and 5a) and more southern locations in the bay (sites 7a, 10, and 12). PC2 was responsible for 23.7% of the total variability in the water quality data, with phosphorus, nitrogen, and chlorophyll a highest in summer and fall (Fig 5b).

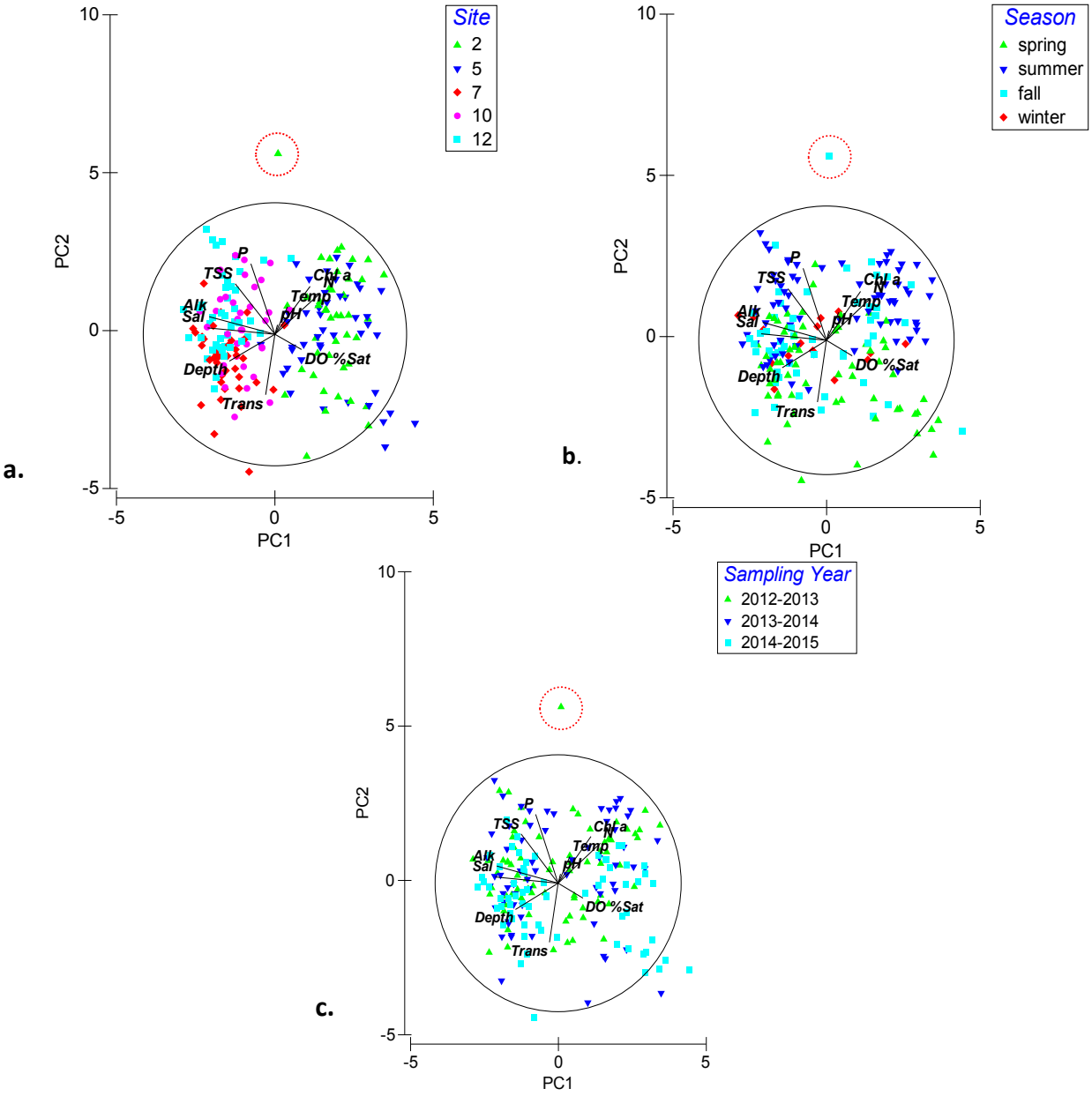


Figure 5. PCA of nutrient and abiotic water quality data by **a**) site, **b**) season, and **c**) sampling year. Alk = alkalinity, Chl a = chlorophyll a, N = total nitrogen, P = total phosphorus, TSS = total suspended solids, Temp = temperature, Sal = salinity, DO % Sat = dissolved oxygen % saturation, Trans = transparency. PC1 = 29.3%, PC2 = 21.2%. Red circle represents data collected at BB02 in November 2012 (one month after Superstorm Sandy).

5.2 Zooplankton

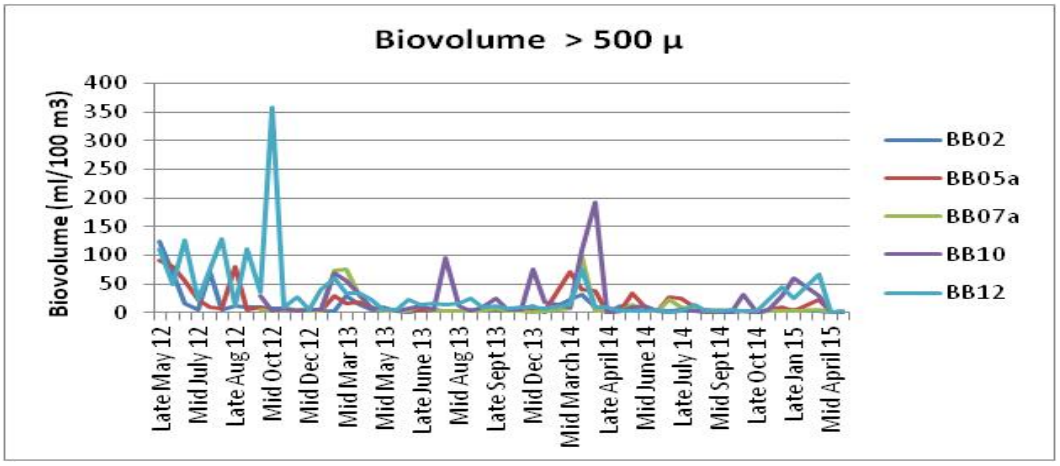
5.2.1. Zooplankton Biovolume

Biovolume is a measure of the overall content of a plankton sample and is useful as a proxy for secondary production (Hare 2015) and in discerning patterns of abundance. Biovolume in the > 500 µ size class, comprised of meso- and macrozooplankton, was variable throughout the sampling period, with the greatest values occurring in Fall 2012 after Superstorm Sandy, and in Spring 2014, associated with the spring bloom (Fig 6a). The greatest biovolume during the June 2014 - April 2015 period occurred in early spring 2015, for plankton in the > 500 µ size fraction. It appears that the spring bloom in this time period, which was a smaller bloom than the previous year, developed in January but declined by April. As the bay was partially or completely frozen over in February and much of March 2015, this may have impacted the strength and duration of the bloom. An alternative possibility may be that the bloom did occur under the ice, and as sampling did not occur, any increase in biovolume for that month would have gone undocumented. Abundance of smaller mesozooplankton in the 200 – 500 µ size fraction was highest in late Spring/early Summer 2012 and 2013, and peaked again in Spring 2014. However, biovolume in this size fraction remained relatively low in the Year 3 sampling period (Fig 6b).

Overall, the biovolume of the larger > 500 µ fraction was much greater than that of the 200 - 500 fraction, with a maximum volume of approximately 350 ml 100 m-3 (Fig 7a and b). Average biovolume per tow for the > 500 µ fraction was significantly greater at 17.9 ml 100 m^{-3}, while that of the 200 - 500 µ fraction was 7.8 ml 100 m^{-3} (t-test, $F = 18.114$, $p < 0.001$). There were significant differences in the amount of biovolume collected each sampling year for both the > 500 µ fraction (ANOVA, $F = 10.598$, $p < 0.001$) and the 200 - 500 µ fraction (ANOVA, $F = 9.561$, $p < 0.001$). Significantly more biovolume was collected for both fractions in Year 1 than in the subsequent years of the study (Tukey post-hoc tests). Although Years 2 and 3 were not significantly different from each other for either fraction, the difference was greater between Years 2 and 3 for the 200 - 500 µ fraction ($p = 0.051$) than for the > 500 µ fraction ($p = 0.418$).

NOAA has monitored the coastal and shelf plankton communities from the Mid-Atlantic Bight (MAB) to Georges Bank for several decades (Hare 2015). Biovolume in this region exhibits strong seasonality, with levels increasing from a winter low to a spring/summer high, then decreasing on the outer shelf in early fall but remaining high along the MAB coast until late fall. Values in coastal MAB range from < 12 ml 100 m-3 in winter to a late summer/early fall high of > 55 ml 100 m-3. Although trends in plankton abundance as determined by biovolume are not as defined in Barnegat Bay as they are in the MAB coastal region, biovolume (and thus secondary production) in the estuary is generally similar to or much higher than the coast (Fig 6 and 7).

a.



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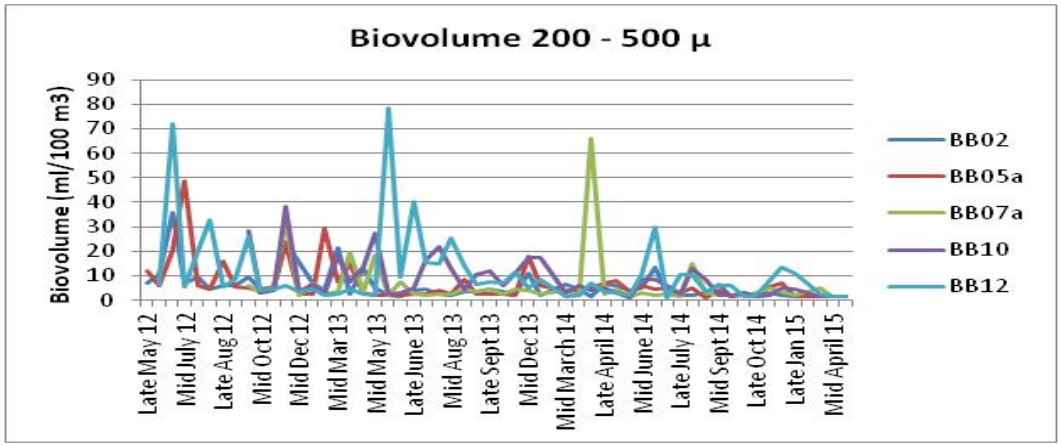
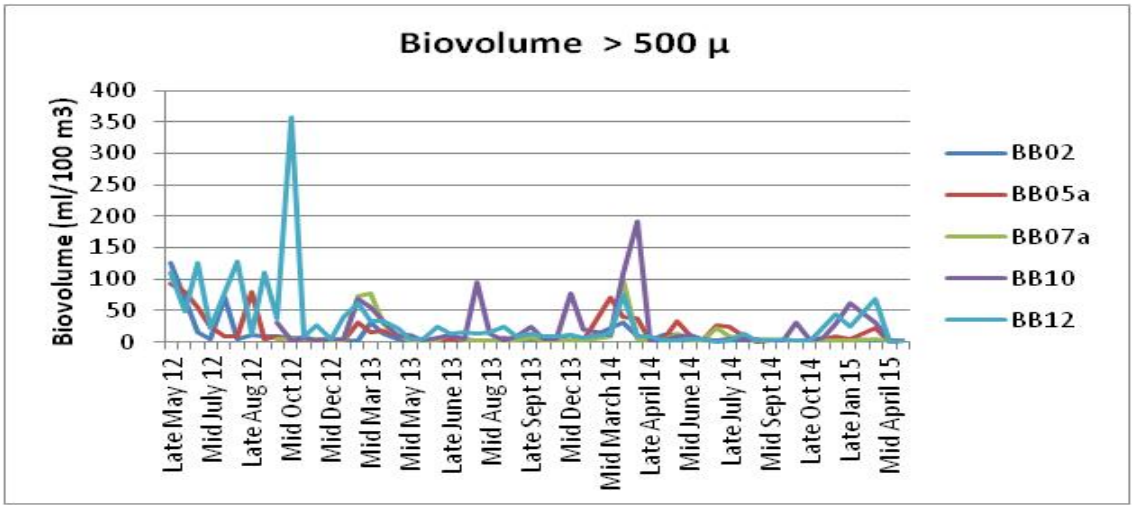


Figure 6. Biovolume collected in 500 µ and 202 µ nets at Sites BB2, BB5a, BB7a, BB10, and BB12 in May 2012 – May 2014. **a**) Samples from 500 µ net. **b**) Samples from 202 µ net, which were filtered to separate and process the 200 – 500 µ fraction. Note that the y-axis is *not* on the same scale for both figures.

a.



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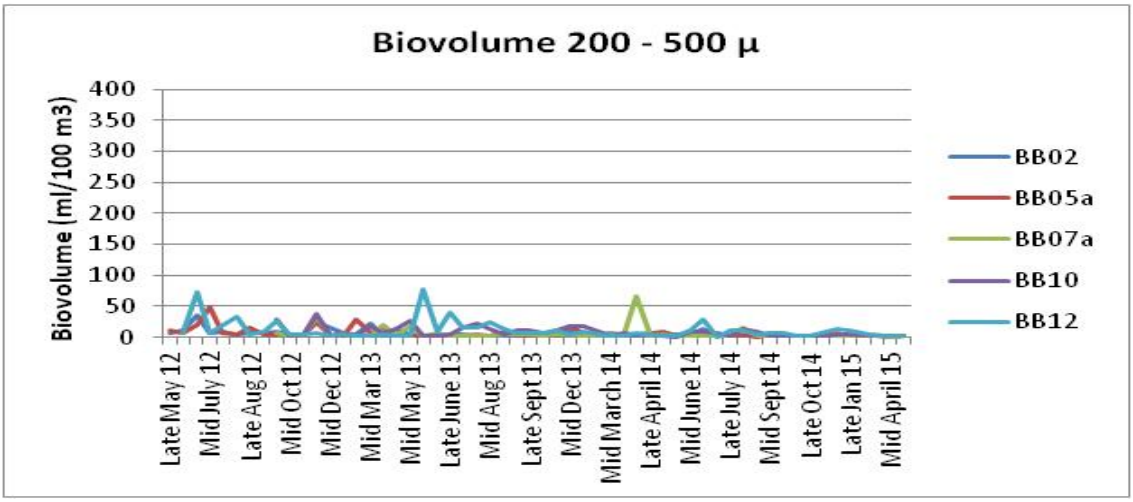


Figure 7. Biovolume collected in 500 µ and 202 µ nets at Sites BB2, BB5a, BB7a, BB10, and BB12 in May 2012 – April 2015. **a**) Samples from 500 µ net. **b**) Samples from 202 µ net, which were filtered to separate and process the 200 – 500 µ fraction. Note that the y-axis *is* on the same scale for both figures.

5.2.2. Zooplankton Community Dynamics

In general, interannual variability was observed in the intensity of spring and fall blooms as measured by biovolume. There also appeared to be spatial variability in the blooms, with no consistent pattern in the intensity or location of blooms. *Acartia* spp. was the most abundant taxon in the samples, with locally intense periodic blooms. Coastal copepod species were most often collected at Sites 7a, 10, and 12, which are exposed to more oceanic impact. However, to examine trends in the overall zooplankton community structure, a non-parametric multivariate approach was employed.

Zooplankton Community Metrics

Zooplankton community analyses were based on 54 routine sampling events conducted at five Barnegat Bay sites over three years. Samples were sorted into 200 - 500 μ and >500 μ size fractions and processed to the lowest possible taxonomic level. A total of 501 samples were analyzed. To be included in the analyses, taxa must have been present in ≥ 5% of all samples. Mean abundance data were calculated as number of individuals 100 m^{-3} of water. Fractions were analyzed combined and separately.

When zooplankton taxonomic data from all routine samples were totaled (combined fractions), a total of 34 taxa appeared in at least 5% of all samples (Table 2). Mean abundance of each taxon within each sample was then totaled to determine total mean abundance for each sample. For the combined fractions, the total mean abundance was 64,992 specimens. The copepod genus *Acartia* occurred in 91% of the samples, and comprised 56.7% of the total mean abundance. *Acartia* spp. and the copepod genus *Eurytemora* together made up 71.8% of the total mean abundance. The most commonly occurring non-copepod taxon was Balanidae (acorn barnacles), which appeared in 63% of the samples and comprised 3.8% of the total mean abundance.

When the > 500 μ fraction was analyzed separately from the 200 - 500 μ fraction, 31 taxa were present in the samples at or greater than a 5% frequency. In this case *Acartia* spp. was not the dominant taxon, probably because of size differences in the copepod groups. *Eurytemora* spp. made up 41.8% of the total, and when combined with two other copepod species, *Centropages hamatus* and *Temora longicornis*, these three comprised 81% of the total number of individuals in this collection (Table 3). Although *Acartia* spp. was not as abundant in this fraction, with a frequency of 85.7% it still appeared quite often. This is in contrast with the three most numerically abundant taxa in this group, which each appeared in less than 50% of the samples (*Eurytemora* spp. - 30.3%, *C. hamatus* - 45.8%, *T. longicornis* - 36.3%). This pattern reflects the seasonality of population growth of these three coastal taxa within the estuary, while it is apparent that the estuarine *Acartia* spp. is a commonly occurring resident in Barnegat Bay.

Although 27 taxa appeared in ≥ 5% of samples in the 200 - 500 μ fraction, *Acartia* spp. dominated the collection (Table 4). The copepod genus appeared in 97.2% of all routine samples of this fraction, and made up 65.3% of the total mean abundance of 72,464 individuals. *Acartia*

spp. and *Eurytemora* spp. together comprised 75.6% of the total mean abundance. Acorn barnacles (Balanidae) and snails (Gastropoda) also commonly occurred, with frequencies of 81.6% and 58% respectively.

Table 2: Zooplankton taxa collected in Barnegat Bay, NJ, May 2012 - April 2015. Fractions (>500 μ, 200 - 500 μ) were combined.

Taxon	Total Mean Abundance (# indiv 100 m-3)	% of Total	Cumulative %	Frequency (% occurrence in samples)
Acartia spp.	36550	56.7	56.7	91.4
Eurytemora spp.	9747	15.1	71.8	33.3
Centropages hamatus	2447	3.8	75.6	37.1
Balanidae	2433	3.8	79.4	63.1
Temora longicornis	2390	3.7	83.1	31.9
Gastropoda	2295	3.6	86.6	46.3
Centropages spp	1706	2.6	89.3	25.7
Calanoida	1309	2.0	91.3	60.5
Podon spp.	1062	1.6	92.9	12.4
Oithona spp.	957	1.5	94.4	36.5
Polychaeta	891	1.4	95.8	33.7
Coelenterata	614	< 1	96.8	44.3
Brachyura	445	< 1	97.4	31.7
Evadne spp.	437	< 1	98.1	24.4
Harpacticoida	334	< 1	98.6	48.9
Centropages typicus	255	< 1	99.0	27.1
Copepoda	223	< 1	99.4	24.2
Bivalvia	212	< 1	99.7	22.8
Decapoda	202	< 1	99.9	31.5
Paracalanus spp.	163	< 1	99.9	9.4
Temora spp.	85	< 1	99.9	7.2
Cyclopoida	40	< 1	99.9	16.8
Caridea	35	< 1	99.9	19.8
Isopoda	27	< 1	99.9	17.4
Pseudocalanus minutus	24	< 1	99.9	8.8
Tortanus discaudatus	24	< 1	99.9	10.6
Calanus finmarchicus	21	< 1	99.9	8.4
Foraminifera	18	< 1	99.9	7.2
Ostracoda	9	< 1	99.9	8.2
Gammaridea	8	< 1	99.9	14.6
Mysida	8	< 1	99.9	12.0
Pontellidae	8	< 1	99.9	11.8
Chaetognatha	7	< 1	99.9	5.8
Amphipoda	6	< 1	100.0	13.2
Total	64992			

Table 3: Zooplankton taxa collected in Barnegat Bay, NJ, May 2012 - April 2015. >500 µ fraction.

Taxon	Total Mean Abundance (# indiv 100 m-3)	% of Total	Cumulative %	Frequency (% occurrence in samples)
Eurytemora spp.	7981	41.8	41.8	30.3
Centropages hamatus	4072	21.3	63.1	45.8
Temora longicornis	3414	17.9	81.0	36.3
Coelenterata	897	4.7	85.7	64.9
Acartia spp.	779	4.1	89.8	85.7
Brachyura	509	2.7	92.5	45.8
Centropages typicus	431	2.3	94.7	41.4
Balanidae	338	1.8	96.5	44.6
Decapoda	197	1.0	97.5	50.2
Gastropoda	87	< 1	98.0	33.5
Caridea	56	< 1	98.3	32.3
Centropages spp	46	< 1	98.5	8.4
Calanus finmarchicus	41	< 1	98.7	16.3
Evadne spp.	39	< 1	98.9	23.5
Tortanus discaudatus	37	< 1	99.1	17.1
Calanoida	34	< 1	99.3	43.4
Copepoda	18	< 1	99.4	12.0
Mysida	16	< 1	99.5	23.1
Chaetognatha	16	< 1	99.6	9.6
Gammaridae	15	< 1	99.7	27.9
Polychaeta	12	< 1	99.7	19.5
Pontellidae	11	< 1	99.8	17.9
Pseudocalanus minutus	7	< 1	99.8	8.4
Cyclopoida	6	< 1	99.8	6.0
Bivalvia	6	< 1	99.9	15.9
Harpacticoida	6	< 1	99.9	21.5
Isopoda	5	< 1	99.9	30.3
Amphipoda	5	< 1	99.9	22.3
Oithona spp	4	< 1	99.9	16.3
Ostracoda	0	< 1	99.9	6.0
Cumacea	0	< 1	100.0	7.2
Total	**19088**			

Table 4: Zooplankton taxa collected in Barnegat Bay, NJ, May 2012 - April 2015. 200 - 500 µ fraction.

Taxon	Total Mean Abundance (# indiv 100 m-3)	% of Total	Cumulative %	Frequency (% occurrence in samples)
Acartia spp.	72464	65.27	65.3	97.2
Eurytemora spp.	11520	10.38	75.6	36.4
Balanidae	4536	4.09	79.7	81.6
Gastropoda	4513	4.06	83.8	58
Centropages spp	3372	3.04	86.8	43.2
Calanoida	2595	2.34	89.2	72.8
Podon spp.	2128	1.92	91.1	20.4
Oithona spp.	1913	1.72	92.8	56.8
Polychaeta	1773	1.60	94.4	48.4
Temora longicornis	1363	1.23	95.6	27.6
Evadne spp.	836	< 1	96.4	25.2
Centropages hamatus	815	< 1	97.1	28.4
Harpacticoida	664	< 1	97.7	74
Copepoda	429	< 1	98.1	38.8
Bivalvia	419	< 1	98.5	29.6
Brachyura	382	< 1	98.8	17.6
Coelenterata	329	< 1	99.1	22.8
Paracalanus spp.	326	< 1	99.4	15.6
Decapoda	207	< 1	99.0	12.8
Temora spp.	170	< 1	99.0	12
Centropages typicus	78	< 1	99.0	12.8
Cyclopoida	75	< 1	99.0	27.6
Pseudocalanus minutus	41	< 1	99.0	9.2
Foraminifera	36	< 1	99.0	12
Ostracoda	17	< 1	99.0	10.4
Caridea	14	< 1	99.0	7.2
Pontellidae	4	< 1	100.0	5.6
Total	**111018.42**			

Similarity/Dissimilarity of Zooplankton Communities

Primer-E software (v. 6.1.15, Clarke and Warwick 2001) was utilized to examine the similarities and differences between zooplankton communities across samples, seasons, and sites. Abundance data was fourth-root transformed to decrease the weight of high-abundance taxa (e.g. *Acartia* spp). The resultant data were converted to a resemblance matrix using a Bray-Curtis similarity index. Non-metric multidimensional scaling (MDS) plotted resemblance matrix data such that distance reflects dissimilarity; ANOSIM tested the similarities of the zooplankton assemblages, and SIMPER determined how taxa contributed to those similarities. Species diversity indices (species richness (Margalef), Shannon index, Pielou's evenness, and Simpson index) were calculated for each sample then averaged over site, month, and season. Season (astronomical) was determined by sample date.

Taxonomic mean abundances were compared across sampling date, season, and site in order to test for similarities and differences in the zooplankton community. Zooplankton community structure differed throughout the three years of the study ($R = 0.204$, $p < 0.001$), and seasonality was evident ($R = 0.204$, $p < 0.001$). Differences were especially marked between summer and winter ($R = 0.491$, $p < 0.001$), and were significant but not as strongly dissimilar between most other seasonal combinations (e.g. spring/summer, spring/fall, etc.). The only non-significant pairing was that of spring and winter. Community structure of the combined zooplankton fractions was weakly significantly different across sites ($R = 0.025$, $p = 0.003$) . The combinations of BB02/BB12, BB05a/BB12, and BB05a/BB07a were significantly different ($p < 0.001$, < 0.001, $= 0.029$ respectively).

Samples were too numerous to provide meaningful results when each sample community was analyzed for percent similarity/dissimilarity. Within-site similarity indices indicate that community structure at each site was variable throughout the three year sampling period.

Because significant differences in community structure were observed, it is useful to determine which taxa are the most important contributors to those differences. Community structure of each sample was compared within and across site, and within and across season. Community structure for each sample was compared for similarity within each treatment (site, season), and then between sites or seasons for dissimilarity. The top five contributing taxa to each comparison were determined, as well as with percent contribution.

Within-site similarities (Table 5) were lowest in the > 500 µ fraction (16.85 - 22.46 %) and highest in the samples from the 200 - 500 µ fraction (36.27 - 46.71%). The smaller plankton appear to create a more stable community at each site (less variability over the three year sampling period), which may be because 200 - 500 µ plankton tend to be holoplanktonic and remain more consistently associated with the planktonic community whereas larger plankton (e.g. Brachyura) are meroplankton that are transient in the planktonic community.

Within-season similarities (Table 5) exhibited a pattern similar to that of within-site similarities described above. The 200 - 500 µ fraction maintained a more stable planktonic community (more similar community structure) within each season. Larger plankton, typically meroplanktonic, often appeared in the samples in pulses (e.g. Decapoda, Brachyura, Bivalvia). Although holoplanktonic copepods were most abundant in blooms, some genera such as *Acartia* and *Eurytemora* were common in most samples.

Community structure was compared between sites and between seasons to evaluate differences and examine taxa contributing to those differences. There were strong differences in communities between sites (Group Average Dissimilarity, Table 6), especially for the >500 µ size fraction. The presence of taxa such as *Eurytemora* spp., *C. hamatus*, Coelenterata, and Brachyura contributed to those differences in community structure between sites. As the 200 - 500 µ taxa are smaller, they may be more likely to be advected throughout the bay than larger taxa, thus the community structure for smaller taxa is more spatially uniform.

Seasonal differences were very strong for the > 500 µ fraction, as larger coastal copepods (e.g. *C. hamatus*) are abundant in the winter in Barnegat Bay, and meroplankton exhibit strong seasonal spawning pulses (Table 7). Greatest differences in community structure were between summer and winter communities for all samples. The 200 - 500 µ fraction again exhibited a more stable and uniform planktonic community compared with the larger fraction.

Table 5. Similarity indices comparing community structure of samples across sites and seasons. Group Avg Sim = group average similiarity index - how similar are the samples' community structure within the treatment. Avg Sim = average similarity of taxon among samples. % Contrib = percent contribution of that taxon to the Group Average Similarity.

Site/Season		Combined Fractions				> 500 Fraction				200 - 500 Fraction			
Site		Group Avg Sim	Taxon	Avg Sim	% Contrib	Group Avg Sim	Taxon	Avg Sim	% Contrib	Group Avg Sim	Taxon	Avg Sim	% Contrib
	2	23.83	*Acartia* spp	8.71	36.53	16.85	*Acartia* spp	5.21	30.94	36.27	*Acartia* spp	14.45	39.85
			Balanidae	3.49	14.65		Coelenterata	2.09	12.41		Balanidae	7.4	20.4
			Gastropoda	1.58	6.63		Brachyura	1.87	11.09		Gastropoda	3.48	9.59
			Calanoida	1.46	6.12		Decapoda	1.1	6.53		Harpacticoida	2.77	7.64
			Coelenterata	1.24	5.22		Caridae	0.95	5.62		Calanoida	2.66	7.34
					69.15				66.59				84.82
	5a	27.96	*Acartia* spp	11.05	39.5	19.11	*Acartia* spp	7.01	36.69	46.71	*Acartia* spp	18.57	39.75
			Balanidae	4.81	17.21		Brachyura	2.47	12.95		Balanidae	10.42	22.32
			Gastropoda	1.64	5.88		Coelenterata	2.22	11.64		Gastropoda	3.42	7.33
			Coelenterata	1.38	4.95		Balanidae	1.26	6.61		Calanoida	3.36	7.19
			Calanoida	1.18	4.22		Decapoda	1.06	5.52		Harpacticoida	2.25	4.81
					71.77				73.41				81.39
	7a	27.5	*Acartia* spp	8.05	29.26	19.78	*Acartia* spp	3.96	20	41.19	*Acartia* spp	13.91	33.78
			Balanidae	2.63	9.55		*C. hamatus*	2.41	12.2		Harpacticoida	4.08	9.9
			C. hamatus	1.59	5.77		Decapoda	2.25	11.35		Balanidae	3.92	9.52
			Calanoida	1.51	5.49		Brachyura	2.13	10.79		Calanoida	3.41	8.29
			T. longicornis	1.45	5.26		*C. typicus*	2.06	10.4		*Oithona* spp.	2.7	6.54
					55.33				64.75				68.03
	10	30.17	*Acartia* spp	10.97	36.37	19.55	*Acartia* spp	6.28	32.1	44.65	*Acartia* spp	16.43	36.79
			Calanoida	2.78	9.22		Coelenterata	2.49	12.76		Harpacticoida	5.86	13.11
			Harpacticoida	2.31	7.67		*C. hamatus*	2.02	10.35		Calanoida	5.74	12.86
			Eurytemora spp.	1.57	5.2		Brachyura	1.77	9.07		Gastropoda	2.49	5.59
			Balanidae	1.56	5.17		Decapoda	1.48	7.59		Balanidae	2.37	5.3
					63.62				71.87				73.65
	12	30.29	*Acartia* spp	7.99	26.38	22.46	*Acartia* spp	4.17	18.55	44.43	*Acartia* spp	11.84	26.65
			Calanoida	2.55	8.41		Brachyura	3.65	16.27		Calanoida	6.37	14.34
			Balanidae	2.24	5.6		Decapoda	2.94	13.08		Harpacticoida	4.77	10.73
			C. hamatus	1.7	5.6		*C. hamatus*	2.31	10.31		Balanidae	4.26	9.58
			Brachyura	1.57	5.18		Coelenterata	2.05	9.12		*Oithona* spp.	2.88	6.49
					52.98				67.34				67.79

Season												
Spring	31.24	*Acartia* spp	7.95	25.45	22.8	*C. hamatus*	4.14	18.16	42.87	*Acartia* spp	13.31	31.05
		Balanidae	3.21	10.28		*Acartia* spp	3.69	16.18		Balanidae	5.1	11.89
		C. hamatus	3.17	10.15		Coelenterata	3.05	13.4		*Eurytemora* spp.	4.52	10.55
		Eurytemora spp.	2.91	9.32		*C. typicus*	2.35	10.3		Harpacticoida	2.99	6.98
		Coelenterata	2.07	6.62		*T. longicornis*	1.74	7.64		*Centropages* spp.	2.99	6.98
				61.83				65.68				67.45
Summer	33.68	*Acartia* spp.	10.2	30.29	29.72	Brachyura	11.22	37.76	48.82	*Acartia* spp	18.31	37.51
		Gastropoda	4.99	14.82		*Acartia* spp	5.44	18.29		Gastropoda	9.3	19.06
		Brachyura	4.9	14.56		Decapoda	4.49	15.1		Balanidae	7.13	14.6
		Balanidae	2.86	8.48		Coelenterata	2.29	7.72		Calanoida	5.56	11.38
		Calanoida	2.3	6.82		Gastropoda	1.71	5.75		Harpacticoida	3.59	7.35
				74.96				84.61				89.89
Fall	27.77	*Acartia* spp	11.03	39.71	20.88	*Acartia* spp	8.7	41.67	47.48	*Acartia* spp	17.22	36.26
		Calanoida	3.59	12.93		Coelenterata	2.19	10.48		Calanoida	6.76	14.24
		Harpacticoida	2.08	7.47		Calanoida	1.58	7.57		Harpacticoida	5.95	12.53
		Balanidae	1.85	6.65		Decapoda	1.35	6.46		Balanidae	4.07	8.57
		Oithona spp.	1.22	4.4		*C. hamatus*	1.07	5.14		*Oithona* spp.	3.61	7.61
				71.17				71.32				79.2
Winter	42.04	*Eurytemora* spp.	7.54	17.95	34.91	*C. hamatus*	9.65	27.64	45.92	*Acartia* spp	7.96	17.33
		Acartia spp.	7.35	17.48		*T. longicornis*	8.14	23.31		*Eurytemora* spp.	7.4	16.12
		T. longicornis	6.83	16.26		*Eurytemora* spp.	6.77	19.39		*Centropages* spp.	6.03	13.14
		C.hamatus	5.55	13.21		*Acartia* spp	4.13	11.82		Balanidae	4.71	10.25
		Balanidae	4.96	11.79		Balanidae	2.53	7.24		*T. longicornis*	4.36	9.5
				76.68				89.4				66.34

Table 6. Dissimilarity indices comparing community structure of samples between sites. Group Avg Dis = group average dissimilarity index - how different are the samples' community structure between the treatments. Avg Dis = average dissimilarity of taxon between samples. % Contrib = percent contribution of that taxon to the Group Average Dissimilarity.

		Combined Fractions				> 500 Fraction				200 - 500 Fraction			
Sites		Group Avg Dis	Taxon	Avg Dis	% Contrib	Group Avg Dis	Taxon	Avg Dis	% Contrib	Group Avg Dis	Taxon	Avg Dis	% Contrib
	2 vs 5a	74.01	*Acartia* spp.	10.53	14.23	81.45	*Eurytemora* spp.	9.98	12.26	58.93	*Acartia* spp.	8.5	14.43
			Balanidae	6.6	8.91		*Acartia* spp.	9.95	12.22		*Eurytemora* spp.	5.6	9.5
			Eurytemora spp.	5.97	8.07		Coelenterata	7.33	9		Gastropoda	5.48	9.3
			Gastropoda	5.13	6.94		*C. hamatus*	6.96	8.54		Balanidae	5.29	8.97
			Calanoida	3.84	5.18		Brachyura	6.75	8.28		Calanoida	3.89	6.6
					43.34				50.31				48.8
	2 vs 7a	75.58	*Acartia* spp.	9.17	12.13	82.93	*C. hamatus*	9.68	11.68	63.78	*Acartia* spp.	7.99	12.53
			Eurytemora spp.	5.39	7.13		*Eurytemora* spp.	8.07	9.74		*Eurytemora* spp.	5.3	8.3
			Balanidae	4.81	6.37		*T. longicornis*	7.18	8.66		Balanidae	4.33	6.78
			C. hamatus	4.23	5.6		*Acartia* spp.	7.08	8.54		*Centropages* spp.	4.16	6.52
			T. longicornis	4.03	5.34		Brachyura	6.46	7.8		Gastropoda	4.11	6.44
					41.87				46.41				40.58
	2 vs. 10	74.04	*Acartia* spp.	9.8	13.24	82.69	*Eurytemora* spp.	10.49	12.69	62.27	*Acartia* spp.	9.04	14.52
			Eurytemora spp.	6.2	8.38		*Acartia* spp.	10.01	12.1		*Eurytemora* spp.	5.74	9.21
			Balanidae	4.57	6.17		*C. hamatus*	9.36	11.32		Gastropoda	4.9	7.88
			Gastropoda	4.47	6.04		Coelenterata	8.02	9.7		Balanidae	4.73	7.59
			C. hamatus	4.33	5.84		Brachyura	7.9	9.56		Calanoida	4.4	7.06
					39.67				55.38				46.25
	2 vs. 12	74.67	*Acartia* spp.	8.46	11.33	82.56	*C. hamatus*	9.66	11.7	63.15	*Acartia* spp.	8.4	13.3
			Balanidae	4.49	6.01		Brachyura	9.44	11.43		Calanoida	4.98	7.89
			Calanoida	4.44	5.95		Decapoda	7.36	8.92		Gastropoda	4.64	7.35
			C. hamatus	4.17	5.59		*T. longicornis*	7.1	8.6		Balanidae	4.2	6.66
			Eurytemora spp.	4.13	5.53		*Acartia* spp.	7.08	8.57		*Eurytemora* spp.	4.14	6.56
					34.41				49.23				41.76
	5a vs 7a	73.44	*Acartia* spp.	8.65	11.77	82.1	*C. hamatus*	9.9	12.05	58.35	*Acartia* spp.	6.23	10.67
			Eurytemora spp.	5.07	6.9		*Eurytemora* spp.	8.13	9.9		*Eurytemora* spp.	4.84	8.29

		Balanidae	5.02	6.84		*T. longicornis*	7.35	8.96		Balanidae	4.25	7.28
		Gastropodapoda	4.04	5.5		*Acartia* spp.	6.96	8.48		Gastropoda	4.06	6.97
		C. hamatus	3.98	5.42		Brachyura	6.48	7.89		*Centropages* spp.	4.01	6.88
				36.43				47.29				40.08
5a vs 10	72.13	*Acartia* spp.	9.03	12.52	82.07	*Eurytemora* spp.	10.49	12.78	57.42	*Acartia* spp.	6.98	12.16
		Eurytemora spp.	5.82	8.08		*Acartia* spp.	9.81	11.96		*Eurytemora* spp.	5.13	8.93
		Balanidae	4.94	6.84		*C. hamatus*	9.53	11.61		Balanidae	5.07	8.83
		Gastropoda	4.48	6.21		Coelenterata	8.34	10.17		Gastropoda	4.76	8.29
		C. hamatus	4.05	5.61		Brachyura	7.89	9.61		*Centropages* spp.	3.69	6.42
				39.26				56.13				44.62
5a vs 12	72.82	*Acartia* spp.	8.04	11.04	82.18	*C. hamatus*	9.83	11.96	58.44	*Acartia* spp.	7.12	12.17
		Balanidae	4.75	6.53		Brachyura	9.3	11.32		Gastropoda	4.52	7.74
		Calanoida	4.17	5.73		*T. longicornis*	7.21	8.77		Balanidae	4.34	7.43
		Gastropoda	4.12	5.66		Decapoda	7.07	8.6		Calanoida	4.18	7.15
		C. hamatus	3.94	5.41		*Acartia* spp.	7.02	8.55		*Eurytemora* spp.	3.75	6.41
				34.36				49.2				40.91
7a vs 10	71.83	*Acartia* spp.	8.16	11.36	81.19	*C. hamatus*	10.77	13.26	57.98	*Acartia* spp.	6.84	11.79
		Eurytemora spp.	5.36	7.46		*Eurytemora* spp.	9.01	11.1		*Eurytemora* spp.	4.94	8.52
		C. hamatus	4.59	6.39		*Acartia* spp.	7.96	9.8		*Centropages* spp.	4.41	7.61
		Calanoida	3.74	5.21		Brachyura	7.31	9.01		*Oithona* spp.	3.69	6.36
		T. longicornis	3.73	5.19		Coelenterata	6.55	8.07		Gastropoda	3.54	6.11
				35.61				51.24				40.4
7a vs 12	71.31	*Acartia* spp.	7.18	10.07	79.06	*C. hamatus*	11.05	13.98	57.94	*Acartia* spp.	6.76	11.67
		C. hamatus	4.4	6.17		*T. longicornis*	8.48	10.72		*Centropages* spp.	4.15	7.16
		T. longicornis	4.11	5.77		Brachyura	8.29	10.49		Calanoida	3.81	6.57
		Calanoida	3.89	5.46		Decapoda	7.3	9.24		*Oithona* spp.	3.63	6.26
		Eurytemora spp.	3.55	4.98		*C. typicus*	6.51	8.23		*Eurytemora* spp.	3.56	6.15
				32.44				52.66				37.82

10 vs 12	70.34	*Acartia* spp.	7.57	10.77	79.47	*C. hamatus*	10.59	13.32	56.32	*Acartia* spp.	7.58	13.47
		C. hamatus	4.51	6.42		Brachyura	8.94	11.25		*Centropages* spp.	4.03	7.16
		Eurytemora spp.	4.32	6.14		*Acartia* spp.	7.56	9.52		Gastropoda	4.03	7.15
		Calanoida	4.11	5.84		*Eurytemora* spp.	7.02	8.83		*Eurytemora* spp.	3.94	7
		Gastropoda	3.67	5.22		*T. longicornis*	6.1	7.68		Calanoida	3.85	6.83
				34.38				50.6				41.62

Table 7. Dissimilarity indices comparing community structure of samples between seasons. Group Avg Dis = group average dissimilarity index - how different are the samples' community structure between the treatments. Avg Dis = average dissimilarity of taxon between samples. % Contrib = percent contribution of that taxon to the Group Average Dissimilarity.

		Combined Fractions				> 500 Fraction				200 - 500 Fraction			
Seasons		**Group Avg Dis**	**Taxon**	**% Contrib**	**Avg Dis**	**Group Avg Dis**	**Taxon**	**% Contrib**	**Avg Dis**	**Group Avg Dis**	**Taxon**	**% Contrib**	**Avg Dis**
	Spring vs. Summer	75.9	*Acartia* spp.	8.48	11.17	83.17	*C. hamatus*	9.91	11.92	63.19	*Acartia* spp.	7.39	11.69
			Eurytemora spp.	5.8	7.65		Brachyura	9.73	11.69		*Eurytemora* spp	6.35	10.06
			Gastropoda	5.02	6.62		Coelenterata	8.16	9.81		Gastropoda	5.41	8.57
			Balanidae	4.81	6.33		*Eurytemora* spp	7.49	9		Balanidae	4.26	6.74
			C. hamatus	4.8	6.32		Decapoda	6.81	8.19		*Centropages* spp.	4.2	6.65
					38.09				50.61				43.7
	Spring vs. Fall	74.83	*Acartia* spp.	8.18	10.93	83.9	*C. hamatus*	11.21	13.36	59.72	*Acartia* spp.	6.68	11.19
			Eurytemora spp	5.95	7.96		Coelenterata	8.72	10.4		*Eurytemora* spp	5.83	9.77
			C. hamatus	4.84	6.47		*Eurytemora* spp	8.3	9.89		*Centropages* spp.	4.12	6.89
			Balanidae	4.37	5.85		*Acartia* spp.	6.55	7.81		Balanidae	3.86	6.47
			Coelenterata	3.87	5.17		*C. typicus*	6.48	7.73		Calanoida	3.82	6.39
					37.37				49.19				40.7
	Spring vs. Winter	66.32	*Eurytemora* spp	7.5	11.31	77.51	*Eurytemora* spp	15.4	19.86	57.95	*Eurytemora* spp	6.54	11.28
			Acartia spp.	5.71	8.61		*C. hamatus*	13.57	17.51		*Acartia* spp.	6.41	11.06
			T. longicornis	5.58	8.41		*T. longicornis*	12.15	15.67		*Centropages* spp.	4.58	7.9
			C. hamatus	5.4	8.15		*Acartia* spp.	5.95	7.68		*T. longicornis*	3.86	6.66
			Centropages spp.	3.85	5.81		Coelenterata	5.38	6.94		*Oithona* spp.	3.43	5.91
					42.29				67.67				42.82
	Summer vs Fall	73.47	*Acartia* spp.	11.06	15.05	81.66	Brachyura	13.41	16.43	56.96	*Acartia* spp.	8.56	15.02
			Gastropoda	5.81	7.91		*Acartia* spp.	11.22	13.74		Gastropoda	5.72	10.04
			Calanoida	5.34	7.27		Decapoda	8.74	10.71		Calanoida	4.59	8.05
			Balanidae	5.11	6.96		Gastropoda	5.1	6.25		Balanidae	4.45	7.81
			Brachyura	4.73	6.44		Coelenterata	4.78	5.86		*Oithona* spp.	3.7	6.5
					43.63				52.98				47.42

Summer vs. Winter	81.09	*Eurytemora* spp	9.14	11.27	93.29	*C. hamatus*	17.68	18.95	70.43	*Acartia* spp.	8.32	11.81
		Acartia spp.	7.49	9.23		*Eurytemora* spp	16.84	18.05		*Eurytemora* spp	7.9	11.22
		T. longicornis	7.47	9.22		*T. longicornis*	15.19	16.29		Gastropoda	6.27	8.9
		C. hamatus	6.93	8.55		*Acartia* spp.	8.18	8.77		*Centropages* spp.	5.74	8.14
		Balanidae	4.47	5.51		Brachyura	5.18	5.55		*T. longicornis*	4.64	6.58
				43.78				67.61				46.66
Fall vs. Winter	75.19	*Eurytemora* spp	8.58	11.41	87.82	*C. hamatus*	17.9	20.38	62.26	*Acartia* spp.	7.68	12.34
		Acartia spp.	7.22	9.6		*Eurytemora* spp	17.44	19.86		*Eurytemora* spp	6.82	10.95
		T. longicornis	7.18	9.54		*T. longicornis*	15.64	17.81		*Centropages* spp.	4.93	7.91
		C. hamatus	6.61	8.8		*Acartia* spp.	8.53	9.71		*T. longicornis*	4.31	6.92
		Balanidae	4.21	5.6		Balanidae	4.75	5.41		Calanoida	3.85	6.19
				44.95				73.17				44.31

Relationships in the taxonomic data were visualized by analyzing the Bray-Curtis resemblance matrix with principal coordinates analysis (PCO). PCO is similar to PCA but more appropriate for biological community data, which even with transformations is typically non-normally distributed. Taxa (Table 8) were evaluated with multiple correlation on the PCO plots. Taxa with correlations ≥ 0.25 are represented by vectors on the plots to better evaluate those driving the variability in the community data.

The PCO of the entire zooplankton data set did not group the communities according to site, but did exhibit a trend in the data along the PCO1 axis, with variability (23.1%) driven primarily by seasonal differences in the zooplankton communities (Fig 8). PCO2 (18%) varied somewhat with sampling year. The most important taxa (correlation ≥ 0.25) driving the seasonal trend were the copepods *C. hamatus*, *C. typicus*, *T. longicornis*, and *Eurytemora spp*, which appeared regularly in the winter and early spring samples. The extremely elevated abundances of *Acartia* spp. in 2012-2013 was responsible for the high correlation between that taxon and the PCO2 axis.

The results of the PCO for the 200-500 μ zooplankton community was similar to those PCO plots created for the complete dataset, with PCO1 (22.4%) affected mainly by seasonal differences, while PCO2 (18%) varied with sampling year (Fig 9). The zooplankton community did not differentiate strongly according to site. *C. hamatus*, *T. longicornis*, *Eurytemora* spp., and additional copepods *Centropages* spp., and *Oithona* spp. are correlated with seasonal differences, as in this study they were most typically found in the winter/early spring zooplankton community. Highest abundances of *Acartia* spp. and snails *Gastropoda* (order of magnitude greater than the other years) occurred in 2012-2013; they are likely important in driving the interannual trends in this dataset.

The ≥500 μ zooplankton fraction exhibited similar trends in the PCO as the previous two data sets (Fig 10). PO1 contributed 22.2% of the variability, while PCO2 was responsible for only 10.9%. Sites were not strongly differentiated in this data set. *C. hamatus*, *C. typicus*, *T. longicornis*, *Eurytemora* spp., and the cladoceran genus *Evadne* spp were again typical of the winter/spring community. These copepod species were collected in both size fractions, as both larval stages and adults were identified and enumerated in this study. The meroplankton taxa Brachyura, Decapoda, and Isopoda were abundant in spring/summer samples. *Acartia* spp. and Bivalvia drove interannual variability. The spring samples for the ≥500 μ zooplankton fraction were more spread out on the plot, indicating a lower similarity than was evident in the other data sets. This may be due to a higher prevalence of meroplankton, which tend to spawn in pulses. Samples were only collected monthly (early spring) or every two weeks (late spring/summer), sampling at a higher frequency may smooth the variability.

Table 8. Key to taxa in PCO and dbRDA plots created to examine the relationships in zooplankton community data in Barnegat Bay.

Assigned Number	Taxon
1	*Calanus finmarchicus*
2	*Centropages hamatus*
3	*Centropages typicus*
4	*Pseudocalanus minutus*
5	*Temora longicornis*
6	*Acartia* spp.
7	Calanoida
8	*Centropages* spp
9	Copepoda
10	Cyclopoida
11	*Eurytemora* spp.
12	Harpacticoida
13	*Oithona* spp.
14	*Paracalanus* spp.
15	Pontellidae
16	*Temora* spp.
17	*Tortanus discaudatus*
18	Amphipoda
19	Balanidae
20	Brachyura
21	Caridea
22	Chaetognatha
23	Coelenterata
24	Decapoda
25	*Evadne* spp.
26	Foraminifera
27	Gammaridea
28	Gastropoda
29	Isopoda
30	Mysida
31	Ostracoda
32	Bivalvia
33	*Podon* spp.
34	Polychaeta

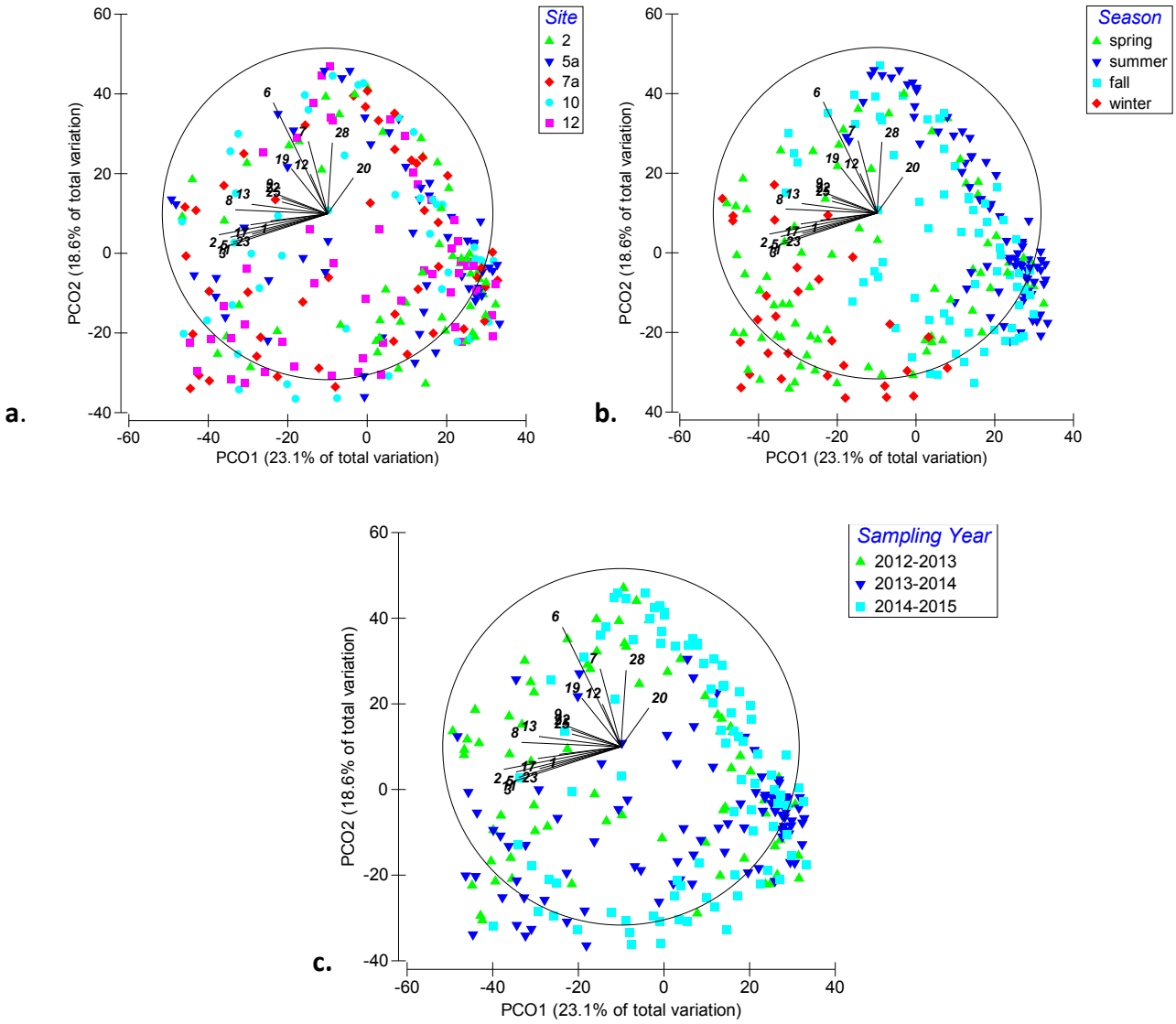


Figure 8. PCO of zooplankton community taxa for both the 200-500 µ and >500 µ fractions for each sampling event. Each data set is organized by **a**) site, **b**) season and **c**) sampling year. Vectors are zooplankton taxa that are correlated at or above 0.25. Taxa are identified by numbers as in Table 8. PCO1 = 23.1%, PCO2 = 18.6%.

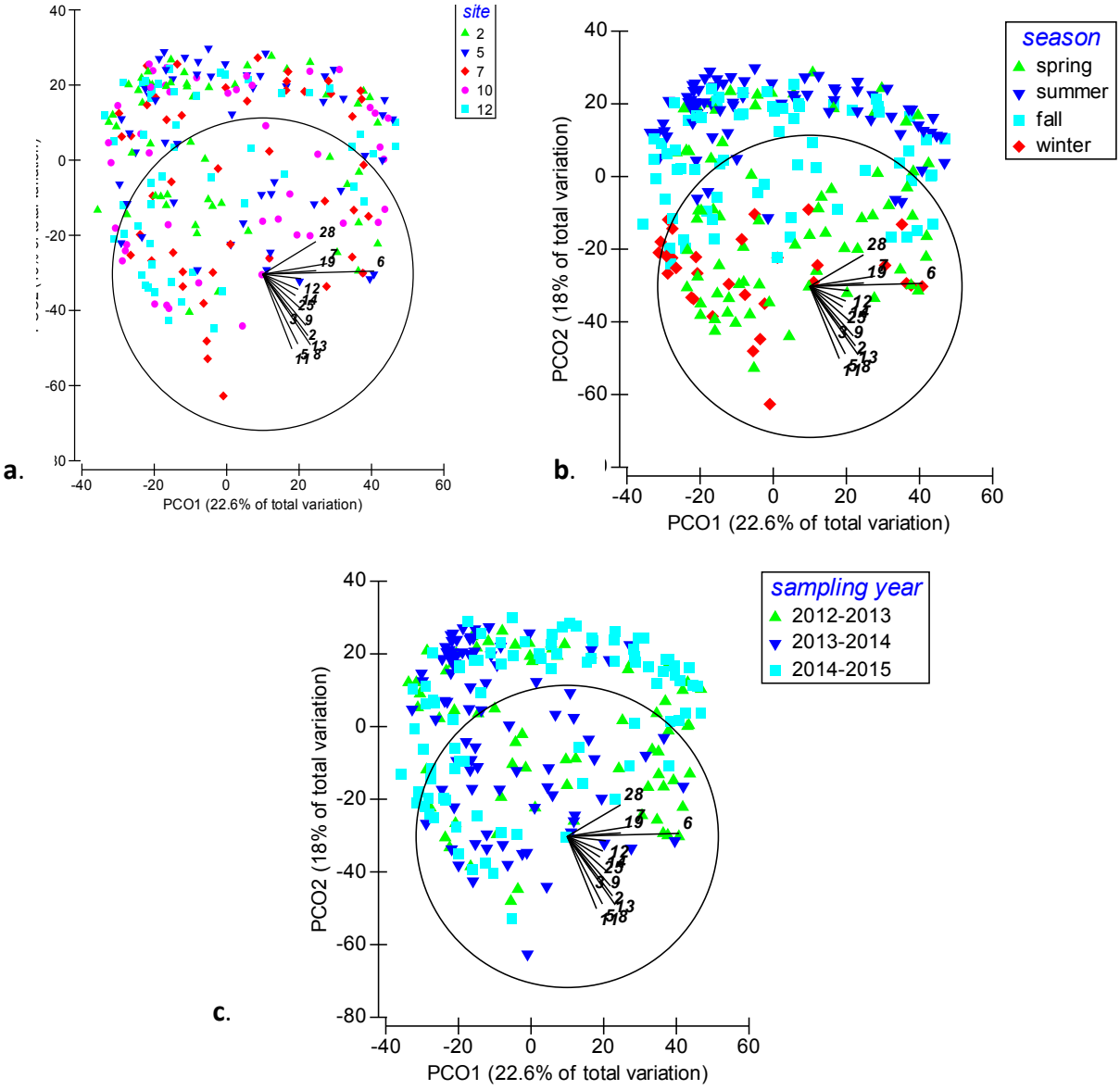


Figure 9. PCO of zooplankton community taxa for the 200-500 µ fraction for each sampling event. Each data set organized by **a**) site, **b**) season and **c**) sampling year. Vectors are zooplankton taxa that are correlated at or above 0.25. Taxa are identified by numbers as in Table 8. PCO1 = 22.6%, PCO2 = 18.0%.

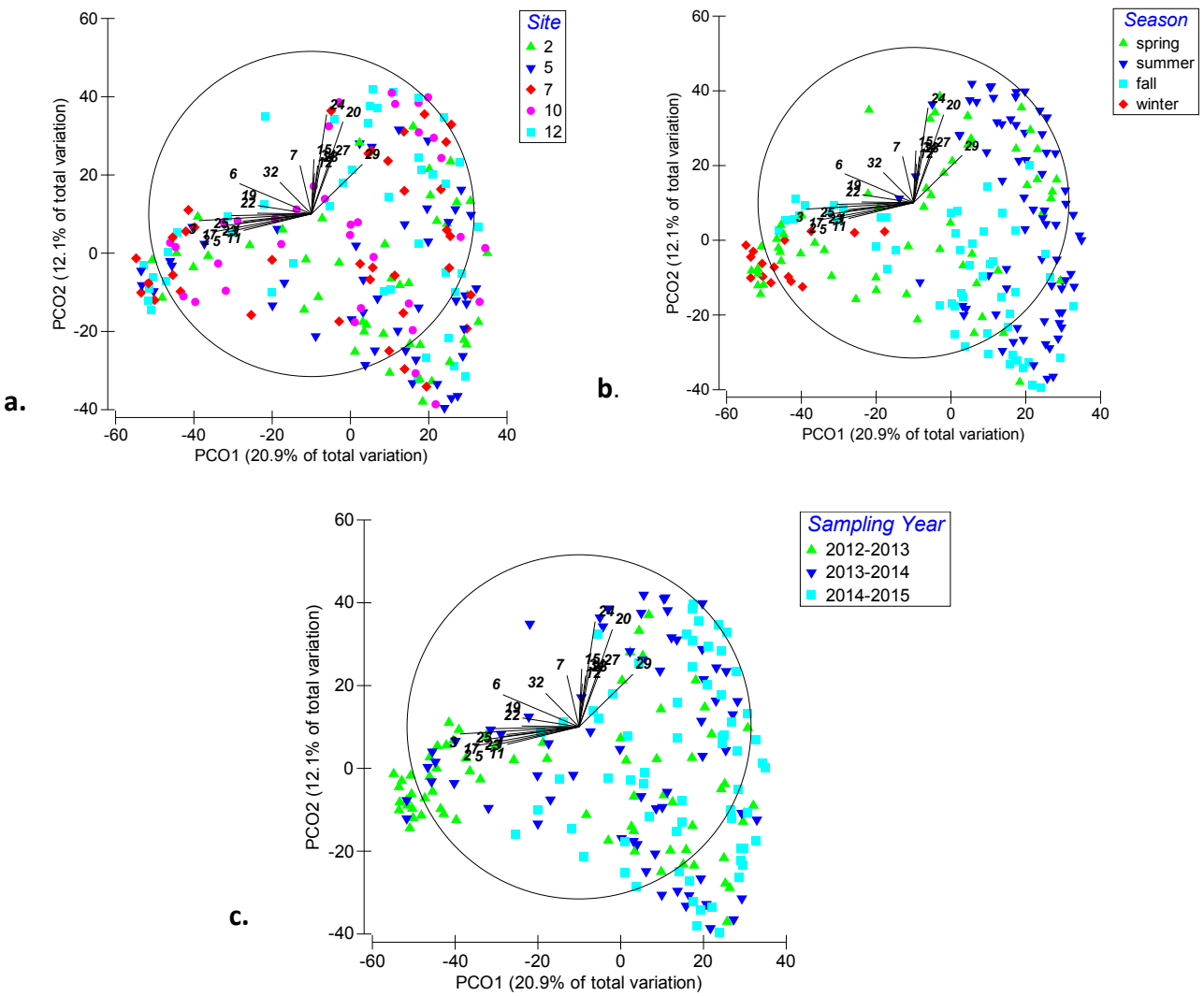


Figure 10. PCO of zooplankton community taxa for the ≥500 µ fraction for each sampling event. Each data set organized by **a**) site, **b**) season and **c**) sampling year. Vectors are zooplankton taxa that are correlated at or above 0.25. Taxa are identified by numbers as in Table 8. PCO1 = 22.2%, PCO2 = 10.9%.

Species Diversity

Species diversity indices were calculated to examine overall diversity of the zooplankton in Barnegat Bay. Although this does not provide us with specific information about community structure, it does provide us with a comparison of overall diversity.

Total taxa and mean abundance were provided elsewhere (Tables 2 - 4). Diversity increased with decreasing latitude (Fig 11), which is as expected as the southern bay is more pristine and is subjected to greater oceanic impact. Copepod taxa most often collected in coastal ocean habitats (e.g. *Centropages* spp., *Calanus finmarchicus*) were more abundant at Sites 7a, 10, and 12. The Simpson index rose slightly as latitude decreased, while the Pielou's Evenness index remained stable.

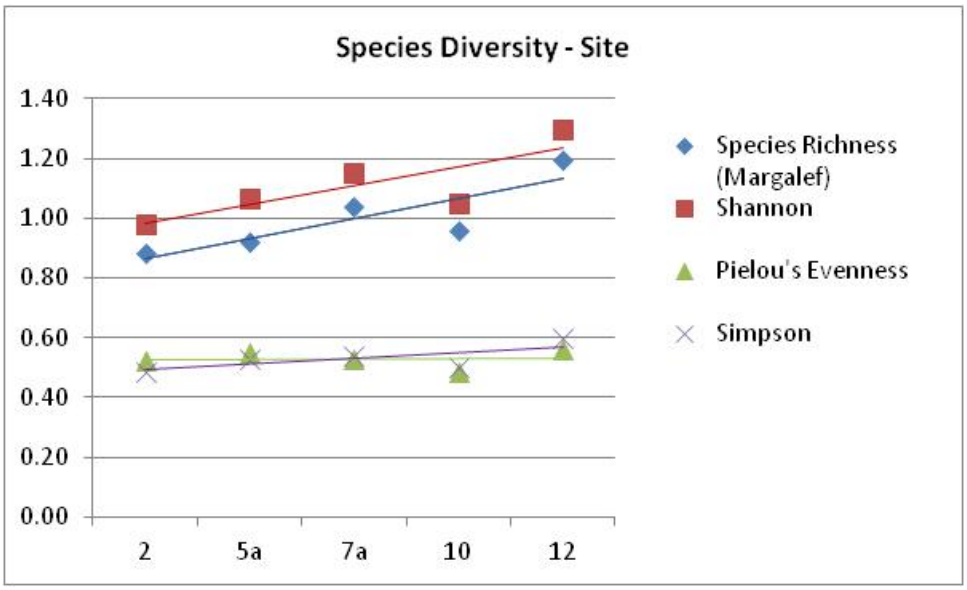
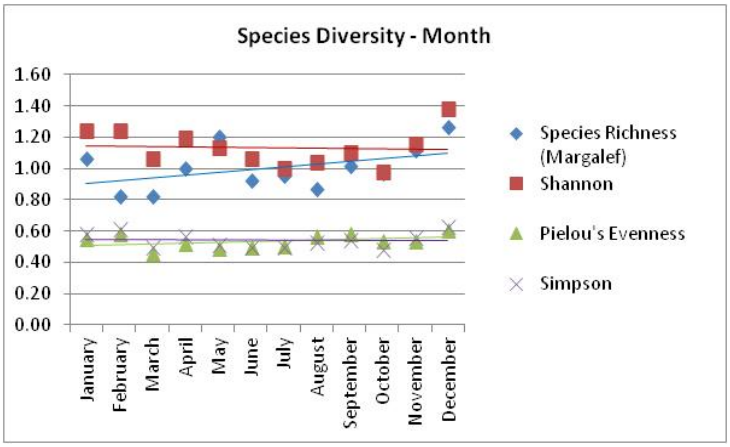


Figure 11. Species diversity analyses for zooplankton samples collected in Barnegat Bay, NJ, May 2012 - April 2015. Taxa were present in ≥ 5% of samples. Species Richness: $R^2 = 0.7228$, y = 0.066x + 0.0812. Shannon: $R^2 = 0.6518$, y = 0.0629x + 0.9206.Pielou's: $R^2 = 0.0131$, y = 0.0021x + 0.5228. Simpson: $R^2 = 0.5226$, y = 0.0196x + 0.4716.

Samples were parsed into month and season to examine temporal changes in species diversity (Fig 12). A variable pattern was evident, especially in Species Richness and the Shannon index, with highest values of Species Richness in May and December, and Shannon in December - February (Fig 12a). Pielou's and Simpson indices were lower and more stable than the other two indices (Fig 12a and b).

While Species Richness values are similar in the spring and winter, the Shannon index is much higher than Species Richness in the winter (Fig 12b). The Shannon index incorporates both species richness and abundance ("evenness") of each taxon; this indicates that the winter community is more biodiverse than that of the spring. Although many taxa may be present, a lower Shannon index in the spring is likely due to uneven abundance patterns, particularly the dominance of a few taxa (e.g. *Acartia*) associated with blooms. A higher Shannon index coupled with higher Species Richness in the winter indicates that abundances are more evenly distributed among the taxa and one taxon is not highly dominant, and is likely driven by the winter appearance of coastal copepod species.

a.



b.

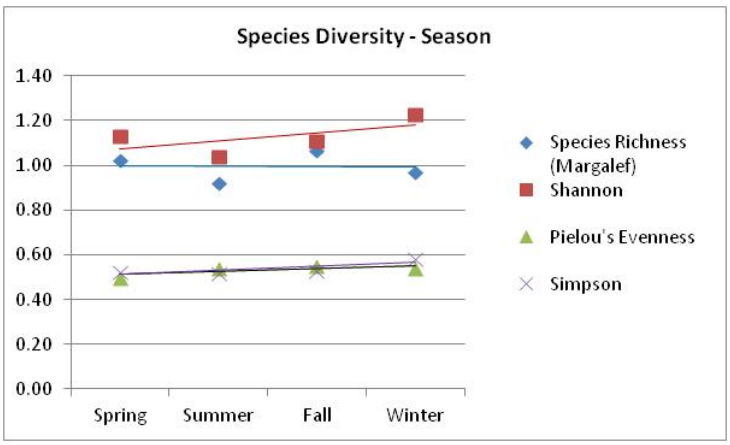


Figure 12. Species diversity analyses for zooplankton samples collected in Barnegat Bay, NJ, May 2012 - April 2015. Taxa were present in ≥ 5% of samples. **a)** Species diversity indices sorted by month. Species Richness (Margalef): $R^2 = 0.2027$, $y = 0.0175x + 0.8888$; Shannon: $R^2 = 0.0036$, $y = -0.0019x + 1.1447$; Pielou's Evenness: $R^2 = 0.1462$, $y = 0.0046x + 0.5054$; Simpson: $R^2 = 0.0032$, $y = -0.0007x + 0.5458$. **b)** Species diversity indices sorted by season. Species Richness (Margalef): $R^2 = 0.0017$, $y = -0.002x + 1.0011$; Shannon: $R^2 = 0.363$, $y = 0.0354x + 1.0381$; Pielou's Evenness: $R^2 = 0.5059$, $y = 0.0137x + 0.4975$; Simpson: $R^2 = 0.6592$, $y = 0.0178x + 0.4937$.

5.2.3 Distribution and Abundance of Taxa

Copepods

Over 32,500,000 individual zooplankters were collected over the duration of the study, with a mean total per tow (200 μ and 500 μ nets) of 65,093 individuals m^{-3}. For the 200 μ tows over 27,700,000 specimens were collected, and each tow averaged 111,086 individuals per m^3. Over 4,700,000 zooplankters were collected in the 500 μ tows, with a mean total of 19,081 individuals per m^{-3} per tow. These mean abundance values differ slightly from those presented in Tables 2 - 4, as those tables included only the taxa that appeared in ≥ 5% of all samples. Copepods, an integral component of the holoplankton and the most important estuarine primary consumer, comprised 86.6% of the total zooplankton collected. The calanoid copepod *Acartia* spp. was the most abundant copepod taxon, with 56% of all zooplankton specimens collected, while another calanoid copepod taxon, *Eurytemora* spp. (15% of total zooplankton), was the second most abundant taxonomic group. No other taxonomic group was above 4% in total abundance.

Trends in abundance indicate that *Acartia* spp. was especially associated with spring and fall blooms in Barnegat Bay (Fig 13a, 14a). *Acartia* spp. abundance was highest in late June 2012, very abundant in the spring and fall of 2012, and moderately abundant in the spring of 2013. However, *Acartia* spp. did not reappear for the fall bloom of 2013. The spring bloom of 2014 was delayed, with greatest numbers of *Acartia* seen during June and July of that year. The delay in the appearance of the *Acartia* bloom in spring 2014 may have been a result of overwintering *Acartia* being adversely affected by the extreme cold of the 2013-2014 winter. That seemingly anomalous summer bloom extended into the early fall of 2014, but did not maintain enough intensity to produce a true fall bloom, such as the bloom observed in fall 2013. As sampling for this study was completed in April 2015 with no evidence of a spring bloom, it is suggested that, due to the extreme cold of the 2014-2015 winter, the spring bloom may again have been delayed.

NOAA monitors several common coastal species in the mid-Atlantic bight, including *Temora longicornis, Calanus finmarchicus, Pseudocalanus minutus, Centropages hamatus*, and *Centropages typicus*. Although these species are common along the coast, they are not as abundant in Barnegat Bay. When they do occur, their occurrence is most often associated with the spring bloom (Fig 13b – f, 14b - f). *C. typicus,* in particular, is strongly associated with the spring bloom in Barnegat Bay (Fig 13f, 14f).

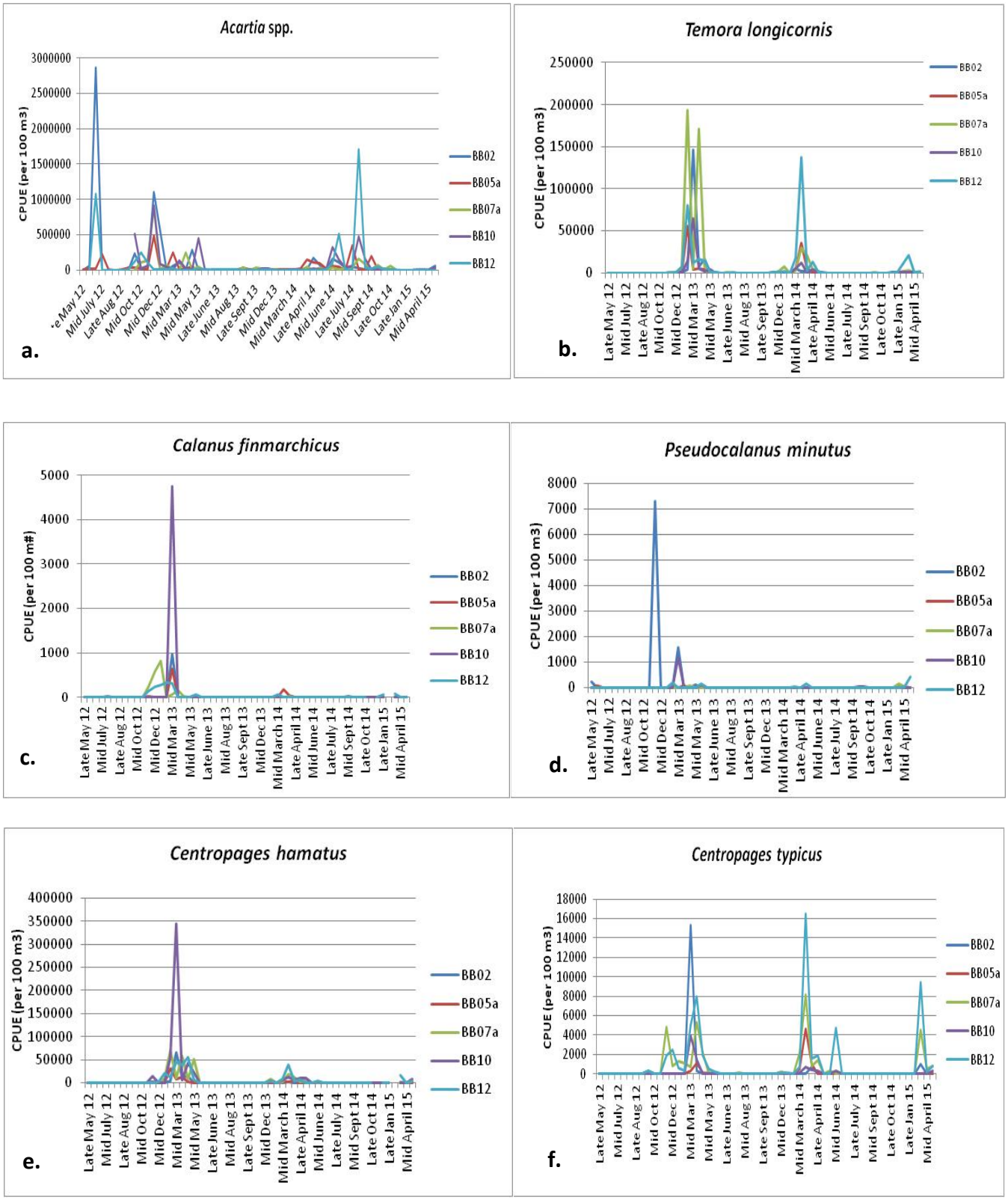


Figure 13. Abundance of copepod species collected at Sites BB2, BB5a, BB7a, BB10, and BB12 in May 2012 – April 2015. Sites BB7a and BB10 were added in late September 2012. **a**) *Acartia* spp. **b**) *Temora longicornis.* **c**) *Calanus finmarchicus* **d**) *Pseudocalanus minutus* **e**) *Centropages hamatus* **f**) *Centropages typicus*.

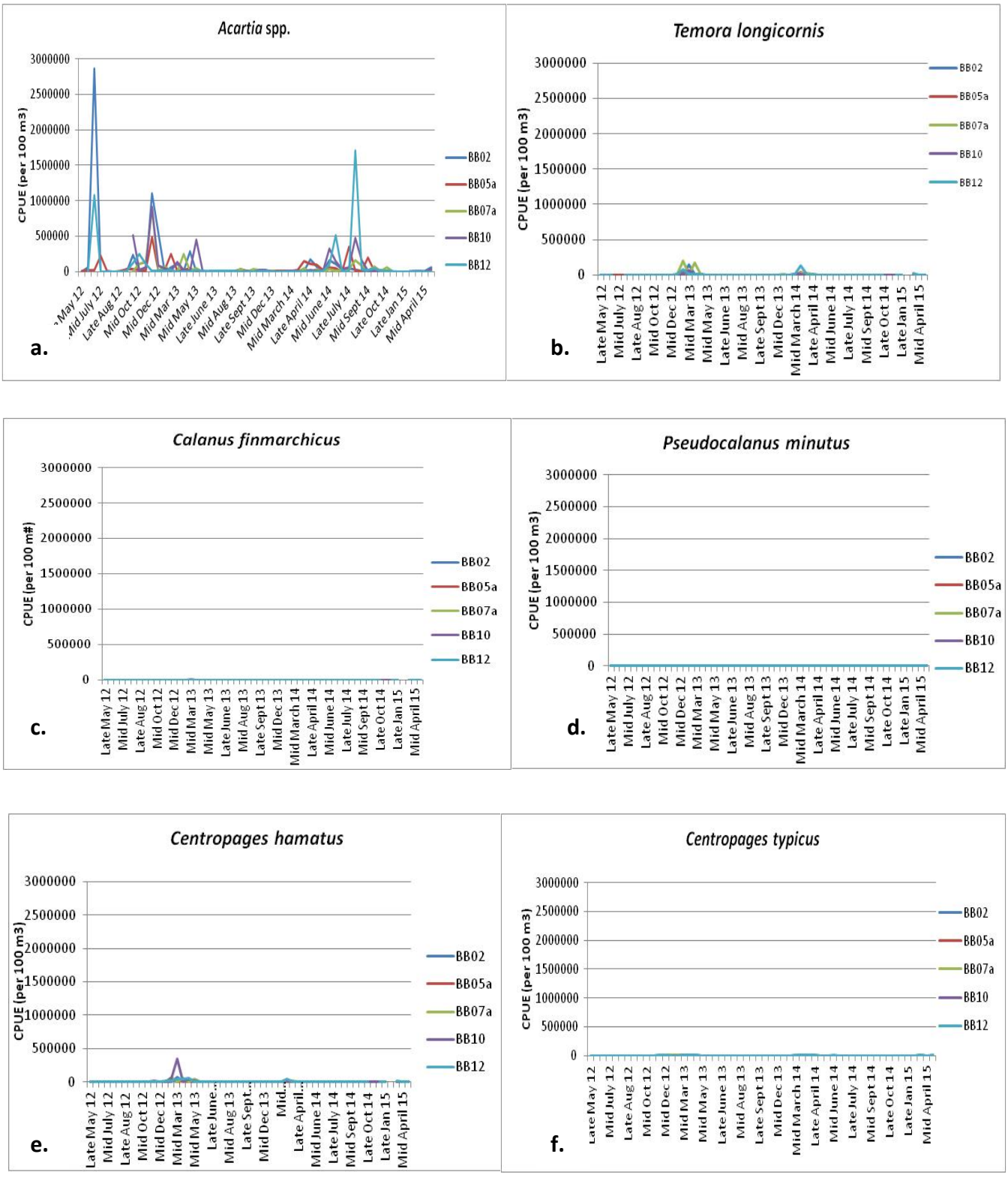


Figure 14. Abundance of copepod species collected at Sites BB2, BB5a, BB7a, BB10, and BB12 in May 2012 – April 2015. Sites BB7a and BB10 were added in late September 2012. *Y axis is standardized to the Acartia figure for comparison.* **a**) *Acartia* spp. **b**) *Temora longicornis*. **c**) *Calanus finmarchicus* **d**) *Pseudocalanus minutus* **e**) *Centropages hamatus* **f**) *Centropages typicus*.

To quantify the trends in abundance demonstrated graphically, as well as to examine the importance of specific copepod taxa such as *Acartia* spp., *Eurytemora* spp., and NOAA-monitored species to the Barnegat Bay zooplankton community, total abundance and mean abundance of copepod taxa were calculated for each year, each season, and each site; percent abundance of each copepod taxon relative to total copepod abundance was also calculated for each of the aforementioned parameters. Total and mean abundance varied annually, with the highest numbers collected in 2012 (total = 10,459,280, mean = 222,538), and the lowest in 2015 (total = 658,360, mean = 32,918). In 2014 the total number of copepods collected was comparable to that in 2012 (10,271,778), although the mean abundance was half of that in 2012 (109,274). However, it is important to note that the duration and timing of sampling effort differed in 2012 and 2015: samples were collected May - December in 2012, but January - April in 2015. Copepod abundance in 2012 is therefore extremely high even with a shortened (May - December) sampling period, when compared with 2014.

Acartia spp. was the dominant copepod taxon over the entire study, comprising 64.9% of the total collection of copepods, with contributions from *Eurytemora* spp. (17.3%) and several other taxa below 5% abundance. Although *Acartia* spp. is the most important copepod taxon in Barnegat Bay in terms of total numbers and mean abundance, several other taxa are also prevalent at certain times of the year and in certain locations. In 2012, mean abundance of *Acartia* spp. relative to all other copepods reached 91.1% (Table 9), while the taxon's contribution to mean total abundance of copepods varied greatly in 2013, 2014, and 2015 (35.6, 60.3, and 25.3%, respectively). In 2013, *Eurytemora* spp. (20.1%), *Centropages hamatus* (14.4%) and *Temora longicornis* (12.5%) were also prevalent in the bay. *Eurytemora* spp. was also abundant in 2014 (30.7%), and in 2015 was more abundant (50.9%) than *Acartia* spp (25.3%). For comparison purposes, total and mean abundance were therefore split into similar time periods in 2013 and 2014 (Table 9). For the January - April time period (2013 - 2015), total copepod abundance was highest in 2013 (5,563,818) and almost an order of magnitude less in 2015 (658,360). Mean abundance was also considerably higher in 2013 (222,553) than in 2015 (32,918), likely due to the lack of bloom in early spring 2015. When considering the three sampling years during the January - April time period, it becomes apparent that *Acartia* spp. is not always the dominant copepod taxon in the bay. For the January - April 2013 sampling period, *Acartia* spp. (27.4%) is only slightly more abundant than *Eurytemora* spp. (23.9%), while *Centropages hamatus* (16.9%) and *Temora longicornis* (15.1%) are also somewhat abundant. In that sampling period in 2014, *Eurytemora* spp. (71.4%) is by far the dominant taxon, although *Acartia* spp. (13.5%) and *T. longicornis* (7.1%) both add to the total abundance. January- April was the only sampling period in 2015; in this time period *Eurytemora* (50.9%) was twice as abundant as *Acartia* spp. (25.3%). For the May - December time period in 2012 - 2014, total abundance in 2012 (10,459,280) was twice as high as 2014 (5,585,901), and much greater than 2013 (571,706). *Acartia* was the dominant taxon for May - December 2012 (91.1%) and 2014 (98.6%). However in 2013, in addition to *Acartia* spp. (70.9%), the cyclopoid copepod *Oithona* (7.9%) contributed to the total copepod abundance, as did calanoid (8.3%) and harpacticoid

copepods (5.9%). Calanoida are calanoid copepods that could not be identified to a higher resolution, so it is unknown whether they were *Acartia* or another calanoid copepod genus.

Copepod total and mean abundances were calculated for season (astronomical). As sampling effort differed between November - March and April - October, mean abundances, rather than total abundances, are the only appropriate metric for comparison. Contrary to the paradigm of the temperate zone spring bloom, the spring copepod mean abundance was slightly less than the summer value (114,704 and 120,673, respectively); additionally, the fall temperate zone bloom was not as apparent in this study, as the overall winter mean abundance (126,350) was considerably higher than that of the fall (94,083) (Table 10). This disparity is likely due to the influence of a large copepod bloom 1-2 months after Superstorm Sandy, which occurred in late October 2012 (discussed further in Section 6.0). The copepod community differed seasonally as well, with the contribution of *Acartia* much lower in the spring (35.2%) than in the summer (94.7%), with *Eurytemora* (41.6%) more abundant than *Acartia* in the spring. *Acartia* remained prevalent in the fall (88%), but abundance declined in the winter (20.9%) with other taxa in the community contributing to the overall copepod abundance, e.g. *Eurytemora* spp. (32.3%), *C. hamatus* (18.8%), *T. longicornis* (16.9%), and *Centropages* spp. (5.7%).

Sampling effort was similar for all sites, facilitating comparisons of total abundance as well as mean abundance between them. Copepod total and mean abundance were similar at Sites 2, 7a, and 10 (total ≈ 6,000,000, mean ≈ 130,000) and slightly less at Site 12 (total = 5,486,133, mean = 105,503), but only about half of those values at Site 5a (total = 3,425,868, mean = 63,442) (Table 11). *Acartia* spp. was the dominant taxon at Sites 2 (80.5%), 5a (71.9%), and 10 (61%) while *Eurytemora* was the other prevalent species at these locations (11%, 15.9%, and 21.5% respectively). *Acartia* spp. was also dominant at Site 12 (76.6%), however the other important contributors to overall abundance were unidentified calanoid copepods (6.5%), *T. longicornis* (5.9%) and *C. hamatus* (5.0%). The copepod community characteristics differed at Site 7a, with *Acartia* spp. and *Eurytemora* spp. being similarly abundant (37.6%, 35.2%), but *Centropages* spp., *T. longicornis*, and *Oithona* spp. contributing 4 - 8% each.

Although *Acartia* is the most abundant copepod in the bay, its dominance is highly variable and other taxa are occasionally more numerous. This trend was apparent in a previous study, as *Acartia* accounted for 63% of mean annual abundance of all copepods in Barnegat Bay in Sept 1975 - Aug 1976 (Tatham 1977), but the following year *Oithona* spp. was dominant (51% of total copepods) (Tatham 1978). Overall, the trend in the current study appears to be that *Acartia* is more prevalent in summer and fall than in winter and spring, when other copepod taxa, e.g. *Eurytemora* spp. and *T. longicornis*, are more common. These coastal species are likely less tolerant of the warm summer temperatures characteristic of the bay's shallow waters. *Acartia* is almost uniformly abundant throughout the bay, except for Site 7a. This location is close to Barnegat Inlet, which provides an interchange with coastal waters; this is evident in the appearance of coastal taxa such as *Centropages* spp., *T. longicornis*, and *Oithona* at this site.

Comparing copepod abundance in Barnegat Bay with other estuaries is challenging, as there is inconsistency in methodologies (mesh size, sampling effort, etc.) in available studies. The copepods sampled in this study included larval (nauplii) and juvenile (copepodite) stages, as well as adults, combined into one total count for each taxon. As they are smaller than adults, more nauplii and copepodites were collected in the 200 u net than the 500 net, but younger nauplii were likely missed as they are smaller than 200 u.

The zooplankton community in a Long Island, NY estuary was dominated by copepods and exhibited greatest abundance in early spring and summer (Turner 1982). Copepods collected in a 202 µ net reached a maximum of 2,000,000 individuals 100 m^{-3} in August 1979, similar to the abundance of *Acartia* at Site 12 in late summer 2014 in this study (Fig 13). However, there is marked interannual variability in Barnegat Bay, and copepod abundances were much lower in a similar time period in the two previous years of the present study. Rothenberger et al. (2014) sampled Raritan Bay, NJ, with a Schindler-Patalas trap and undisclosed mesh size in April - November, and found that zooplankton abundance reached a maximum of 100,000 individuals 100 m^{-3} and was greatest in late spring/early summer. Their report notes that rotifers, copepods, and copepod nauplii comprised most of the zooplankton community, which indicates that their mesh size was smaller than the present study, as rotifers were not collected in our 200 µ net. Thus maximum zooplankton abundance in Raritan Bay is considerably lower than the maximum seen in Barnegat Bay (> 2,500,000 indiv 100 m^{-3}, in May 2012), which may indicate lower secondary productivity in Raritan Bay. Shaheen and Steimle (1995) sampled the Navesink/Shrewsbury, NJ estuary using a 203 µ net. Sampling occurred during one summer (May - July) and collected on average approximately 200,000 individual 100 m^{-3}, which was higher than our summer average of 120,673 indiv 100 m^{-3}. A mean of 152,700 indiv 100 m^{-3} copepod adults and 70,100 indiv 100 m^{-3} nauplii were collected with a 80 µ net in Chesapeake Bay from May - October (Harding 2001); adult copepod values were higher than average copepod values found in Barnegat Bay (Table 9). Elliot and Tang (2011) collected copepods in Chesapeake Bay with a 200 µ net with abundances ranging from <100,000 - 2,000,000 indiv 100 m^{-3}, and found that copepod abundance, dominated by *Acartia* sp., peaked in March - June and July - October, and was lowest in winter. Average copepod abundance in Barnegat Bay was highest in winter and lowest in the fall during the present study.

Copepod abundance in Barnegat Bay appears to be comparable to other MAB estuaries. Maximum copepod abundance in Barnegat Bay was similar to that observed in a Long Island estuary, was higher than in Raritan Bay, but lower, at least during one summer sampling study, than that observed in the Navesink/Shrewsbury estuary. Mean abundance was somewhat higher in Chesapeake Bay in one study, but maxima were comparable in another. Trends in appearance of blooms was variable, with peaks seen in August in Long Island, early spring/summer in Raritan Bay and Chesapeake Bay, and late summer/early fall in Chesapeake Bay. Abundance in Barnegat Bay exhibited strong interannual variability, with maxima observed in May and

November/December in one year, late summer in another, and minimal peaks for nearly one year.

Copepods are the primary consumers in Barnegat Bay, and as such provide important food for a variety of organisms. Copepod total and mean abundance varied annually, seasonally, and spatially in this study. Although a pattern of spring and fall copepod blooms may be a paradigm typical of some MAB estuaries, the results of this study seem to suggest otherwise for Barnegat Bay, and potentially other estuaries with similar features. Factors such as survivability of copepod overwintering stages, phytoplankton abundance, and nutrient loading may impact the timing, intensity, and duration of blooms in the bay. Additionally, freshwater influence in the northern bay may result in a pulsed system that could affect bloom patterns of the zooplankton community, potentially causing an increase in zooplankton abundance (and secondary productivity) in response to an increase (Mann 2000) or decrease (Boynton et al. 1982, Day et al. 1989) in freshwater input. Further analyses examining the effects of phytoplankton abundance and distribution, as well as riverine flow volume, on zooplankton metrics are essential to elucidate patterns in zooplankton community dynamics.

Table 9. Total, mean and percent abundances of Barnegat Bay copepods by year. Data for 2013 and 2014 are also split to reflect sampling efforts in 2012 and 2015. Units are individuals 100 m-3 of water.

		Acartia spp.	Calanoida	*Calanus finmarchicus*	*Centropages hamatus*	*Centropages typicus*	*Centropages* spp.	Copepoda	Cyclopoida	*Eurytemora* spp.	Harpacticoida
2012											
May - Dec											
	Total	9526137.88	445024.18	1368.00	27966.52	10923.68	112635.97	59993.27	2519.04	25780.70	48829.07
	Mean	202683.78	9468.60	29.11	595.03	232.42	2396.51	1276.45	53.60	548.53	1038.92
	% Abundance	91.08	4.25	0.01	0.27	0.10	1.08	0.57	0.02	0.25	0.47
2013											
Jan - Dec											
	Total	2422119.44	70104.16	8437.07	977786.97	52360.06	602687.31	29182.14	10113.93	1370322.05	74677.90
	Mean	26912.44	778.94	93.75	10864.30	581.78	6696.53	324.25	112.38	15225.80	829.75
	% Abundance	35.58	1.03	0.12	14.36	0.77	8.85	0.43	0.15	20.13	1.10
Jan - Apr											
	Total	1522544.67	20704.26	8362.45	938477.74	49505.63	538088.86	24502.14	2810.82	1327419.56	4180.76
	Mean	60901.79	828.17	334.50	37539.11	1980.23	21523.55	980.09	112.43	53096.78	167.23
	% Abundance	27.37	0.37	0.15	16.87	0.89	9.67	0.44	0.05	23.86	0.08
May - Dec											
	Total	405227.49	47574.41	74.62	3427.49	908.58	11484.28	4638.12	6890.40	6616.44	33720.26
	Mean	6753.79	792.91	1.24	57.12	15.14	191.40	77.30	114.84	110.27	562.00
	% Abundance	70.88	8.32	0.01	0.60	0.16	2.01	0.81	1.21	1.16	5.90
2014											
Jan - Dec	**Total**	6196643.91	137041.28	376.53	180081.90	46556.70	102023.44	14139.55	7540.76	3151801.64	42227.66
	Mean	65921.74	1457.89	4.01	1915.76	495.28	1085.36	150.42	80.22	33529.80	449.23
	% Abundance	60.33	1.33	0.00	1.75	0.45	0.99	0.14	0.07	30.68	0.41
Jan - Apr											
	Total	595997.77	5475.46	339.07	152938.27	40935.52	66790.35	8825.77	693.69	3140209.07	7045.08
	Mean	23839.91	219.02	13.56	6117.53	1637.42	2671.61	353.03	27.75	125608.36	281.80
	% Abundance	13.54	0.12	0.01	3.48	0.93	1.52	0.20	0.02	71.36	0.16
May - Dec											
	Total	5371316.03	128837.22	37.46	6678.20	5562.60	15712.24	5181.05	6847.07	3488.04	34218.02
	Mean	83926.81	2013.08	0.59	104.35	86.92	245.50	80.95	106.99	54.50	534.66
	% Abundance	98.63	2.37	0.00	0.12	0.10	0.29	0.10	0.13	0.06	0.63
2015											
Jan - Apr	**Total**	166556.59	3832.75	197.17	40006.00	17820.75	37331.85	8342.88	24.99	335280.41	1725.15
	Mean	8327.83	191.64	9.86	2000.30	891.04	1866.59	417.14	1.25	16764.02	86.26
	% Abundance	25.30	0.58	0.03	6.08	2.71	5.67	1.27	0.00	50.93	0.26

Table 9 (cont'd). Total, mean and percent abundances of Barnegat Bay copepods by year. Data for 2013 and 2014 are also split to reflect sampling efforts in 2012 and 2015. Units are individuals 100 m-3 of water.

		Oithona spp.	*Paracalanus* spp.	Pontellidae	*Pseudocalanus minutus*	*Temora longicornis*	*Temora* spp.	*Tortanus discaudatus*	Grand Total
2012									
May - Dec									
	Total	116993.59	71764.08	303.94	7634.49	459.83	904.96	40.90	10459280
	Mean	2489.23	1526.90	6.47	162.44	9.78	19.25	0.87	222538
	% Abundance	1.12	0.69	0.00	0.07	0.00	0.01	0.00	
2013									
Jan - Dec									
	Total	293208.80	8992.59	1134.68	3515.34	853516.61	20905.81	9017.73	6808083
	Mean	3257.88	99.92	12.61	39.06	9483.52	232.29	100.20	75645
	% Abundance	4.31	0.13	0.02	0.05	12.54	0.31	0.13	
Jan - Apr									
	Total	245330.28	8952.18	0.00	3176.86	840815.64	20455.10	8491.50	5563818
	Mean	9813.21	358.09	0.00	127.07	33632.63	818.20	339.66	222553
	% Abundance	4.41	0.16	0.00	0.06	15.11	0.37	0.15	
May - Dec									
	Total	45354.21	40.41	1091.97	212.83	3696.10	450.71	297.32	571706
	Mean	755.90	0.67	18.20	3.55	61.60	7.51	4.96	9528
	% Abundance	7.93	0.01	0.19	0.04	0.65	0.08	0.05	
2014									
Jan - Dec	**Total**	53326.50	488.05	2344.00	304.62	314119.68	19890.98	2870.72	10271778
	Mean	567.30	5.19	24.94	3.24	3341.70	211.61	30.54	109274
	% Abundance	0.52	0.00	0.02	0.00	3.06	0.19	0.03	
Jan - Apr									
	Total	47395.33	127.76	0.00	48.98	311665.97	19567.24	2252.56	4400308
	Mean	1895.81	5.11	0.00	1.96	12466.64	782.69	90.10	176012
	% Abundance	1.08	0.00	0.00	0.00	7.08	0.44	0.05	
May - Dec									
	Total	5084.51	347.71	2289.59	104.67	58.63	136.00	1.85	5585901
	Mean	79.45	5.43	35.77	1.64	0.92	2.12	0.03	87280
	% Abundance	0.09	0.01	0.04	0.00	0.00	0.00	0.00	
2015									
Jan - Apr	**Total**	15900.28	213.12	0.00	777.43	29352.63	986.65	10.91	658360
	Mean	795.01	10.66	0.00	38.87	1467.63	49.33	0.55	32918
	% Abundance	2.42	0.03	0.00	0.12	4.46	0.15	0.00	

Table 10. Total, mean and percent abundances of Barnegat Bay copepods by season. Although total abundance is provided, sampling effort differed between the two time periods November - March and April - September. Units are individuals 100 m-3 of water.

Season		*Acartia* spp.	Calanoida	*Calanus finmarchicus*	*Centropages hamatus*	*Centropages typicus*	*Centropages* spp.	Copepoda	Cyclopoida	*Eurytemora* spp.	Harpacticoid
Spring	Total	3070301.31	36555.49	609.07	48286.36	83351.80	514357.22	21357.55	6203.42	362451 0.83	5451 1.3
	Mean	40398.70	480.99	8.01	635 3.54	1096.73	6767.86	281.02	81.62	4769 0.93	717.2
	% Abundance	35.22	0.42	0.01	5.54	0.96	5.90	0.24	0.07	41.58	0.6
Summer	Total	8803452.47	396868.98	61.86	609.40	204.82	634.21	9715.82	4747.88	1.97	5861 8.8
	Mean	114330.55	5154.14	0.80	7.91	2.66	8.24	126.18	61.66	0.03	761.2
	% Abundance	94.74	4.27	0.00	0.01	0.00	0.01	0.10	0.05	0.00	0.6
Fall	Total	5644156.62	204365.19	1347.88	29934.48	11422.67	122853.36	58510.48	7125.76	3588 3.21	4788 1.4
	Mean	83002.30	3005.37	19.82	440.21	167.98	1806.67	860.45	104.79	527.69	704.1
	% Abundance	88.22	3.19	0.02	0.47	0.18	1.92	0.91	0.11	0.56	0.7
Winter	Total	793547.42	182 12.70	8359.97	71242 8.17	32681.91	216833.78	22073.99	2121.66	122 278 8.81	644 8.2
	Mean	26451.58	607.09	278.67	2374 7.61	1089.40	7227.79	735.80	70.72	4075 9.63	214.9
	% Abundance	20.94	0.48	0.22	18.80	0.86	5.72	0.58	0.06	32.26	0.1

Season		*Oithona* spp.	*Paracalanus* spp.	Pontellidae	*Pseudocalanus minutus*	*Temora longicornis*	*Temora* spp.	*Tortanus discaudatus*		Grand Total	
Spring	Total	239765.24	4058.95	2530.27	1827.09	554491.17	14962.36	5269.02		871753 1.51	
	Mean	3154.81	53.41	33.29	24.04	7295.94	196.87	69.33		11470 4.36	
	% Abundance	2.75	0.05	0.03	0.02	6.36	0.17	0.06			
Summer	Total	15991.36	252.26	406.39	32.94	180.51	47.08	0.00		929182 6.77	
	Mean	207.68	3.28	5.28	0.43	2.34	0.61	0.00		12067 3.07	
	% Abundance	0.17	0.00	0.00	0.00	0.00	0.00				
Fall	Total	148810.20	71686.69	845.96	7428.55	3883.73	1428.76	73.42		639763 8.38	
	Mean	2188.39	1054.22	12.44	109.24	57.11	21.01	1.08		9408 2.92	
	% Abundance	2.33	1.12	0.01	0.12	0.06	0.02	0.00			
Winter	Total	74862.36	5459.94	0.00	2943.31	638893.34	26250.19	6597.81		379050 3.56	
	Mean	2495.41	182.00	0.00	98.11	21296.44	875.01	219.93		12635 0.12	
	% Abundance	1.97	0.14	0.00	0.08	16.86	0.69	0.17			

Table 11. Total, mean and percent abundances of Barnegat Bay copepods by site. Units are individuals 100 m-3 of water.

Site		*Acartia* spp.	Calanoida	*Calanus finmarchicus*	*Centropages hamatus*	*Centropages typicus*	*Centropages* spp.	Copepoda	Cyclopoida	*Eurytemora* spp.	Harpacticoida
2											
	Total	5568161.46	132764.91	1001.62	105977.69	18075.58	45295.02	3379.82	1379.79	762983.27	17814.86
	Mean	105059.65	2505.00	18.90	1999.58	341.05	854.62	63.77	26.03	14395.91	336.13
	% Abundance	80.50	1.92	0.01	1.53	0.26	0.65	0.05	0.02	11.03	0.26
5a											
	Total	2463316.16	55314.46	881.88	65809.63	6975.42	79279.77	9525.74	841.14	545080.48	10701.69
	Mean	45616.97	1024.34	16.33	1218.70	129.17	1468.14	176.40	15.58	10094.08	198.18
	% Abundance	71.90	1.61	0.03	1.92	0.20	2.31	0.28	0.02	15.91	0.31
7a											
	Total	2351750.07	38792.52	1995.56	229800.85	37268.81	497619.64	56564.12	3123.78	2201051.15	17858.75
	Mean	51125.00	843.32	43.38	4995.67	810.19	10817.82	1229.65	67.91	47848.94	388.23
	% Abundance	37.59	0.62	0.03	3.67	0.60	7.95	0.90	0.05	35.18	0.29
10											
	Total	3727394.49	73776.64	4909.60	550325.04	8060.41	166110.01	27443.60	6458.42	1313050.74	63035.80
	Mean	81030.32	1603.84	106.73	11963.59	175.23	3611.09	596.60	140.40	28544.58	1370.34
	% Abundance	60.98	1.21	0.08	9.00	0.13	2.72	0.45	0.11	21.48	1.03
12											
	Total	4200835.64	355353.83	1590.12	273928.19	57280.97	66374.13	14744.57	8395.58	61019.17	58048.69
	Mean	80785.30	6833.73	30.58	5267.85	1101.56	1276.43	283.55	161.45	1173.45	1116.32
	% Abundance	76.57	6.48	0.03	4.99	1.04	1.21	0.27	0.15	1.11	1.06

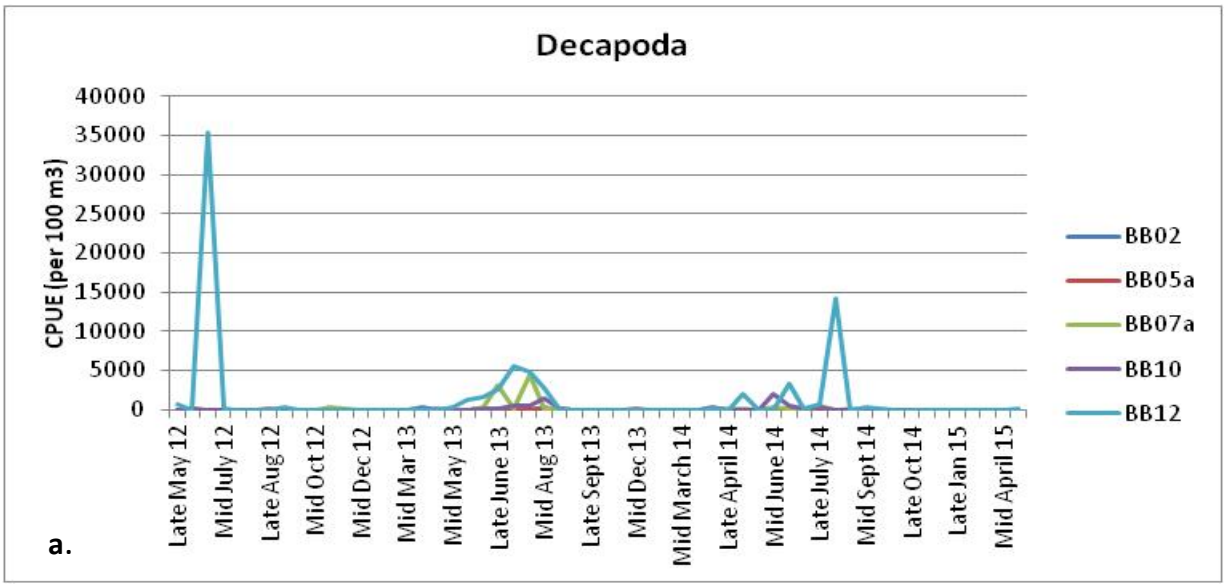
Table 11 (cont'd). Total, mean and percent abundances of Barnegat Bay copepods by site. Units are individuals 100 m-3 of water.

Site			*Oithona* spp.	*Paracalanus* spp.	Pontellidae	*Pseudocalanus minutus*	*Temora longicornis*	*Temora* spp.	*Tortanus discaudatus*		Grand Total
2											
		Total	47351.32	19867.20	18.13	9425.36	181697.60	805.63	798.89		6916798
		Mean	893.42	374.85	0.34	177.84	3428.26	15.20	15.07		130506
		% Abundance	0.68	0.29	0.00	0.14	2.63	0.01	0.01		
5a											
		Total	33182.75	5218.41	107.42	257.37	115546.32	33177.99	651.68		3425868
		Mean	614.50	96.64	1.99	4.77	2139.75	614.41	12.07		63442
		% Abundance	0.97	0.15	0.00	0.01	3.37	0.97	0.02		
7a											
		Total	299751.57	46916.30	526.29	245.29	462344.48	6705.00	4224.65		6256539
		Mean	6516.34	1019.92	11.44	5.33	10050.97	145.76	91.84		136012
		% Abundance	4.79	0.75	0.01	0.00	7.39	0.11	0.07		
10											
		Total	52066.40	1330.87	544.66	1264.89	113413.44	1258.82	1718.39		6112162
		Mean	1131.88	28.93	11.84	27.50	2465.51	27.37	37.36		132873
		% Abundance	0.85	0.02	0.01	0.02	1.86	0.02	0.03		
12											
		Total	47077.11	8125.07	2586.13	1038.98	324446.92	740.94	4546.65		5486133
		Mean	905.33	156.25	49.73	19.98	6239.36	14.25	87.44		105503
		% Abundance	0.86	0.15	0.05	0.02	5.91	0.01	0.08		

Decapods and Bivalves

Although decapod and brachyuran specimens have not been identified to species, the overall trend in both taxonomic groups shows highest abundances in the spring and summer (Fig. 15). The order Decapoda includes shrimp, lobster, hermit crabs, and other crustacean taxa with ten legs, while the infraorder Brachyura within Decapoda includes the true crabs. For this study, brachyurans were enumerated separately from the decapods. Peak abundance of decapod and brachyura larvae occurred in the summers of 2012 and 2014. The largest spawning pulse of this study occurred in the summer of 2012 at Site 12 in the southern bay. Decapod samples rose to over 35,000 individuals 100 m^{-3} of water, while brachyuran abundance was also extremely high at over 85,000 individuals 100 m^{-3} of water. Intensity and timing of these spawning pulses varied over the course of the study. The intense pulse in June 2012 may have been due to the warm winter of 2012-2013, while the later, less intense pulses observed in 2013 and 2014 may have been the result of the anomalously cold winters of 2013-2014 and 2014-2015.

As the brachyuran blue crab *Callinectes sapidus* is a valuable fishery stock, taxonomic analysis with higher resolution than presented in this study would be useful in reaffirming the value of Barnegat Bay as a nursery ground for the species. However, further examination of the interaction between environmental factors and the timing and intensity of spawning pulses is warranted to determine the extent of density-independent population dynamics.



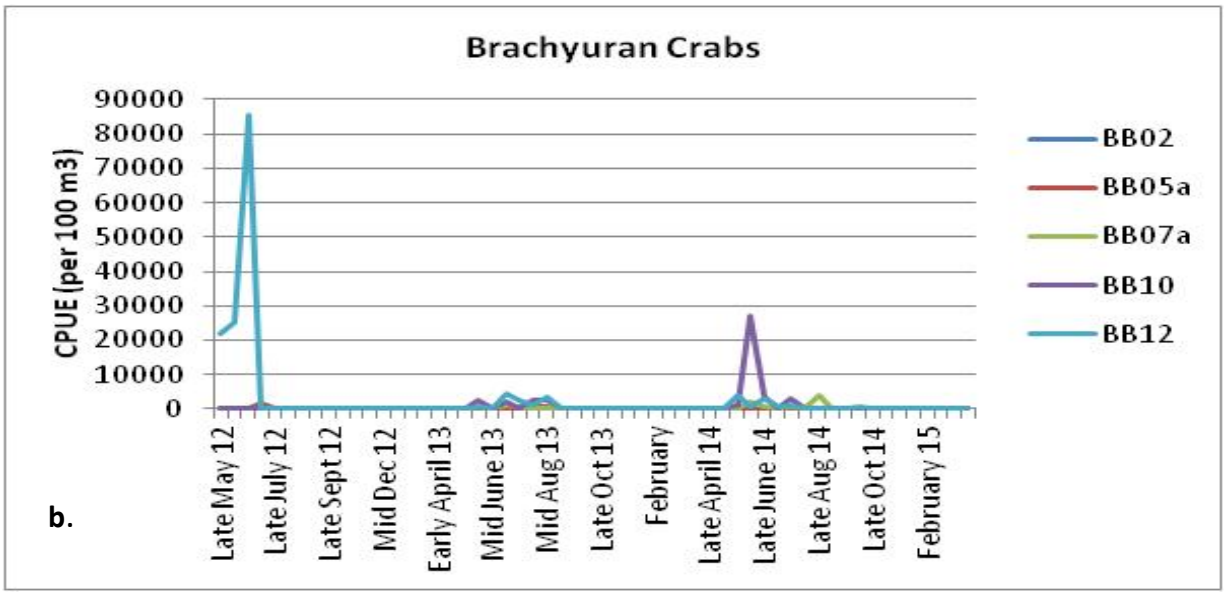


Figure 15. Abundance of arthropod larvae collected at Sites BB2, BB5a, BB7a, BB10, and BB12 in May 2012 – April 2015. **a**. Decapoda **b**. Brachyura (crabs). Sites BB7a and BB10 were added in late September 2012.

Several bivalve spawning events occurred during this study. Approximately 10,000 individuals 100 m^{-3} of water were collected at Site 2 in June 2012, with lower abundances collected at Sites 5a and 12 as well (Sites 7 and 10 were not sampled until September 2012) (Fig 16). Another small pulse occurred around the same time period in 2014, but primarily at Site 5a. Greatest abundance of bivalve larvae occurred in Fall 2012, one month after Superstorm Sandy, with an extremely large event evident in November and a smaller pulse in January. These two blooms were at Site 7a, the station closest to Barnegat Inlet, so it is unclear whether these bivalve larvae are from the bay or from coastal populations. A relatively small spawning event occurred in June-August 2013, with a maximum of 91 (Site 2) and 85 (Site 7a) individuals 100 m^{-3} collected during that time period (not visible on figure because of scale of y axis). Bivalve abundance throughout the rest of the study was low relative to the numbers seen during the spawning events.

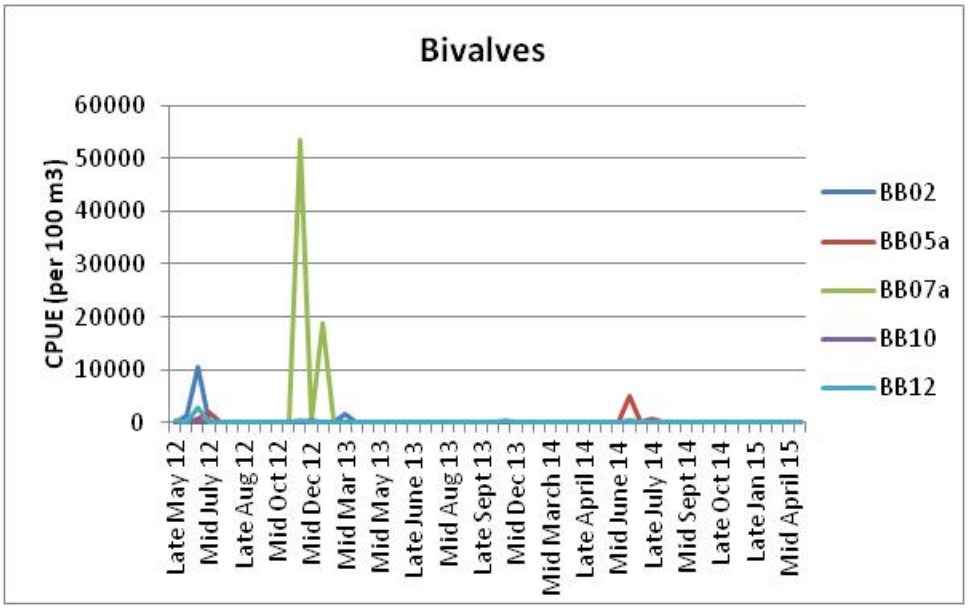


Figure 16. Abundance of bivalve veliger larvae collected at Sites BB2, BB5a, BB7a, BB10, and BB12 in May 2012 – April 2015. Sites BB7a and BB10 were added in late September 2012.

5.3 Effects of Environmental Parameters on Zooplankton Community Dynamics.

Zooplankton community data matrices were linked to those for environmental data. The RELATE and BioENV routines were first utilized to determine relatedness of the data sets; distance-based linear models (DistLM) and distance-based redundancy analyses (dbRDA) with multiple correlations were then used to determine the most parsimonious set of environmental factors contributing the most variability to the data. NJDEP-provided "nutrient" environmental data (alkalinity, chlorophyll a, nitrogen, phosphorus, and total suspended solids) covered 80% of this study's sampling events, therefore sampling events that did not have associated nutrient data were discarded (primarily late fall/winter 2013-2014 and 2014-2015). "Abiotic" environmental data (temperature, salinity, DO % saturation, pH, transparency, and water depth) were collected in the present study and thus represented 100% of the sampling events. When nutrient and abiotic environmental data were analyzed together, those sampling events that did not have associated nutrient data were discarded. These analyses were conducted for each sample type: 200µ, 500µ, and combined fractions (Table 12). This approach was taken to enable a comprehensive evaluation of the available data, and to determine if the nutrient and abiotic data could be combined into one analysis for each sample type.

Although none of the R^2 values for BioENV or DistLM are high relative to the maximum of 1, in the context of the study, highest R^2 values are seen in the abiotic data sets, driven by temperature. Although several variables created the most parsimonious set, temperature is by far the most important factor driving variability in the Barnegat Bay zooplankton community. The R^2 value for this factor was always an order of magnitude higher than the other factors, whether analyzed only with the abiotic group, or combined with the nutrient group. Although the nutrient R^2 values are low relative to temperature, the highest variability in this group can be attributed to alkalinity, nitrogen, and phosphorus.

Because of the strong variability in the zooplankton community due to temperature, the data were separated into seasons and analyzed with the statistics mentioned above. As the results of the previous analyses (Table 12) showed that there was not a large difference in the DistLM R^2 between abiotic (100% of samples) and abiotic+nutrient (80%) of samples, only the abiotic+nutrient analyses were conducted on the seasonal data. Zooplankton community data separate out along the dbRDA1 axis primarily according to sampling year, with phosphorus for the most part, and slight contributions from transparency and pH, driving the separation of 2013-2014 and 2014-2015 from 2012-2013. On the dbRDA2 axis, the data trend along a spatial gradient, with variability in Sites 2 and 5a (northern bay) driven by nitrogen and chlorophyll a, and variability in Sites 7, 10, and 12 driven by alkalinity, salinity, and to some extent phosphorus (Fig 17).

Although temperature remained the abiotic factor driving variability in the spring and fall samples, phosphorus was important in the fall as well. During summer and winter months when temperature remained stable, other variables became important, e.g. total suspended solids and transparency; the presence of both as important variables is not surprising given their

relationship (Table 13). One example of the data results represented in Table 13 is presented in for combined fractions for summer (Figure 18). Data separated again according to sampling year, with 2014-2015 grouping separately from the other years. Data also grouped according to latitude in the bay, with Sites 2 and 5a clustered separately from 7a, 10, and 12. Taxa driving the groupings included barnacles and polychaetes in the northern bay and decapods and gammarids in the southern bay.

5.4 Gelatinous Macrozooplankton

Targeted gelatinous macrozooplankton included the ctenophores Mnemiopsis leidyi and Beroe ovata, as well as the cnidarian scyphozoan Chrysaora quinquecirrha. Although initially abundant in the spring and fall of 2012, *M. leidyi* abundance has declined over the duration of this study (Fig 11a, b). Although abundance was also high in the winter of 2012-2013, *M. leidyi* was not collected during the two subsequent winters. In 2014, the ctenophore did not appear in samples until May, which was later than the previous spring; abundance during Summer 2014 was also lower than in previous summers. *M. leidyi* was not collected at all in 2015 before sampling was completed in April 2015. Ctenophore size distribution was variable across the bay, with a greater number and larger individuals collected in the southern sampling sites (Figs 12 – 16).

The uneven temporal distribution of *M. leidyi* was highly significant in a two-way ANOVA of date vs. site on abundance ($F = 2.205$, $p < 0.001$), probably because none were collected in the winters of 2013-2014 and 2014-2015. Although abundance patterns were generally uneven throughout the bay (Fig. 9 a, b), site was not significant in this analysis ($F = 0.774$, $p = 0.543$). However, the interaction of date and site was highly significant ($F = 10164$, $p <0.001$), most likely due to the great abundance of *M. leidyi* collected in the northern bay in the spring and summer in 2012.

As *M. leidyi* has historically been a common and abundant resident in Barnegat Bay, the overall decline in abundance over this three year study is a cause for concern, as it may be an indicator of greater issues in the bay. *M. leidyi* has no specialized life stages for overwintering (Costello et al. 2012). If a population dies or is advected out of the system, replenishment from another source would need to occur to reestablish the population. It appears that historically, Barnegat Bay has maintained an overwintering source population of *M. leidyi*, as is typified by the abundance patterns in this study over the winter of 2012-2013. In the two subsequent winters of this study, Barnegat Bay has changed from a source to a sink for *M. leidyi*. Although advection out of the system is possible, given the overall poor flushing in the bay it is more likely that the cold winter temperatures in 2013-2014 and 2014-2015 impacted *M. leidyi* populations. Although *M. leidyi* is characterized by a broad temperature tolerance range of 0 - 32ºC, the lower thermal limit is raised when salinity decreases to below approximately 20 – 22 ppt (Costello et al. 2012). Survivability is thus impacted with water temperatures approaching or reaching freezing (-1.9ºC for seawater at 35 ppt) and low salinity. Such conditions were typical of the upper bay during the latter two winters of this study, with measured water temperatures approaching 0ºC and salinities below 20 ppt. Reproduction in *M. leidyi* populations does not begin until temperatures reach 10 -

12 ºC. In late May 2012 when this study began, water temperatures were already above 25ºC, so *M. leidyi* spring reproduction would have been well established by then. In subsequent springs during this study, water temperature increased later in the spring so that temperatures were 5 - 10ºC lower at the same time of year.

As *M. leidyi* are important predators of zooplankton and ichthyoplankton in mid-Atlantic estuarine systems, the density-independent interannual variability observed in this study may have the potential to impact zooplankton community dynamics and potentially fishery stocks. Further analyses examining the effects of environmental factors on *M. leidyi* populations are essential to determine the extent of the top-down control *M. leidyi* exerts on zooplankton and ichthyoplankton communities in Barnegat Bay.

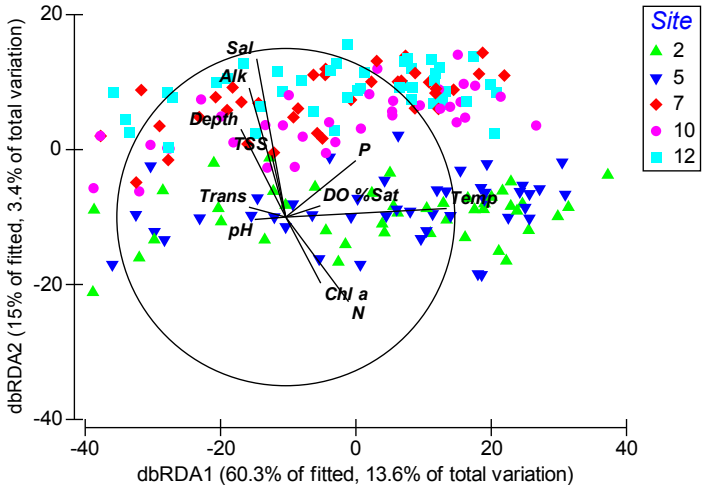
A predator of *M. leidyi*, the sea nettle *Chrysaora quinquecirrha* was collected in small numbers during each summer of the study (Fig 17 a, b). Abundance was highest in the northern bay in 2012 and 2013 but was also found at Site 12 in the southern bay in Summer 2013 and Spring 2014. Anecdotal evidence suggests that numbers were highest in the lagoons and embayments throughout the estuary during these time periods, so low abundance observed in this study may be an artifact of reduced encounter rates due to location of the organisms. Further, the large size of adult *C. quinquechirrha* often precludes them from being effectively collected with a 0.5 m plankton net.

The ctenophore predator *Beroe ovata* often co-occurs with its preferred prey *M. leidyi*. However, *B. ovata* occurred only rarely in the bay, and was only collected in very small numbers in the northern bay during periods of largest *M. leidyi* abundance, spring and summer of 2012 (Fig 18 a, b).

Table 12. Statistical tests examining the relationships between environmental variables and zooplankton community data. Environmental data matched study sampling event (zooplankton collections) as follows: nutrient = 80%, abiotic = 100%, nutrient+abiotic=80%. Unmatched sampling events were excluded from the analyses. Most pars. = most parsimonious match of variables. Highest indiv. R^2 = starred variable in most parsimonious set of variables had the highest individual R^2 value. Variables are numbered as follows: 1 = alkalinity, 2 = chlorophyll a, 3 = total nitrogen, 4 = total phosphorus, 5 = total suspended solids, 6 = temperature, 7 = salinity, 8 = dissolved oxygen % saturation, 9 = pH, 10 = transparency, 11 = water depth.

	Statistical Test		200-500 *u* Fraction		> 500 *u* Fraction		Both Fractions	
Nutrients	*PCO1,2*		24.70%	15.80%	20.90%	12.10%	23.80%	17.30%
	RELATE		p=0.016		p=0.001		p=0.007	
	BIOENV		p=0.001	corr=0.107	p=0.001	corr=0.107	p=0.001	corr=0.108
		most pars.:	4,5		3,4,5		4,5	
	DistLM-Best	*AICc*	1554.8		1631.3		1560.6	
		R^2	0.102		0.087		0.124	
		most pars.:	1*,2,4*		1,2,4*,5		1,2,3*,4*,5	
		**highest indiv R^2*	0.03		0.03		0.034	
	dbRDA 1, 2	*fitted%*	6.03	2.22	5.74	2.09	6.63	2.72
		total %	59.25	21.83	65.55	23.93	53.3	21.89
Abiotic	*PCO1,2*		22.60%	18%	22.20%	11%	23.10%	19%
	RELATE		p=0.001		p=0.001		p=0.001	
	BIOENV		p=0.001	corr = 0.298	p=0.001	corr = 0.419	p=0.01	corr=0.358
		most pars.:	6		6		6	
	DistLM	*AICc*	1908.5		1999.5		1908.8	
		R^2	0.21		0.2		0.23	
		most pars.:	*6*,7,8,10,11*		*6*,7,8,9,10*		*6*,7,8,9,10*	
		**highest indiv R^2*	0.12		0.15		0.14	
	dbRDA 1, 2	*fitted%*	12.27	4.62	15.09	2.58	14.82	3.64
		total %	59.08	22.22	75.61	12.94	62.82	15.42
Nutrients & Abiotic	*PCO1,2*		24.7%	15.8%	20.9%	12.1%	23.8%	17.3%
	RELATE		0.001		p=0.001		p=0.001	
	BIOENV		p=0.001	corr=0.259	p=0.001	corr=0.431	p=0.001	corr=0.341
		most pars.:	6		6		6	
	DistLM	*AICc*	1540.2		1606.8		1535.7	
		R^2	0.19		0.2		0.226	
		most pars.:	1,2,4,6*,7,10		4,6*,7,8,9		3,6*,7,8,10	
		**highest indiv R^2*	0.09		0.14		0.13	
	dbRDA 1, 2	*fitted%*	53.75	25.11	71.45	14.54	60.26	13.61
		total %	10.24	15.02	14.58	2.97	14.99	3.39

a.



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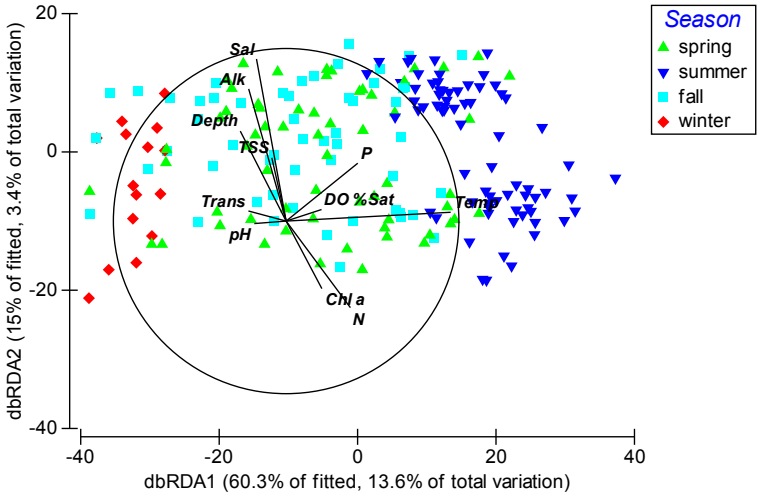

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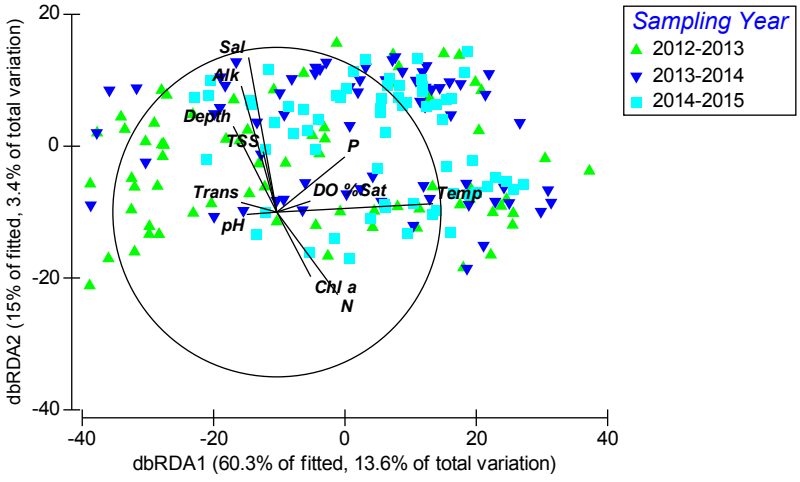


Figure 17. Distance-based redundancy analysis (dbRDA) plots of the zooplankton community data Bray-Curtis resemblance matrix for combined environmental variables (nutrient + abiotic) and combined fractions. **a**) by site, **b**) by season, **c**) by sampling year.

Table 13. Statistical tests examining the relationships between environmental variables and zooplankton community data for season and sample type. Environmental data included both NJDEP nutrient data and this study's abiotic data; data matched 80% of the study sampling events (zooplankton collections). Unmatched sampling events were excluded from the analyses. Most pars. = most parsimonious match of variables. Highest indiv. R^2 = starred variable in most parsimonious set of variables had the highest individual R^2 value. Variables are numbered as follows: 1 = alkalinity, 2 = chlorophyll a, 3 = total nitrogen, 4 = total phosphorus, 5 = total suspended solids, 6 = temperature, 7 = salinity, 8 = dissolved oxygen % saturation, 9 = pH, 10 = transparency, 11 = water depth.

Statistical Test			200-500 u Fraction		> 500 u Fraction		Both Fractions	
Spring	PCO 1,2		24.1%	18.9%	28.8%	13.7%	26.40%	19.30%
	RELATE		p=0.001		p=0.001		0.001	
	BIO ENV		p=0.001	corr=0.302	p=0.001	corr=0.445	p=0.001	corr=0.360
		most pars.:	2,6,7,10		6		6,7	
	DistLM-Best	AICc	459.04		476.03		459.92	
		R^2	0.24		0.299		0.335	
		most pars.:	6*,7,10		6*,7,8		6*,7,8,10	
		*highest indiv R^2	0.136		0.197		0.188	
	dbRDA 1,2	fitted %	60.53	23.03	67.67	24.63	57.92	19.63
		total %	14.53	5.53	20.21	7.36	19.4	6.57
Summer	PCO 1,2		31.8%	16.1%	25.0%	12.0%	30.70%	15%
	RELATE		p=0.183		0.125		p=0.106	
	BIO ENV		p=0.57	corr=0.106	p=0.18	corr=0.154	p=0.001	corr=0.848
		most pars.:	1,6,7,8,10		2,3,5,6		1,2,5,8,11	
	DistLM	AICc	550.06		567.12		546.06	
		R^2	0.1		0.112		0.10392	
		most pars.:	1,10*		5*,9,10		1,10*	
		*highest indiv R^2	0.056		0.045		0.056	
	dbRDA 1,2	fitted %	58.3	41.17	73.12	17.39	54.31	45.69
		total %	5.89	4.12	8.19	1.95	5.64	4.75

Table 13 (cont'd). Statistical tests examining the relationships between environmental variables and zooplankton community data for season and sample type. Environmental data included both NJDEP nutrient data and this study's abiotic data; data matched 80% of the study sampling events (zooplankton collections). Unmatched sampling events were excluded from the analyses. Most pars. = most parsimonious match of variables. Highest indiv. R^2 = starred variable in most parsimonious set of variables had the highest individual R^2 value. Variables are numbered as follows: 1 = alkalinity, 2 = chlorophyll a, 3 = total nitrogen, 4 = total phosphorus, 5 = total suspended solids, 6 = temperature, 7 = salinity, 8 = dissolved oxygen % saturation, 9 = pH, 10 = transparency, 11 = water depth.

Statistical Test			200-500 *u* Fraction		> 500 *u F*raction		Both Fractions	
Fall	*PCO1,2*		33.0%	17.2%	23.5%	10.2%	31.0%	16.4%
	RELATE		p=0.001		p=0.002		p=0.001	
	BIOENV		p=0.001	corr=0.390	p=0.001	corr=0.833	p=0.001	corr=0.407
		most pars.:	4,6,8,11		2,3,4,7,9		5,6,8,11	
	DistLM	*AICc*	403.4		430.3		402.5	
		R^2	0.334		0.232		0.346	
		most pars.:	4*,6*,7,8		4,6*,7		4*,6,7,8,10	
		**highest indiv R^2*	4=0.11, 6 = 0.12		0.144		0.104	
	dbRDA 1, 2	*fitted%*	44.68	28.86	65.63	22.36	41.48	30.57
		total %	14.9	9.62	15.25	5.2	14.35	10.58
Winter	*PCO1,2*		36.9%	19.7%	41.9%	24.7%	33.4%	18.2%
	RELATE		p=0.11		0.002		0.033	
	BIOENV		p=0.15	corr=0.348	p=0.001	corr=0.531	p=0.04	corr=0.424
		most pars.:	1,2,7,10		1,6,8,10		1,8	
	DistLM	*AICc*	119.49		114.17		114.27	
		R^2	0.144		0.381		0.3	
		most pars.:	1*		1*,8		7*,8*	
		**highest indiv R^2*	0.144		0.27		0.16	
	dbRDA 1, 2	*fitted%*	100	0	100	0	100	0
		total %	14.4	0	26.98	0	18	0

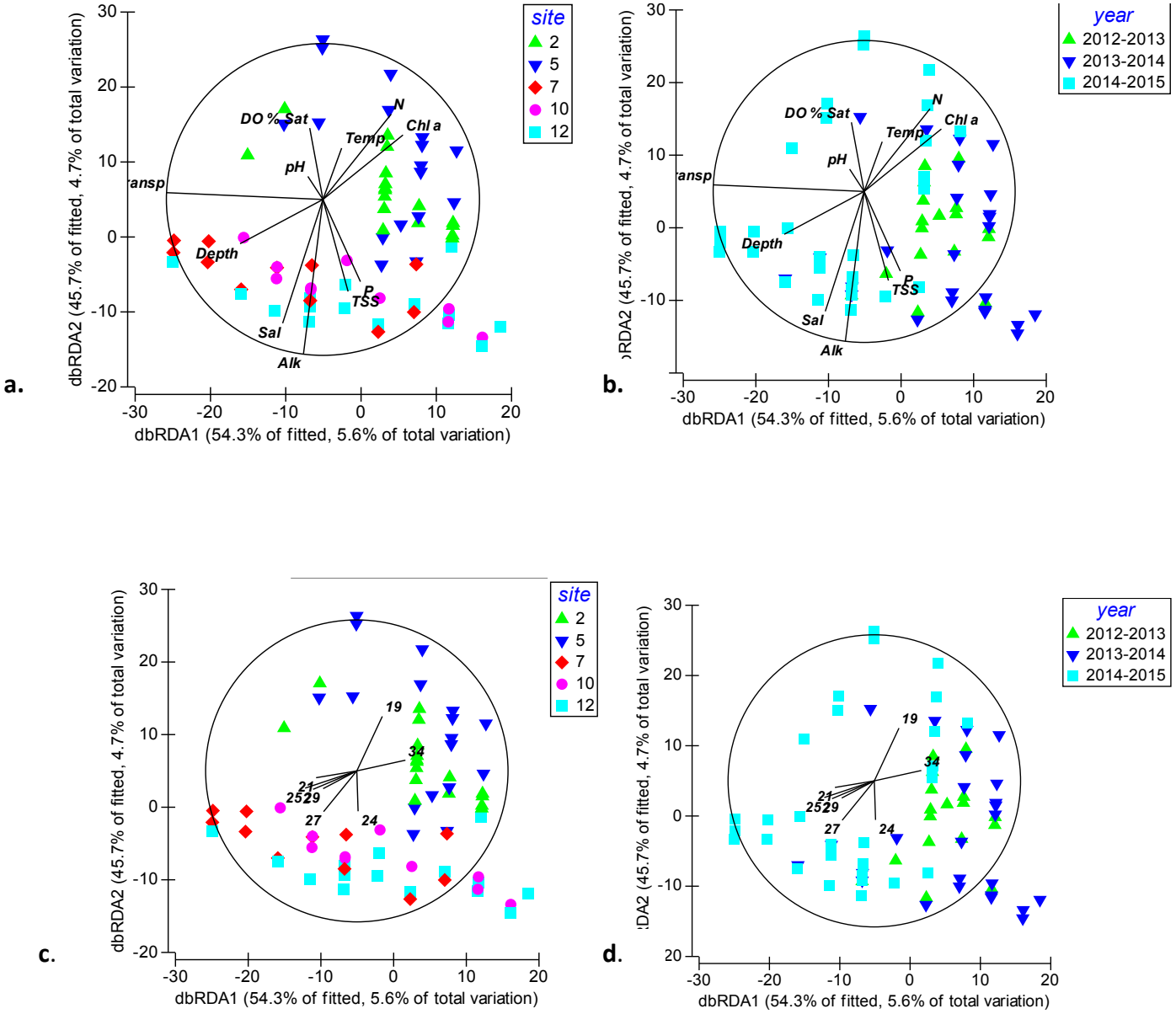
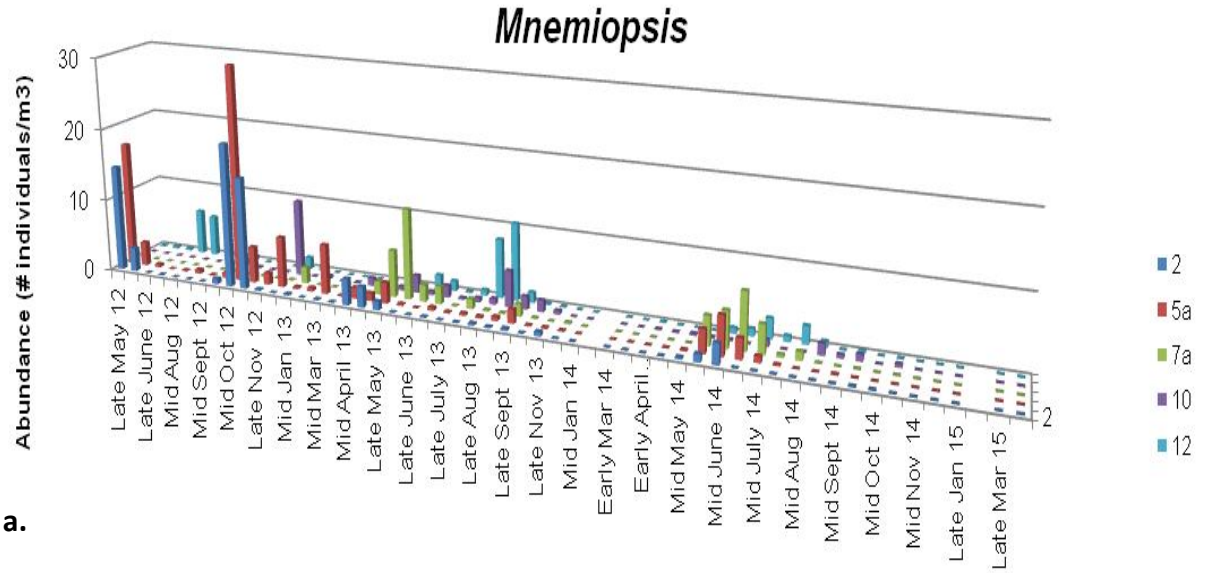


Figure 18. Distance-based redundancy analysis (dbRDA) plots of the zooplankton community data Bray-Curtis resemblance matrix for summer, combined fractions. **a**) by site, with all environmental variables, **b**) by sampling year, with all environmental variables, **c**) by site, with zooplankton taxa, correlation = 0.25, numbered as in Table 8, **d**) by sampling year, with zooplankton taxa, correlation = 0.25, numbered as in Table 8.



a.

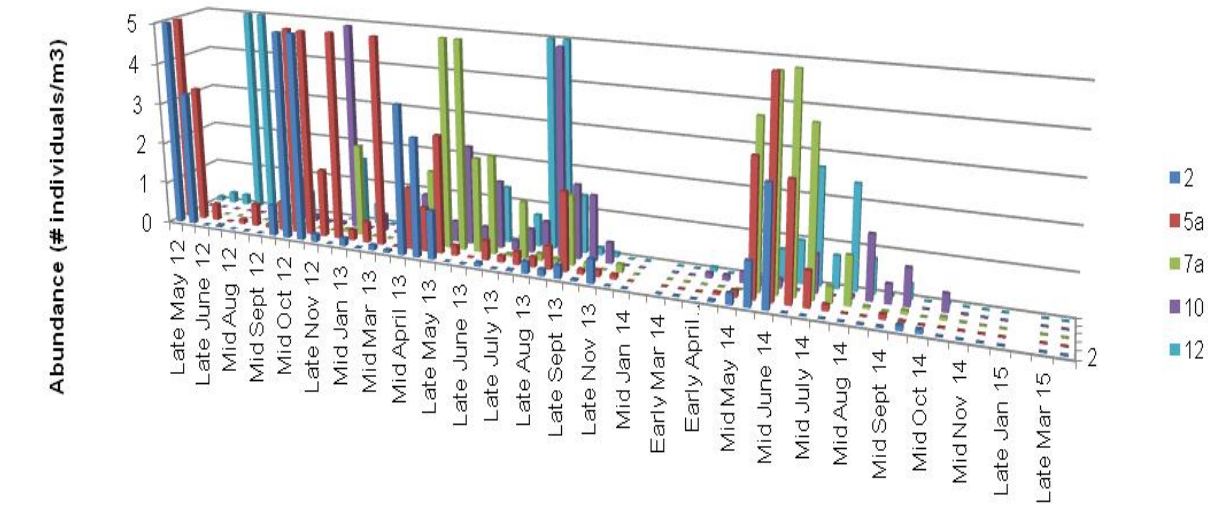


Figure 19. Abundance of *Mnemiopsis leidyi* collected at Sites BB2, BB5a, BB7a, BB10, and BB12 in May 2012 – April 2015. Sites BB7a and BB10 were added in late September 2012. Graphs are presented at two resolutions as the large values prevent a finer-scale assessment of lower abundances. a. coarse resolution; b. fine resolution (note differences in y axis between the two graphs).

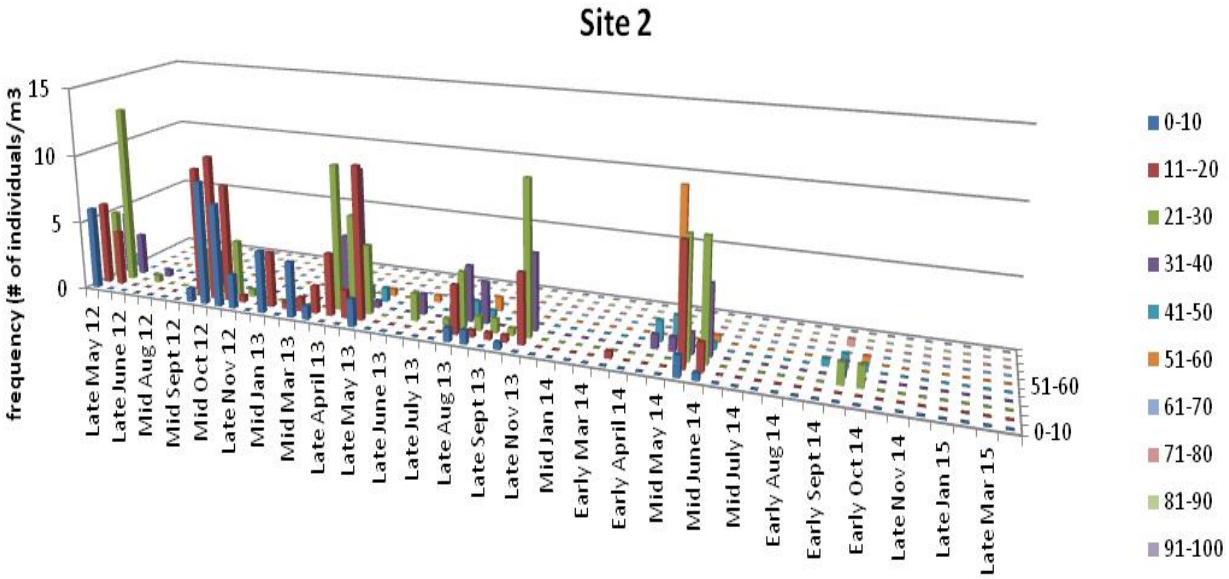


Figure 20. Frequency distribution of *Mnemiopsis leidyi* at Site BB02 collected May 2012 – April 2015. Legend: size classes of bell length (mm).

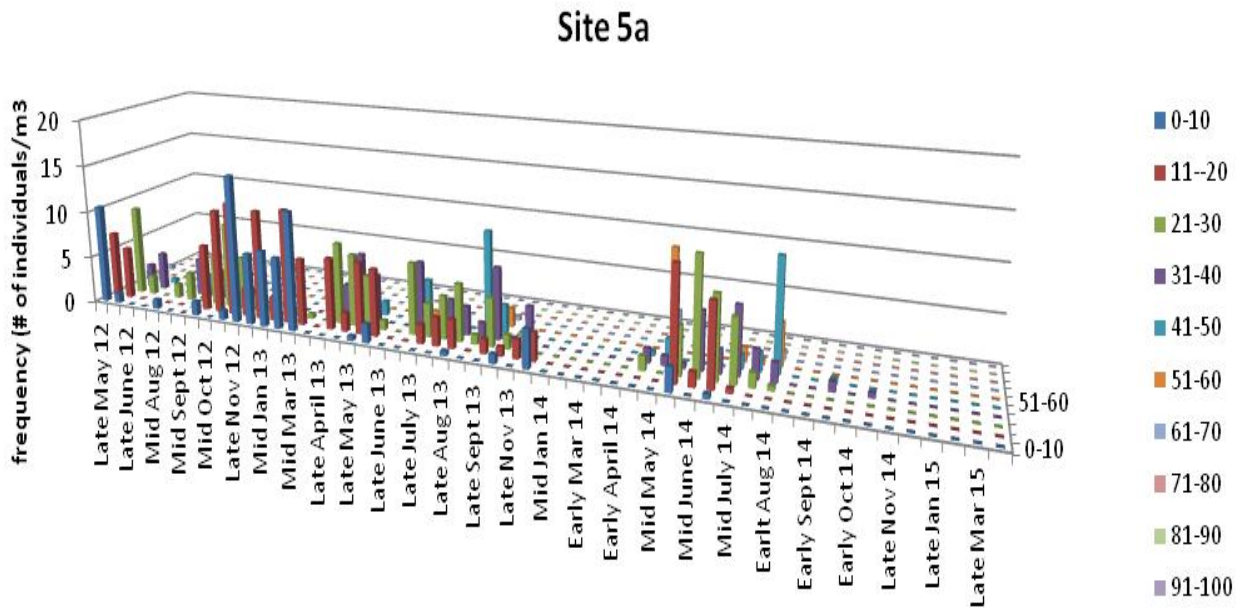


Figure 21. Frequency distribution of *Mnemiopsis leidyi* at Site BB05a collected May 2012 – April 2015. Legend: size classes of bell length (mm).

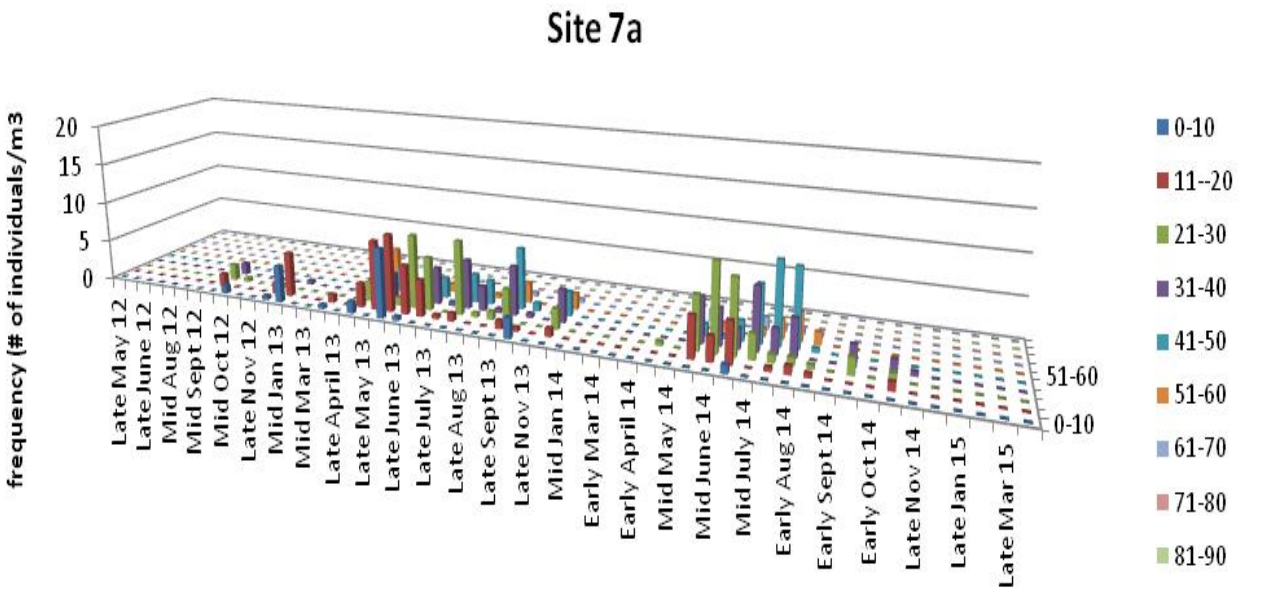


Figure 22. Frequency distribution of *Mnemiopsis leidyi* at Site BB07a collected May 2012 – April 2015. Legend: size classes of bell length (mm).

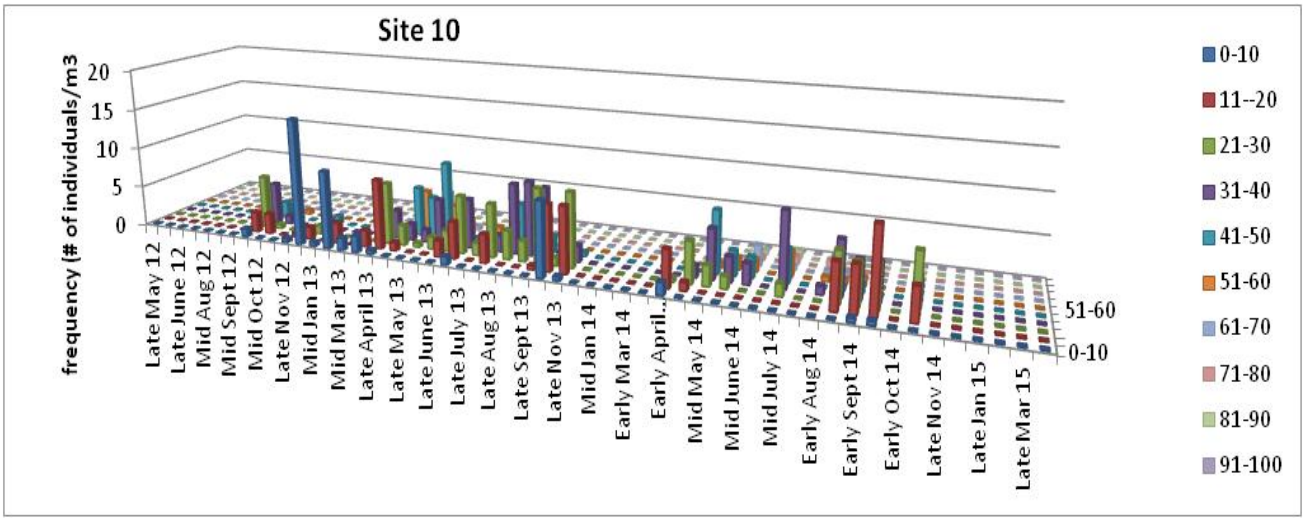


Figure 23. Frequency distribution of *Mnemiopsis leidyi* at Site BB10 collected May 2012 – April 2015. Legend: size classes of bell length (mm).

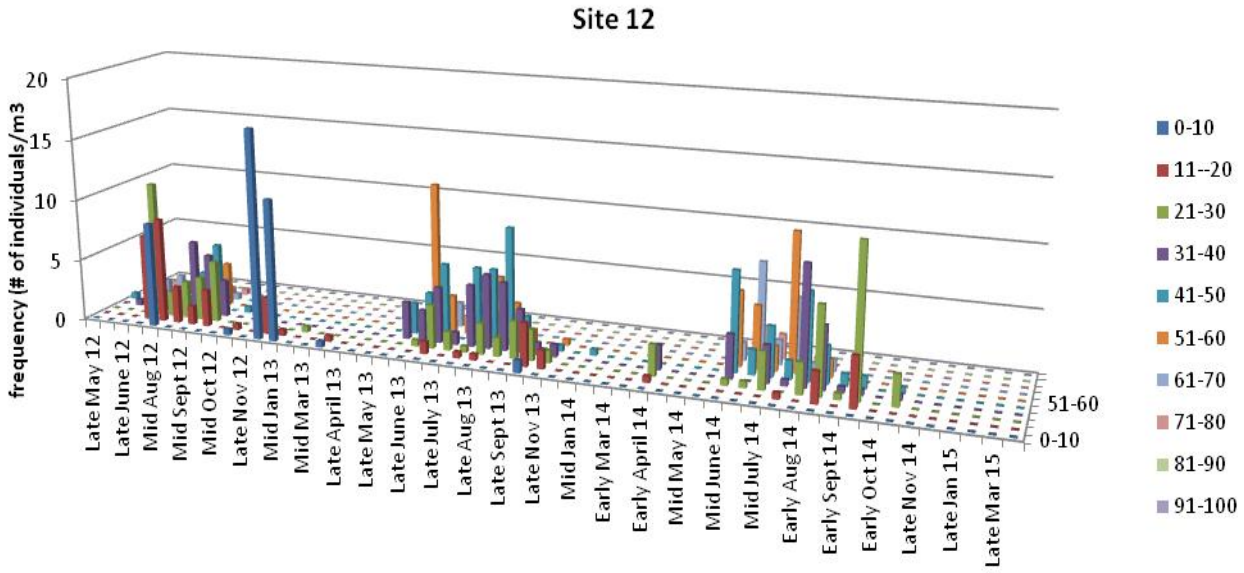
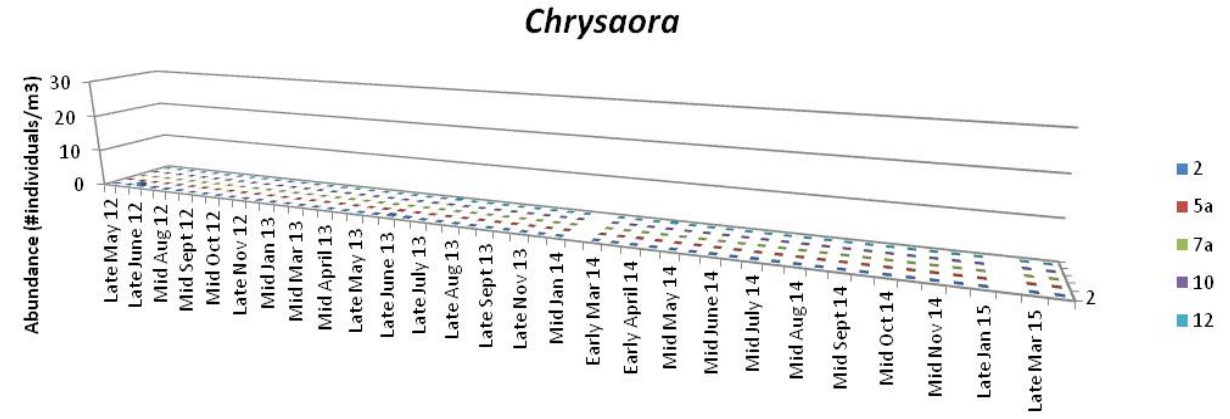


Figure 24. Frequency distribution of *Mnemiopsis leidyi* at Site BB12 collected May 2012 – April 2015. Legend: size classes of bell length (mm).



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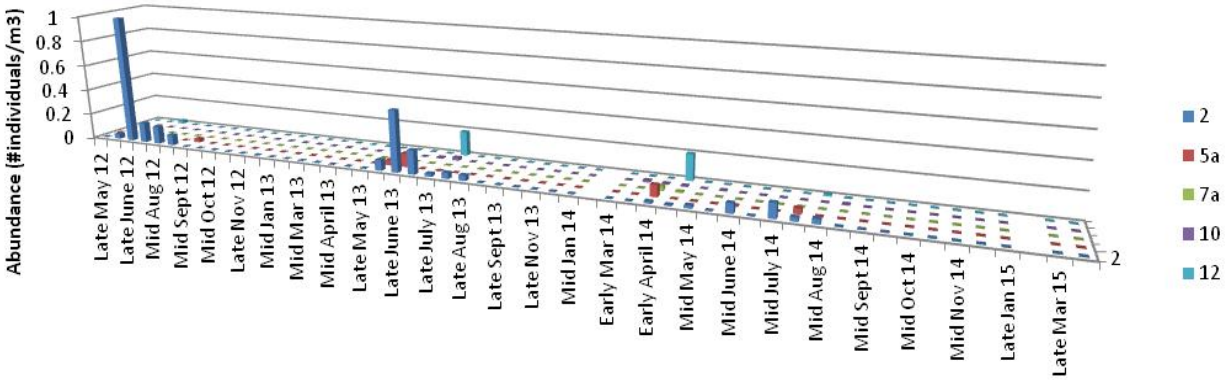
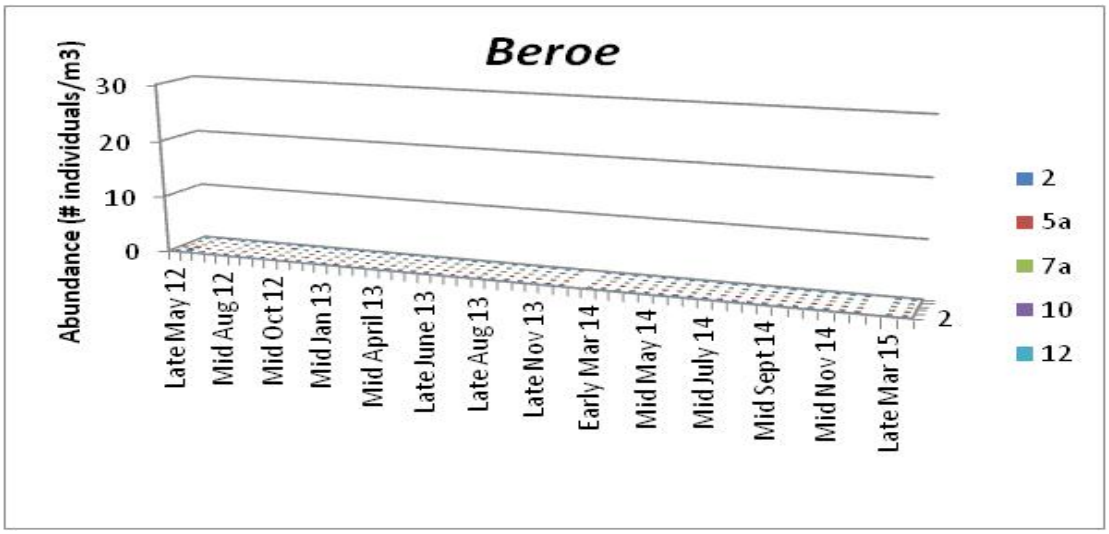
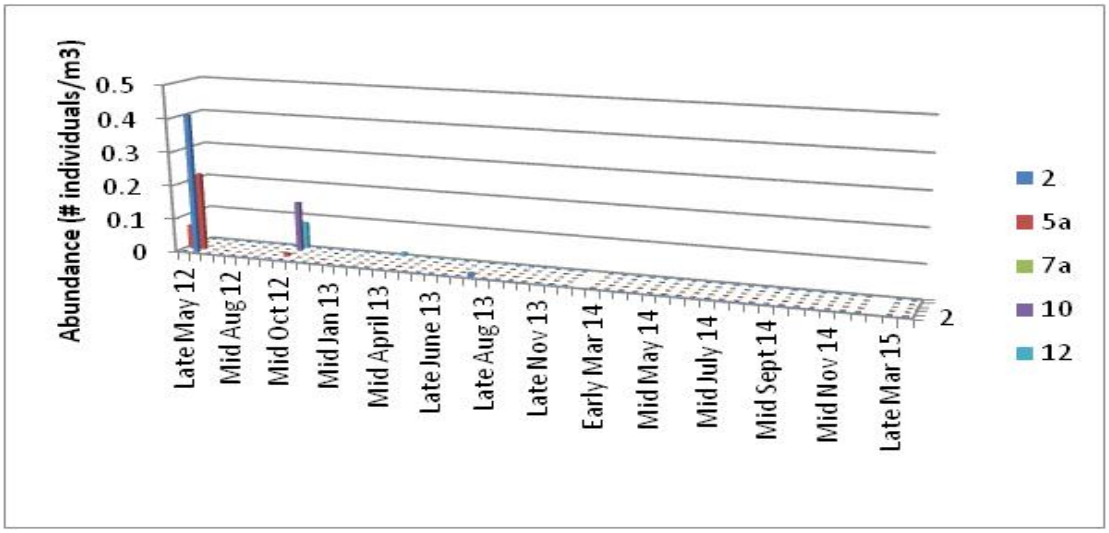


b.

Figure 25. Abundance of *Chrysaora quinquecirrha* collected at Sites BB2, BB5a, BB7a, BB10, and BB12 in May 2012 – April 2015. Sites BB7a and BB10 were added in late September 2012. **a**. y-axis maximum set at 30; **b**. y-axis maximum set at 1.



a.



b.

Figure 26. Abundance of *Beroe ovata* collected at Sites BB2, BB5a, BB7a, BB10, and BB12 in May 2012 – April 2015. Sites BB7a and BB10 were added in late September 2012. **a**. y-axis maximum set at 30; **b**. y-axis maximum set at 1.

5.5 Ichthyoplankton

Ichthyoplankton were removed from fresh samples and preserved in 95% ETOH for later identification. All larval specimens were mid-Atlantic estuarine and coastal species, indicating that the bay is a nursery for these species. Atlantic silverside was the most abundant species in Year 1 samples, comprising 56% of the total number collected. That species, along with winter flounder and northern pipefish, made up almost 88% of the entire Year 1 sample. Although Atlantic silverside was again very abundant in the Year 2 collection, the species only comprised 4% of the total number of fish larvae collected. The majority of ichthyoplankton collected were winter flounder, primarily during the April 2014 intensive sampling event. Winter flounder larvae made up 91% of the Year 2 ichthyoplankton collection.

Four intensive sampling events were conducted during 2012 – 2014. Ichthyoplankton collected during the July 2012 sampling event exhibited nocturnal vertical migration, as most were collected during the midnight tow (Fig 27). Although a few unidentified specimens were seen in the 8 am sample during the October 2012 event, the majority were collected in the 8 pm (20:00) and 4 am samples, not the midnight one (Fig 28). Species differed between the October 2012 and October 2013 (Fig 29) intensive events. Water temperature was warmer during Fall 2012, which may have impacted spawning by certain species in the bay or along the coast. During the April 2014 event, winter flounder *Pseudopleuronectes americanus* began to rise to the surface late in the afternoon, then were collected in large numbers in the plankton tows through early morning (Fig 30).

In the first three intensive sampling events, the majority of specimens were Atlantic silverside Menidia menidia, an important prey species in the bay. However, winter flounder abundance was an order of magnitude greater in the April 2014 sampling event. Further analyses of ichthyoplankton will be presented as an addendum.

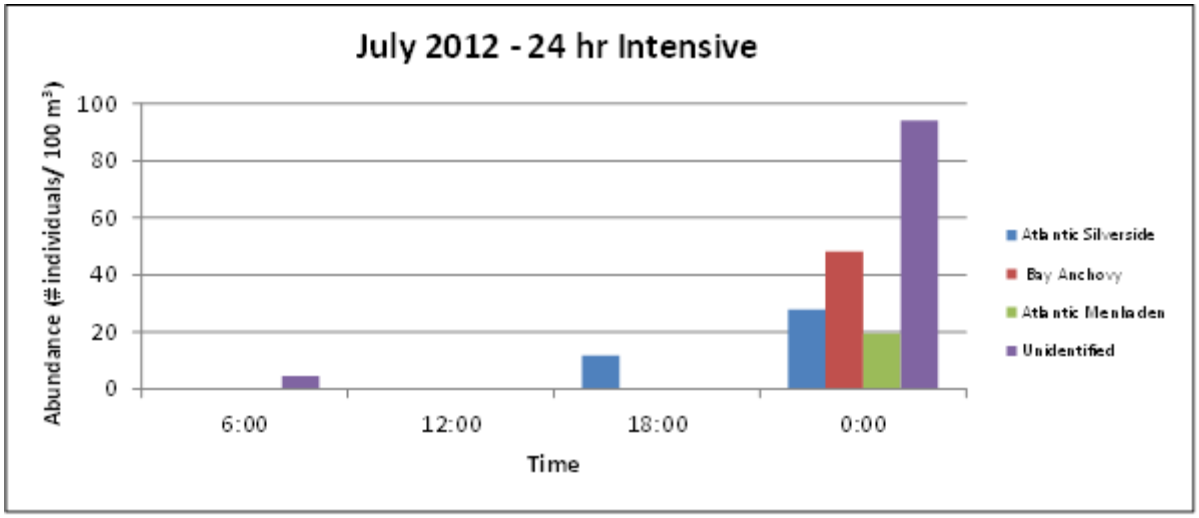


Fig 27. Abundance of ichthyoplankton collected at Site 5a over a 24 hr intensive sampling event in July 2012. Samples were collected every 6 hr.

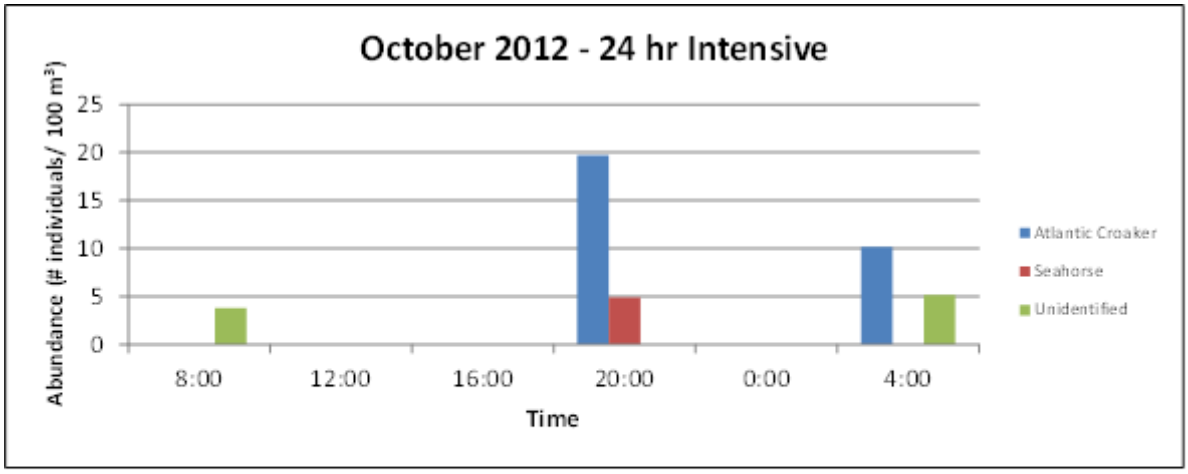


Figure 28. Abundance of ichthyoplankton collected at Site 5a over a 24 hr intensive sampling event in October 2012. Samples were collected every 4 hr.

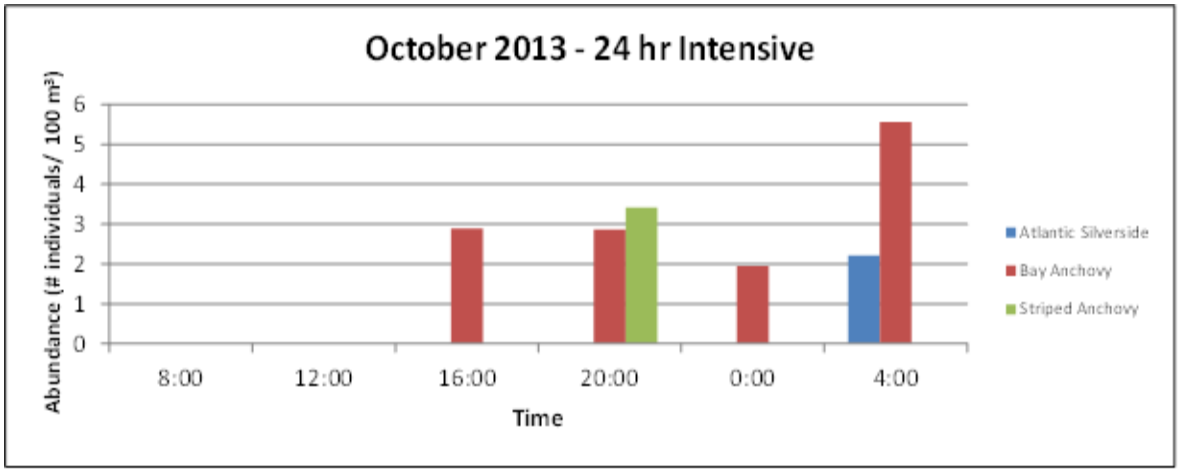
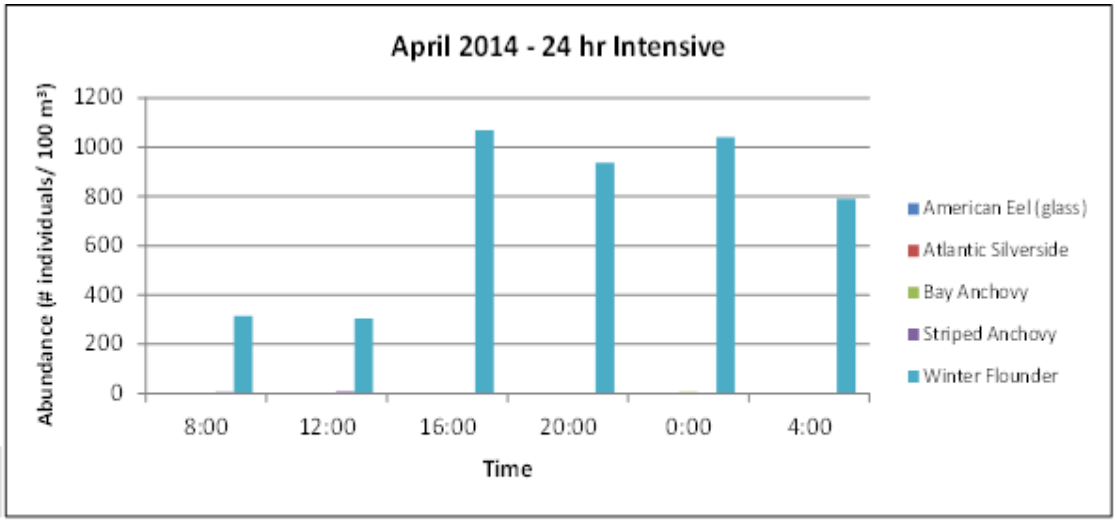
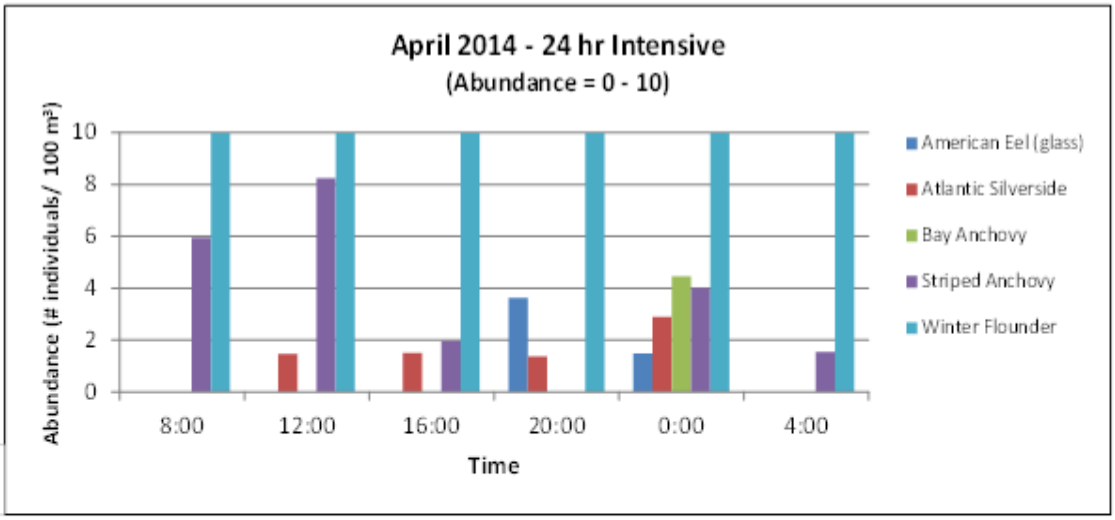


Figure 29. Abundance of ichthyoplankton collected at Site 5a over a 24 hr intensive sampling event in October 2013. Samples were collected every 4 hr.



a.



b.

Figure 30. Abundance of ichthyoplankton collected at Site 5a over a 24 hr intensive sampling event in April 2014. Samples were collected every 4 hr. **a**) normal scale on y-axis; **b**) maximum value on y-axis set to 10 so detail of abundance values for other species is visible.

6.0 CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE RESEARCH

The Barnegat Bay zooplankton community was characterized in a three-year study examining temporal and spatial trends in abundance and distribution. The most recent available studies, conducted in the 1970s (Tatham et al. 1977, 1978), provided a good assessment of two size fractions of the zooplankton community in one location in the central bay. The current study presents analyses of over 500 samples collected continuously over three years, at five sites along a north/south transect in the bay. Further, statistical techniques designed specifically for large sets of biological community data were employed to examine the effects of environmental parameters, as well as certain taxa, in driving the variability quantified in the Barnegat Bay zooplankton community.

Environmental Parameters

This study statistically examined the effects of 11 water quality variables on the distribution and abundance of the zooplankton community in the bay. The variable with the strongest response was temperature, which contributed up to 14% of the variability. For nutrient parameters specifically, nitrogen and phosphorus elicited the strongest response at approximately 4% each. Although the variability due to these nutrients is a third of that due to temperature, nevertheless it is a correlation that contributes to distributional patterns in the bay, with the community in the upper bay (nitrogen) showing a distinction from that of the lower bay (phosphorus). Any additional influx of nutrients may lead to changes in these distributional patterns, ultimately affecting the food web in the bay.

Of primary concern is the nitrogen level in the northern bay, as this area was characterized in this study as having lower species diversity and occasional strong blooms in a few dominant species, e.g. ctenophores and copepods, and has historically been subjected to high densities of sea nettles. As the northern bay is subject to greater impact by the watershed due to riverine input, it has the potential to be severely affected by anthropogenic terrestrial-based non-point source nitrogen (e.g. fertilizer). A strong recommendation is therefore warranted to seek measures to limit nitrogen input into the northern bay.

As the variability of the zooplankton community in the southern bay is influenced by phosphorus, and is distinguished from the north in part by a higher species diversity, the concern is for the potential effect of additional input of phosphorus into the bay. Therefore a strong recommendation is also made to seek measures to limit additional phosphate input into the southern bay.

Trends in Zooplankton Abundance and Diversity

The zooplankton community in Barnegat Bay is characterized by strong spatial, seasonal and interannual trends in abundance and diversity. Spatial variability is most apparent between the northern and southern sections of the bay, with a characteristic suite of taxa and water quality parameters exhibiting statistical correlation with each area. Seasonal and interannual differences are strongly correlated with temperature, but are likely also due to complex interactions with the phytoplankton community that were not addressed in this study. There was great variability in abundance of dominant taxa, e.g. *Acartia* spp. and *M. leidyi*, over the three years of this study; it is therefore not recommended that conclusions be drawn as to the status of these taxa based on only three years of highly variable data.

It is apparent, though, that direct and/or indirect effects of weather patterns affect zooplankton abundance in Barnegat Bay. Density-independent factors (e.g. temperature) strongly contribute to interannual variability in biological systems. This effect may serve to render the zooplankton community (and thus the food web) highly vulnerable to secondary, sub-lethal factors, resulting in potentially catastrophic conditions, e.g. a zooplankton community with low abundance or diversity as a result of several extreme winters is then subjected to a sub-lethal anthropogenic factor such as a pollutant. Additionally, such sensitivity to changes in weather patterns has the potential to cause long-term shifts in the zooplankton community as a result of climate change.

The northern bay (BB02, BB05a) was characterized by higher nitrogen and chlorophyll a, high abundances of *Acartia* and barnacle larvae, and the lowest species diversity of zooplankton and ichthyoplankton in the bay. Alkalinity and phosphorus was higher in the southern bay (BB07a, BB10, BB12), as was species diversity of both zooplankton and ichthyoplankton. This was a typical pattern for the duration of the study, and remained stable even between seasons. Because the water quality issues in the northern bay are exacerbated by poor tidal flushing and increased input from the watershed during the spring freshet, effort should be made to decrease any anthropogenic input of nutrients into the system.

There is a definite spatial difference in the bay, and lower water quality in the northern bay is likely due to increased urbanization coupled with poor flushing/water turnover in the upper bay. This has led to an increase in a few dominant taxa (*Acartia* spp., *M. leidyi*) at the expense of species diversity in the northern bay.

There do appear to be changes in the zooplankton community in the close to 40 years since the previous study was conducted in the bay (Tatham 1977, 1978). One important difference is that for the previous study, the calanoid copepod *Acartia* was dominant one year, while the cyclopoid copepod *Oithona* was dominant another year. Whether the low abundance of *Oithona* in the present study is due to urbanization in the bay watershed, changes in nutrient load, or differential feeding by *M. leidyi* is difficult to answer.

Direct comparisons between the two studies are challenging, as that study employed an 80 µ net and a 500 µ net. Copepod abundance was substantially higher than that seen in the current study, but the smaller net undoubtedly collected more smaller life stages of copepod species. Surprisingly, no copepods were collected in their 500 µ net, and the taxa collected differed somewhat from the current study. One taxonomic group, the polychaetes, was ten times greater in abundance in the present study, while chaetognaths were almost identical between one year of that study and the three-year average of this study. As the present study focused on community structure, further investigation is warranted to examine the community structure in the previous study so comparisons may be made.

Gelatinous Macrozooplankton

This portion of the study focused on the ctenophore *Mnemiopsis leidyi*, which was easily sampled with our plankton nets. Sea nettles were not sampled as readily, so conclusions as to their distribution and abundance cannot be made with great confidence.

M. leidyi is an important carnivore in mid-Atlantic estuarine systems, preying especially on holoplanktonic crustaceans (e.g. copepods) as well as ichthyoplankton. This species historically has produced strong blooms in the northern bay, likely tied to mild overwintering conditions coupled with availability of prey such as copepods. Two strong blooms were observed in this study, but interannual and seasonal variability was great. When the species does bloom, the impact on zooplankton populations may be devastating due to the sheer numbers that they consume (one adult ctenophore can eat up to ten times its weight in zooplanktonic crustaceans per day, Suthers and Rissik 2008). Managing the causal mechanisms of *M. leidyi* blooms therefore becomes an important consideration. Although parsing out the complex suite of conditions leading to a ctenophore bloom is challenging and many components, e.g. overwintering conditions, are outside of the purview of management, one recommendation to limit blooms is to decrease the amount of nitrogen input into the northern bay, which would likely lower prey availability. As sea nettles prey on ctenophores, this may also be an effective strategy to limit sea nettle populations. Further evaluation of *M. leidyi* population dynamics is forthcoming in a separate report.

Ichthyoplankton

The primary goal of this study was to sample zooplankton, so nets appropriate to that purpose were employed. The nets were smaller in mesh size than what is typically used for ichthyoplankton sampling; the smaller the mesh, the more slowly the net tows, and the higher the likelihood of net avoidance by active fish larvae. Additionally, net diameter and tow duration were less than recommended for ichthyoplankton sampling. Unless there has been a recent spawning event, ichthyoplankton tend to be considerably less dense than zooplankton in the water column. Therefore, a lower tow volume decreases the opportunity to collect taxa that are not as abundant in the water column ("rare" species).

Although the number of species collected in the study was lower than what would be expected in an ichthyoplankton study, because of the smaller mesh size we were able to collect extremely small, recently spawned larvae. We happened to sample shortly after winter flounder spawned in spring 2014, and larval abundance was extremely high. Winter flounder larvae were collected around the same time period the previous year, but numbers that year were substantially lower than in 2014. Interannual variability was evident for some species (e.g. winter flounder, northern puffer), but relatively stable in others (bay anchovy, pipefish).

Superstorm Sandy

Superstorm Sandy had a strong impact on water quality and the zooplankton community in Barnegat Bay. We were fortunate in that our October 2012 sampling event occurred four days before Sandy came ashore in NJ on October 29, and we were subsequently able to collect late November 2012 samples as well. Nutrient levels were extraordinarily high in the northern bay in November 2012 (in fact, BB02 for that sample date is an outlier in the data due to the "Sandy effect"). That strong pulse in chlorophyll a, nitrogen, phosphate, and total suspended solids was coupled with an extremely dense copepod bloom in November and December. The bloom was likely initiated by the storm's resuspension of nutrients and copepod resting cysts from bottom sediment.

Long-Term Ecological Perspective

Seasonal variability in the zooplankton community was evident, but these intra-annual differences were interannually regular, such that a community in the southern bay in winter occurred regularly over the three years of the study. The three years of data indicate that the bay could be divided into two sections, each with its characteristic zooplankton communities: the northern bay (BB2, 5a) and the southern bay (BB7a, 10, 12). It appears that the communities within these two habitats are resilient at least in the short term (duration of the study), as the habitats did not exhibit change and zooplankton community composition appeared to remain relatively stable. The northern bay is already impacted (developed watershed, more nitrogen) and is characterized by a few dominant euryhaline estuarine zooplankton taxa. The southern bay, however, is less developed and exhibits lower nitrogen levels, and is characterized by a diverse community characterized by more stenohaline coastal/oceanic copepod species.

The Barnegat Bay zooplankton community exhibited substantial interannual variability in abundance, probably due to differences in temperature/weather patterns and nutrients. As a zooplankton community is typically tightly coupled with the phytoplankton community and supports the remainder of the food web, factors that affect the zooplankton community may ultimately affect the entire food web. Thus anything that impacts zooplankton abundance will affect the food web and ultimately carbon cycling through the web. The zooplankton community in Barnegat Bay has the potential to be highly vulnerable in the wake of severe environmental disturbance.

As herbivorous zooplankton abundance is tied to phytoplankton production, evaluating phytoplankton community structure in conjunction with that of zooplankton will undoubtedly be important. Zooplankton may be subject to transport due to currents, tides, and wind, so examining a hydrodynamic model of the bay in conjunction with this study may help to further elucidate patterns in zooplankton distribution and abundance.

7.0 RECOMMENDATIONS AND APPLICATION AND USE BY NJDEP

NJDEP is currently providing funding for studies on phytoplankton, larger ichthyoplankton, a trophic model, and a hydrodynamic model. Communication has already been established with all of these groups, and zooplankton data have been provided to the group modeling trophic structure. It is recommended that NJDEP continues to facilitate communication among these groups and provide a platform (such as the annual workshop) for ongoing results to be discussed.

Development of Indicators

Intensive biologic and water quality sampling along a latitudinal gradient within Barnegat Bay over three years, coupled with additional water quality data provided by NJDEP, have allowed us to determine factors affecting zooplankton community dynamics in the bay. There are strong spatial, seasonal, and interannual trends, and patterns have emerged which lead to conclusions and recommendations about the zooplankton community within the bay.

The Barnegat Bay zooplankton community is characterized by common estuarine species, as well as taxa found only at specific locations at certain times of the year. Copepods are the most important primary consumers in the estuarine food web and provide food for a variety of species, including recreationally and commercially important fisheries species. The calanoid copepod *Acartia* is by far the most abundant zooplankton taxon in the bay and is ubiquitous throughout the bay, but its abundance is highly variable. This study determined that *Acartia* abundance is closely tied to temperature and seasonal changes in the bay. Copepod abundance is typically closely tied to the phytoplankton community as well, although further analyses with the Barnegat Bay phytoplankton dataset are essential to understanding these complex interactions in the bay. Additionally, as the phytoplankton community is impacted by nitrogen and phosphate levels, monitoring the copepod community provides insight into anthropogenic non-point source nutrient pollution.

Several coastal/oceanic calanoid copepod taxa, e.g. *Centropages hamatus*, *Centropages typicus*, and *Temora longicornis* were prevalent in Barnegat Bay during winter and early spring, especially near oceanic water such as Barnegat Inlet. Their appearance in the zooplankton community only at certain times of the year, as well as their preference for higher salinity water, make them an ideal suite of taxa to monitor for changes in the community, especially with the likelihood of climate change and sea level rise impacting mid-Atlantic estuaries in the coming century.

New Jersey was marked by three climatic events during the study: Superstorm Sandy in October 2012, and subsequently two unusually severe winters in 2013-2014 and 2014-2015. The zooplankton community in Barnegat Bay exhibited responses to these events with fluctuations in abundance, timing of blooms, and species makeup of the community; these events were especially characterized by *Acartia* and several other species.

Acartia and the coastal/oceanic taxa mentioned above were most abundant in 2012-2013; the coastal/oceanic taxa may have been advected into the bay as a result of the Superstorm Sandy storm surge bringing large volumes of oceanic water into Barnegat Bay. A bloom was produced likely as a result of sediment resuspension in the bay and resultant high concentrations of nutrients in the water column. However, given the extremely cold winters of 2013-2014 and 2014-2015, it is difficult to definitively state that this is the case, as we do not have zooplankton abundance data from a mild, non-catastrophic year with which to compare. This highlights the importance of continuous monitoring of the zooplankton community within the bay, as the zooplankton, along with the phytoplankton, are the backbone on which rests the remainder of the Barnegat Bay food web.

In addition to monitoring calanoid copepods for environmental changes, this group is more susceptible to pesticide contamination than cyclopoid copepods (Suthers and Ressik 2008). Cyclopoid copepods such as *Oithona* were more abundant than *Acartia* in a study of Barnegat Bay zooplankton in 1977; decreasing levels of pesticides may have resulted in a shift in the community over the last 30 - 40 years. *Oithona* and/or other cyclopod taxa may therefore provide a useful indicator of pollutant contamination of the bay.

In addition to holoplanktonic taxa such as *Acartia*, meroplanktonic organisms are important members of the zooplankton community, and fluctuations in their abundance and distribution may impact the entire food web of the bay. Small fishes such as the bay anchovy and silverside are important food for many species of economically important recreational and commercial fisheries species in Barnegat Bay and the New Jersey coast. Therefore, monitoring of the larvae of these "feeder fishes" along with the larvae of fisheries species such as winter flounder, black sea bass, croaker, and invertebrate fisheries including blue crab and clam species, will provide us with a better understanding of factors influencing larval mortality.

The ctenophore *Mnemiopsis leidyi* exhibited great variability during this study, with large numbers seen after a warm winter, and extremely reduced numbers after two successive severe winters. *M. leidyi* are voracious predators on copepods and ichthyoplankton and likely exhibit top-down control on these important groups. Extreme fluctuations in *M. leidyi* abundance have important implications for the rest of the food web in Barnegat Bay, so this species should be monitored as well.

Adaptation of Study to Long-Term Monitoring

Zooplankton community characteristics and water quality parameters in Barnegat Bay separate along a latitudinal gradient. *Acartia* and Balanidae (acorn barnacles), lower salinity, and higher nitrogen and chlorophyll a are characteristic of BB02 and BB05a in the northern bay. BB07a, BB10, and BB12 are linked by the zooplankton community of *C. hamatus*, *C. typicus*, and *T. longicornis*, as well as higher salinity, alkalinity, and phosphorus. BB05a is more centrally located in the northern section of the bay, so this site would provide the best location for monitoring of the biological community and water quality parameters. Data for BB07a and BB12 each overlap with BB10, but remain distinctive from each other. Therefore BB10, which is more centrally located in the southern section of the bay, would be the best of the three locations to monitor. However, BB07a is subject to influence by coastal/oceanic water from Barnegat Inlet, so monitoring the biological community there would also be useful to evaluate long-term effects of climate change. As BB07a is located near Oyster Creek Nuclear Generating Station, it is recommended that monitoring take place there to compare pre-closure and post-closure impacts to the zooplankton community.

Although this study provided a very comprehensive picture of zooplankton community dynamics in Barnegat Bay, costs may be streamlined by reducing the number of taxa identified, as well as the taxonomic resolution of the identifications. For this study, there were 119 different taxa (from species to class) that the laboratory could have identified, including 72 copepod taxa. Of the 119 taxa, 72% of them were found in our samples, but only 29% (34 taxa) were found in greater than 5% of our samples. Although specific taxa were mentioned above in terms of focused monitoring, in order to fully understand changes in the zooplankton community, the community itself should be monitored and analyzed with multivariate statistics appropriate for non-normally distributed abundance data. A comprehensive yet cost-effective sampling protocol could be created that would include common Barnegat Bay taxa, e.g. those 34 taxa that were present in $\geq$ 5% of this study's samples, as well as taxa that were well-represented in earlier studies.

Zooplankton blooms in the bay exhibited strong temporal variability. An extremely dense bloom was seen in May 2012, followed by a somewhat smaller bloom in December and January after Superstorm Sandy, and an even smaller bloom in spring 2013. The spring bloom was substantially delayed in 2014, not appearing until the summer, and did not appear at all before the study ended in late April 2015. Overall copepod abundance was very low from May 2013 through March 2014. It is therefore a challenge to suggest ways to streamline the collection of zooplankton monitoring samples when temporal variability is so great. Reducing the numbers of sampling events in the late fall and winter months, unless there is unusual activity such as a late hurricane or a warm winter, may reduce cost.

An additional method to reduce cost may be to decrease the numbers of samples processed for each sampling event. Two nets (200µ and 500µ) were towed separately for each sampling event.

The 200-500µ fraction was saved from the 200µ net, and the >500µ fraction was set aside. The >500µ fraction was collected from the 500µ net because it was hypothesized that the 200µ net would tow more slowly than the 500µ net, so larger organisms would have a greater opportunity to avoid the net. As this study retained the >500µ fraction from the 200µ net, it is suggested that a subset of these samples be analyzed and compared with the results from the >500µ fraction from the 500µ net, to determine if a 200µ net could be used for both the 200-500µ fraction and the >500µ fraction in a potential future monitoring program.

8.0 REFERENCES

BBNEP. 2001. The Barnegat Bay Estuary Program Characterization Report. Barnegat Bay National Estuary Program. Toms River, NJ.

BBNEP. 2005. State of the Bay Report. Barnegat Bay National Estuary Program. Toms River, NJ.

BBNEP. 2006. Getting to Know Our Neighbors -- Sea Nettles. The Barnegat Bay Beat. Volume 5, Issue 2 (Summer/Fall 2006).

Bologna, P., J, Gaynor, and R. Meredith. 2015. Impacts of Invasive Sea Nettles (*Chrysaora quinquecirrha*) and Ctenophores on Planktonic Community Structure and Bloom Prediction of Sea Nettles Using Molecular Techniques. New Jersey Department of Environmental Protection Final Project Report, 137 p.

Boynton, W.R., W.M. Kemp, and C.W. Keefe. 1982. A comparsion analysis of nutrients and other factors influencing estuarine phytoplankton production. Pages 69 - 90 in V.S. Kennedy, ed. Estuarine Comparisons. Academic Press. New York City, NY.

Costello, J.H., K.M. Bayha, H.W. Mianzan, T.A. Shiganova, and J.E. Purcell.. 2012. Transitions of *Mnemiopsis leidyi* (Ctenophora:Lobata) from a native to an exotic species: a review. Hydrobiologia. 690:21-46.

Day, J.W., Jr., C.A.S. Hall, W.M. Kemp, and Y. Yanez-Arancibia. 1989. Estuarine Ecology. Wiley. New York City, NY.

Elliot, D.T. and K.W. Tang. 2011. Spatial and temporal distributions of live and dead copepods in the lower Chesapeake Bay (Virginia, USA). Estuaries and Coasts. 34:1039–1048.

Gewant, D. and S. Bollans. 2005. Macrozooplankton and micronekton of the lower San Francisco estuary: seasonal, interannual, and regional variation in relation to environmental conditions. Estuaries and Coasts. 28(3):473-485.

Harding, J.M. 2001. Temporal variation and patchiness of zooplankton around a restored oyster reef. Estuaries. 24(3):453-466.

Hare, J. 2015. Ecology of the Northeast US Continental Shelf: Zooplankton. NOAA/NEFSC. http://nefsc.noaa.gov/ecosys/ecosystem-ecology/zooplankton.html.

Johnson, W. and D. Allen. 2005. Zooplankton of the Atlantic and Gulf Coasts: A Guide to Their Identification and Ecology. Johns Hopkins University Press. Baltimore, MD.

Kennish, M. 2001. Barnegat Bay – Little Egg Harbor, New Jersey: Estuary and Watershed Characterization. Journal of Coastal Research, Special Issue. SI(32):163-167.

Kingsford, M. and C. Battershill. 2000. Studying Temperate Marine Environments: A Handbook for Ecologists. CRC Press. Boca Raton, FL.

Kremer, P. 1994. Patterns of abundance for *Mnemiopsis* in US coastal waters: a comparative overview. ICES Journal of Marine Science. 51(4): 347-354.

Mann, K.H. 2000. Ecology of Coastal Waters, 2nd ed. Blackwell Science. Malden, MA.

Mianzan, H., E.W. Dawson and C.E. Mills. 2009. Phylum Ctenophora: Comb Jellies. pp. 49-58. *In* New Zealand Inventory of Biodiversity. Volume One. Kingdom Animalia: Radiata, Lophotrochozoa, and Deuterostomia (D.P. Gordon, editor). Canterbury University Press, Christchurch.

McNamara, M., D. Lonsdale and R. Cerrato. 2010. Shifting abundance of the ctenophore *Mnemiopsis leidyi* and the implications for larval bivalve mortality. Marine Biology. 157(2): 401-412.

Purcell, J. undated. Jellyfish in Chesapeake Bay and Nearby Waters. Center of Environmental and Estuarine Studies, Horn Point Lab, University of Maryland. URL:\\http:www.intercom.net\local\shore_journal\jp010716.html.

Rothenberger, M.B., T. Swaffield, A.J. Calomeni and C. D. Cabrey. 2014. Multivariate analysis of water quality and plankton assemblages in an urban estuary. Estuaries and Coasts (2014) 37:695–711.

Sandine, P. 1984. Zooplankton. In: Kennish, M. and R. Lutz. 1984. Ecology of Barnegat Bay, New Jersey. Lecture Notes on Coastal and Estuarine Studies. Springer-Verlag. New York, NY.

Shaheen, P.A. and F.W. Steimle. 1995. Trends in copepod communities in the Navesink and Shrewsbury Rivers, New Jersey: 1962-1992. Estuaries 18(1B):250-254.

Sullivan, B., D. Van Keuren and M. Clancy. 2001. Timing and size of blooms of the ctenophore *Mnemiopsis leidyi* in relation to temperature in Narragansett Bay, RI. Hydrobiologia. 451(1): 113-120.

Suthers, I. and D. Rissik, eds.. 2009. Plankton: A Guide to Their Ecology and Monitoring for Water Quality. CSIRO Publishing. Australia. 272 pp.

Tatham, T., P. Sandine, R. Smith, H. Hoffman, K. Tighe and D. Thomas. 1977. Ecological Studies for the Oyster Creek Generating Station. Ichthyological Associates, Inc. Ithaca, NY.

Tatham, T., P. Sandine, R. Smith, K. Tighe, F. Swiecicki and D. Thomas. 1978. Ecological Studies for the Oyster Creek Generating Station. Ichthyological Associates, Inc. Ithaca, NY.

Turner, J.T. 1982. The annual cycle of zooplankton in a Long Island estuary. Estuaries. 5(4):261-274.

Wilson, S., J. Carleton and M. Meekan. 2003. Spatial and temporal patterns in the distribution and abundance of macrozooplankton on the southern North West Shelf, Western Australia. Estuarine, Coastal and Shelf Science. 56(5-6):897-908.