Generator cooling water effluent restriction effects of Oyster Creek Generating Station closure on the Barnegat Bay fish, crab, and infaunal invertebrate community

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Contents

1.0 Executive Summary

Closure of the Oyster Creek Nuclear Power Generating Station in Forked River, Lacey Township, NJ, in September of 2018 resulted in a 95% reduction of cooling water flow. Since cooling water was drawn from and discharged back into the Barnegat Bay near Barnegat Inlet, the historical effluent plume heated water with the potential to affect the thermal ecology of cold-blooded fish and invertebrates. The cooling water pumps also entrained larval fish and crabs directly and thus potentially affected the mortality of select species in the bay's larval source pool. The effluent plume secondarily affected stratification and flow in the area through production of a warm, low-density, plume . Closure allowed a retrospective examination of these potential effects as well as provided a model for the sensitivity of the local fish and invertebrate community to climate change. This study leveraged previously collected samples of fish, crabs, and invertebrates from as far back as 2012 for comparison with recent sampling (2018-2021) in a Before/After Control/Impact design (for fishes and crabs) or a Before/After/Gradient design (for benthic infauna) to challenge the null hypothesis that there was no effect of closure and to quantify any noted effects relative to natural variation. Measures included abundance/distribution (for fishes, crabs and benthic infauna), assemblage change/beta diversity (for fishes and invertebrates), and size (for fishes) at different life stages as sampled by plankton net, otter trawl, crab traps, and gillnets. The strength of effects and the confidence in their measure was dependent on species and life stage, and for some there were no measurable effects. In all cases, BACI/BAG interactions (effects measured as different after closure in the Impact sites relative to their measure in the Control sites) were secondary to other sources of variation, including habitat, seasonal, and interannual variation, and spatial variation among the control sites. It is apparent that control site choice, as a function of measurement scale, affects the answer, pointing to a recognized and fundamental challenge in ecology. In retrospect, the plant was well sited because the spatial extent and persistence of the plume effects were dampened by regular tidal exchange with the ocean through Barnegat Inlet. Measured effects on sex-specific crab distribution and benthic invertebrate distribution and abundance decreased rapidly with distance from the discharge. Abundance was never seriously depressed (and was increased for adult fish) during operation in the Impact site, most likely because it was never source limited. Fish, benthic infauna, and many of the crabs utilizing the bay arrive from distant spawning sites as larvae, and many of the adult stages arrive as migrants; thus, local consumption by the plant was mitigated. Further, the life history of these species are adapted to and experience, individually and as populations, a greater annual and range-wide thermal variation than that produced by the generating station. This is a function of the station's location near the apex of the Middle Atlantic Bight, and should be expected to differ from similar power-plant cooling water disturbances elsewhere in the country or world.

While the body of this report broadly addresses findings, Appendices provide hundreds of species-specific measures of fit and statistical weight for invertebrates, crabs, and fish of different life stages that can be used to inform and populate synthetic predictive heuristic models (such as Ecopath with EcoSim) that have and continue to be used to understand the Barnegat Bay as habitat for living resources.

2.0 Introduction/Problem Statement

In September 2018, Exelon Corporation's Oyster Creek Nuclear Generating Station (OCNGS) in Forked River (Lacey Township), New Jersey became the first nuclear generating station in the United States to shut down in preparation for decommissioning (World Nuclear News 2018). Until then, the facility, commissioned in December 1969, drew once-through cooling water for a Rankine Cycle condenser from the Barnegat Bay estuary 2.5 billion L/day (BLD) and 2.8 BLD) and discharged 5.3 BLD as heated (average increase of 10.2 ^{o}C) effluent (State of New jersey 2010). Upon plant shutdown, this flow was reduced to about 5% of its historical rate. The effect of the cooling process, including passage through pumps and the heating effects, are thought to be a contributor to the spatial-temporal dynamics of the Barnegat Bay and its fish, crab, and benthic invertebrate communities (Kennish and Lutz 1984, Mayhew et al. 2000).

Estuaries, including the Barnegat Bay specifically, are important spawning, nursery, and harvest areas for fish and invertebrates of recreational, commercial, and ecological importance in the temperate waters of the northeastern U.S., including New Jersey (Able and Fahay 1998, 2010, Able et al. 2017, Valenti et al. 2017). Our knowledge of the life history and ecology of fish, crabs and benthic invertebrates throughout estuaries has been improving in recent years, in part, because the information on these topics is demanded by ichthyologists, estuarine ecologists, pollution biologists and resource managers at local, state, federal and international levels. The fishes constitute one of the largest portions of the animal biomass and thus they are important to estuarine ecosystems. Sport and commercial fishers are also becoming increasingly interested in fish life histories and ecology because representatives from both groups are beginning to play a larger advisory role where fish habitats and fish survival are concerned. Recently, these audiences have been further broadened by an informed general public, who are interested in (and alarmed by) the conflicting interests of aesthetic and recreational uses versus negative impacts resulting from human population pressures that bring habitat destruction and direct and indirect (non-point) sources of pollution. Up to 75% of east coast fish populations valued as a resource are to some degree “estuarine dependent” (McHugh 1976, 1977, Deegan et al. 2000, Pendelton 2008, Able and Fahay 2010). The OCNGS potentially impacted the nursery function of the Barnegat Bay because this estuary is where larval and juvenile fishes encounter several critical life history “bottlenecks” that can greatly affect survival rates and the resulting abundance of certain populations that we wish to harvest or conserve.

One species of particular concern is the economically and ecologically important blue crab, *Callinectes sapidus*. Blue crabs are arguably the most important (in terms of numbers harvested) commercially and recreationally harvested species in Barnegat Bay, and other New Jersey estuaries. They are estuarine dependent, spending all but the earliest life history stage within numerous estuarine habitats (Jivoff and Able 2001). Ecologically, they are a dominant member of estuarine fauna, and they serve as both important predators on other benthic invertebrates and as prey for a variety of fish species (Hines 2007). A recent modelling effort hypothesizes that blue crabs are one of only a few species that would be significantly positively influenced by the shutdown of the OCNGS either directly, due to the elimination of mortality from impingement and entrainment in the OCNGS, or indirectly via enhanced trophic interactions (Summers et al. 1989, Vasslides et al. 2017). This study provided the first empirical test of that hypothesis.

Benthic invertebrates are also important to estuarine ecology. As a bar-built estuary, Barnegat Bay benthic habitats are primarily composed of unconsolidated sediments, and invertebrate sampling focused on infauna and sediment properties.

The objective of this work was to assess the response of fishes, crabs, and infaunal invertebrates in the Barnegat Bay as a response to water flow and temperature decrease (and potential indirect effects of salinity, dissolved oxygen concentration, and velocity) resulting from decommissioning of the OCNGS in the Barnegat Bay, New Jersey. Response was measured through metrics of abundance, composition (assemblage), and size and challenged the Null Hypotheses:

$H0_1$: There are no spatial/temporal differences in the abundance of fishes/crabs/infauna as a result of closure of the OCNGS

$H0_2$: There are no spatial/temporal differences in the assemblage of fishes/crabs/infauna as a result of closure of the OCNGS

$H0_3$: There no spatial/temporal differences in the size of juvenile or small (age 1 adult) fishes as a result of closure of the OCNGS.

3.0 Mobile Fauna

3.1 Methods

3.1.1 Study Design

The study applied Before-After-Control-Impact (BACI) design to assess the status of the fishes and crabs in Barnegat Bay in response to changes associated with the cooling water shut down. The response variables for fishes are a) fish abundance, b) fish species composition (assemblage), and c) fish size (as a proxy of growth). Examination included larvae, juvenile, and adults. Sampling under the current project funds commenced several months prior to shut down and continued afterwards to span a total of three years of sampling (four years total span including a one-year hiatus in response to the Covid-19 pandemic). By using some of the same sites sampled in a three-year (2012-214) study of the status of fishes and crabs relative to urbanization impacts in the Barnegat Bay (Valenti et al. 2017), the BACI design incorporated a longer “Before” component than would otherwise be allowed given the short notice on the plant’s closure.

BACI designs incorporate both spatial and temporal control elements to emulate a clinical trial with a “treatment” using the general model:

$$Y_{(a,b,c)} = A*\text{Period} + B*\text{Location} + (A*\text{Period}|B*\text{Location}) + \text{Random Effects}$$

In the current case, Y is either (a) abundance, (b) assemblage, or (c) size, A is the effect of the period (Before or After), B is the effect of the location (Impacted or Control), and the model contains an interaction term and random effects. The random effects differ for the sampling strategies used to assess settled juvenile fish and crabs or larval fish and are detailed separately in sections pertaining to them. Replicate sample sites are not likely to be spatially auto correlated based on ecological scaling and habitat differences. Although they are not likely to be temporally autocorrelated based on a focus on early life history stages that naturally decouple year-class strength, and partly on the seasonal basis because species recruit and grow into and out of trawl vulnerability on a seasonally specific basis, autocorrelation was nevertheless accounted for in the BACI design by blocking these variables within permutations of the Generalized Linear Mixed Model (GLMM). The treatment, which defined the Impact site (Stratum 3), was the restriction of warm effluent to 5% of its flow from the 47-year historical flow. Indirect effects of cooling flow reduction, such as change in salinity and sedimentation are possible. (Understanding the specific mechanisms through which an effect is promulgated is served by a different experiment). All sites were sampled several times before treatment began and again after cooling water shutdown was implemented. The control sites (In Strata I and sometimes IV) were sufficiently distant from the treatment site so as not to encounter environmental changes from the treatment, but close enough to share a common ecosystem, mobile predators, climate and weather, and larval pool (Able et al. 2017, Valenti et al. 2017). Control site replicates were also temporally and spatially decorrelated by scale and were sampled on the same schedule as treatment sites. In sampling practice, this is the same as an inventory or gradients design, but in analysis, a time series of the control provides a time-varying reference line against which the treatment sites are quantified as a response. It is thus a powerful tool for isolating treatment effects in the presence of high natural variation.

For blue crab abundance as measured by traps, we used 5-way repeated measures ANOVA focused on the creek habitats (the only habitat with a plume) of Strata I and III. The repeated measure was CPUE in time (CPUE in the before years combined versus CPUE in the after years combined) with the following independent factors: month (May-August), strata (I and III), creek site (1 and 2), plume (in and out), and sex (male and female). Individual pair-wise comparisons within interactions with $p < 0.05$ were tested with paired t-tests.

We used alpha = 0.1 as a “clear” indication of difference and alpha = 0.05 as “very clear”, but in keeping with recommendation of Gelman and Stern (2006) and Dushoff et al. (2019), we discuss p levels more generally as levels of confidence that there was an effect, rather than as absolute thresholds of determining whether or not an effect happened (formerly “significance”). We comment on clear main effects in the text, but all effects, including null effects, are reported in the tables and appendices.

For the purpose of assessing compositional change as a response, species abundance data for all included (unambiguous) taxa was expressed as catch-per-unit-effort (CPUE as fish per 100 m^3 of plankton net sampled water, fish per m^2 of trawled area, or fish per minute of soak time for gill net). Samples were ordered by principal components after log(Y+1) transformation or by detrended correspondence analysis following inspection of the overall gradient length of compositional (centered species) data. The first four principal components or correspondence axes were independently tested as response variables because they are orthogonal.

3.1.2 Sampling Campaigns

Four sampling campaigns focused on different aspects of the fish and crab population that could respond differently to the environmental effects of cooling water shutdown. These included a) sampling larval fish stages using a plankton net, b) sampling settled juvenile and small adult species using an otter trawl net, c) sampling large mobile fish using gill nets, and d) sampling crabs using traps. The methods for each of these campaigns is detailed below. It is important to note here that the campaign foci necessitated some differences in the specific site sample distribution and schedules from each other as noted in the Sampling Sites and Sample Timing below. **Tables 1-4** summarize the monthly and annual distribution of samples available for analysis in each campaign based on effort from the current sponsored project (2018, 2019, 2021) as well as those from previously completed and reported projects (2012-2014).

3.1.3 Sample Sites

This study took place in Barnegat Bay using a sampling template from a comprehensive 3-year study of the fishes (see Valenti et al. 2015 for one component) and crabs (see Jivoff et al. 2015 for one component) of this estuary. It applied a naming convention for a stratified sampling design contiguous with previous work using three sample of five sample Strata (Valenti et al. 2015) and useful in the BACI design for continuity with that study. This took advantage of numerous samples collected prior to the current project to increase the sample size of the Before factor. The rational for specific samples sites within strata relate to the needs of a campaign and are addressed separately in the methods sections for each of those.

3.1.4 Sample Timing

Data from the previous study (2012-2014) was applied to the BACI design as part of the Before sample factor with additional sampling in 2018 up to the beginning of the shutdown procedure in September 2018. The second After sampling year was originally planned for April-October 2020 but was canceled due to social distancing policies implemented by Rutgers University to prevent the spread of Covid-19, which became a concern as early as February 2020 and resulted in stay-at-home-orders for most faculty and staff by May 2020. Given the uncertainty of return-to-work dates at that time and the known sensitivity of seasonality on measures of fish and crab recruitment in this highly dynamic region (Szedlmayer and Able 1996, Able and Fahay 2010), the project period was extended by a year with a start date of May 2021 for the second annual cycle of “After” sampling. Thus, sampling halted after November 2019 and resumed in April of 2021 through October 2021 (**Table 1-4**).

3.1.5 Campaign-Specific Methods

3.1.5.1 Larval Fish Plankton Net Sampling

Larvae were collected with a 1 m-diameter, 1 mm mesh, circular plankton net deployed with a General Oceanics flow meter to a depth of approximately 1.5 m. Collections were during the nighttime flood tide for three consecutive 30-minute sets (see Witting et al. 1999, Able et al. 2017 for more details). Fish abundance was standardized to effort as sample density (individuals/1000m^3) by calculating sample volume from the flow value obtained from a calibrated mechanical flow meter (General Oceanics 3-inch rotor) and net diameter. Larval abundances at these near-inlet sampling sites are likely to be indicative of larval supply because the larvae are annually available, abundant, and represented by all developmental stages (preflexion, flexion, postflexion) (Able and Fahay 2010). The late (postflexion) stages of development, which are likely to be indicators of year class strength (Houde 2008), are well represented and a source for settlement in the area (e.g., Chant et al. 2000, Sogard et al. 2001). This same sampling program has proven useful for assessing the late larval abundance of many estuarine resident species as well (Able et al. 2006, Able and Fahay 2010, Able et al. 2011) and as an index of climate change (Able and Fahay 2010, Morson et al. 2019).

Larval fish sampling occurred in fall of each sampling year, rather than year-round, and thus captured a segment of the highly annually variable larval assemblage. Deviation from the proposal occurred for the dates of ichthyoplankton sampling because of changes in the plant operation versus those anticipated from the basis of initial briefing from Exelon. Specifically, the shutdown of the pumps was phased over a period of months so that "After" ichthyoplankton planned for the second half of September would have been during a protracted pump reduction period, rather than after pump shutdown. Thus, ichthyoplankton sampling for "Before" was carried out as intended in September 2018 for two sampling dates but continued for two more dates in September 2018 as "During". Sampling effort intended to be representative of "After" in October 2018, was appropriately delayed until November 2018 and December 2018 (**Table 1**). Samples are thus unbalanced, and Month was added as a main factor into the GLMM to determine if that biased measurement of the BACI main effects. The Impact sampling sites were the Route 9 Bridge over the OCNGS discharge canal, which includes the inflow and discharge, and Rt. 37 Bridge to the north (**Fig. 1**). While the Rt 37 bridge falls geographically with Stratum IV, used as a control in other campaigns, larval fish, which are not well developed as active swimmers, arriving through Little Egg Inlet from coastal spawning sites must pass through the plume; further, pump closure visibly slowed water flow at this site. The Control site was the bridge over Little Sheepshead Creek (3.8 km from Little Egg Inlet). The control site has been continuously in use with the same sampling protocol since 1989 (Able and Fahay 1998, Witting et al. 1999). The seasonal dynamics of larval arrival are already well documented (Able and Fahay 2010a), and the focused sampling schedule (4 weekly visits of 3 net deployments per night per site) help smooth high natural variation so that high stochastic variance is not spuriously attributed to a site or treatment effect. Replicates are weekly samples blocked within months.

Another deviation from the proposed methods occurred when shutdown of the OCNGS pumps slowed water flow through the canals so much that stationary plankton nets fished from the bridges there collapsed and were not able to sample effectively. Ichthyoplankton sampling was therefore moved to a boat-towed operation. The net was towed behind an outboard skiff in the canal through the original sampling location at approximately 1.5 -2 knots to emulate the former flow regime. Catch was again standardized to CPUE from the integrated flow meter.

3.1.5.2 Juvenile Fish Otter Trawl Sampling

Juvenile fishes and crabs were sampled by three 120-second otter trawl tows (4.9 m headrope, 19 mm mesh wings, 6.3 mm mesh cod end liner). Sampling was repeated during the daytime, seasonally (April, June, August, and October) in 2012-2014, 2018, 2019, and 2021 to add 12 new sampling events to the original 12 at each of the 40 sites at each station (**Table 2**), but this followed the same protocol and sampling schedule with the same gear as in 2012-2014 (Valenti et al. 2017). From each tow, all fishes and crabs were identified and counted and twenty of each were randomly measured to the nearest mm total length (TL), fork length (FL) or carapace width (CW) (see Szedlmayer and Able 1996 for additional details).

These sampling efforts were applied in Strata I and IV (Controls) and Stratum III (Impact). Stratum III is a region near the OCNGS and its measured heated plume. Stratum IV, a region to the north of the plume, and Stratum I, at Little Egg Harbor to the south serve as Control sites because the plume has never extended to them. Strata I is otherwise similarly situated near an inlet as Strata III and has a similar salinity regime (**Fig. 1**). Within each of these strata, sampling stations are representative of upper and lower creek habitats, creek mouth habitats, open bay habitats, and submerged aquatic vegetation (SAV). Further, sampling is on the same seasonal time schedule as in previous sampling (April, June, August, October).

For otter trawl samples of juvenile, the random effects are two replicates of four different habitats each. Replicates are representative of different habitats that occur in the region. They are not considered in the model as main effects and have been treated previously in Valenti et al. (2022). All habitats (open bay, submerged aquatic vegetation, creek mouth, and upper creeks, were samples with similar effort in the impact and two Control sites (Stratum 1 and Stratum 4). There is a reasonable expectation that all of these habitats within the Impact site are under the influence of the effluent, as provided by understanding from previous hydrographic research (e.g. Summers et al. 1989, Dephne and Ganju 2015).

3.1.5.3 Adult Fish Gillnet Sampling

Larger juvenile and adult fishes were sampled with gillnets following Able et al. (2009) (**Table 3**, **Fig. 1**) in 2018 and 2019, but was not resumed in 2021 due to a budget change. Gillnetting was seasonally truncated relative to the previous survey effort, which was during the day and not highly informative due to low catch rates. Instead, gillnetting was conducted at night in Spring to target adult fish that may have used the discharge canal as overwintering thermal refuge. Gillnetting sampled the same sites as before in Strata III (Treatment) and Stratum I and IV (Control) (**Fig. 1**). Anchored multi-mesh gillnets (15 m x 2.4 m with 5 panels of 5 mesh sizes [2.5, 3.8, 5.1, 6.4, and 7.6 cm box] and 91 m x 2.4 m with 6 panels of 3 mesh sizes [1.3, 1.9 and 2.5 cm box]) were used. Gillnets were set in the upper creek, creek mouth and nearshore bay habitats at night for approximately 60 minutes. Upon retrieval of each gillnet, all fishes were identified, counted, and measured, and total soak time was recorded. Soak time could vary from the targeted 1 hour when processing of a full net at a previous site delayed retrieval. Only two (rather than three planned replicates) of a gillnet sample at Station 85 in the discharge canal in April 2018 were processed because the third net set was lost. The lost net was recovered on the following day during low tide with no fish in it, but it had been displaced by some tens of meters from its set position and the soak time was not standard, so it was discounted, meaning that the net was not counted as effort and 0 catch was not used in calculating CPUE for that site in 2018.

3.1.5.4 Adult Crab Trap Sampling

Trap sampling for adult crabs occurred for four successive days in each month (May-August) at Strata I, III and IV (**Table 4**, **Fig. 1**). In Strata I and III, two traps were placed at each of the following habitats: inside and outside the plume of two creek mouths (at Stratum III Oyster Creek is one of these sites), SAV bed and open bay. This sampling design allowed examination of impacts of the OCNGS shutdown on crab population characteristics at two spatial scales: regional (between strata) and local (inside versus outside of heated-effluent plume). In Stratum IV, two traps were placed at each of the following habitats: outside the plume of two creek mouths, SAV bed and open bay. All traps were set 24 hours prior to sampling (to ensure equal soak times among the habitats) and baited daily with menhaden. Thus, the locations of trap sampling mirrors that of trawl sampling except that in creek habitats, sampling occurred both inside and outside the plume but did not occur in upper creek habitats. Previous work suggests that upper creeks are primarily used by juveniles (Jivoff and Able 2001), which these traps were not designed to capture. Trapping (deployed monthly) did not occur simultaneously with trawling (deployed seasonally) but as temporally close to one another as possible when the two were performed in the same month.

3.1.6 Environmental Measures

We collected site-specific environmental data coincident with sampling in each campaign. Environmental data (salinity, temperature, pH, dissolved oxygen) were collected by hand-held Yellow Springs Instrument (YSI) meter (Professional Series, Professional Plus, Model: Pro 10102030) at each site visit for otter trawling and crab trap sampling (**Table 5**), as well as gillnetting, and ichthyoplankton sampling. Water depth was recorded by fathometer on the tow boat during trawling. In the adult blue crab sampling campaign, all of the above environmental data were taken with a YSI model 6920.

3.1.7 Quality Assurance

Sampling and data processing was conducted under an approved Quality Assurance Protocol that included Project Organization, Training and Certification for sonde calibration, objectives for precision, bias minimization, data transcription error checking, representativeness, comparability with related local data sets, completeness, and sensitivity in length measures. The QAP was submitted under separate cover.

3.2 Results of Mobile Fauna Study

3.2.1 Environmental Variables

In 2012-2014, before the decommissioning, the environmental variables measured at the otter trawl sampling sites, in Strata I, III, and IV, were similar across these years, but average depth of trawl stations was deeper in 2013 at Stratum III than in other years (**Table 5**). Stratum III was the warmest until 2018 (“Before Impact”), which was the warmest year for all sites, after which Stratum III became the coolest (**Fig. 2a**). Average salinity was always highest in Stratum I followed by Stratum III and lowest in Stratum IV, averaging about 6 -7 ppt lower than in Strata I or III (**Table 5**, **Fig. 2b**). Daytime dissolved oxygen always remained above 6.0 mg/L and thus well above stress levels for fish. Daytime dissolved oxygen reached supersaturation (>8 mg/L) in 2014 in Stratum I (Control) surface water (**Table 5, Fig. 2c**). Average pH in Stratum III (Impact) was similarly high to that in Stratum IV (Control) in 2012 and 2013 and higher than averages for both Control strata in 2014 and 2018 but fell after shutdown in 2018 and was lowest and lower than in both control strata in 2021 (**Table 5, Fig. 2d**). None of the variables were highly correlated, with the maximum absolute value of all 10 pairwise correlations at Rho = 0.4 between Salinity and Depth, and most Rho > 0.1 (**Figure 3**).

During adult blue crab sampling, temperature varied noticeably among Strata and habitats and with the closure of OCNGS. Across Strata and habitats, only the creek habitat in Stratum III showed markedly higher temperatures before the closure than after the closure (**Fig. 4a**). On this spatial scale, salinity showed no variation associated with OCNGS closure while dissolved oxygen showed higher levels before the OCNGS closure but only in Stratum I in the SAV habitat (suggesting these differences are due to annual variation) (**Fig. 4b**). Dissolved oxygen was never below 6 mg/L (**Fig. 4c**). These data justify focusing subsequent analyses on Strata I and III, because in Stratum IV: (1) none of the physical variables showed significant variation associated with the OCNGS closure, (2) there was minimal variation in all variables among habitats, and (3) there is evidence that salinity could represent a confounding variable on a biological response to the OCNGS closure since salinities in each habitat were consistently lower than in the other Strata. These results also suggest that examining physical variables on a local spatial scale (i.e., inside and outside the plume among creeks) and a finer temporal scale (i.e., monthly) is beneficial for testing an effect of the OCNGS closure.

During adult blue crab sampling, temperatures consistently differed inside the Oyster Creek plume compared to outside the plume and only before the OCNGS shutdown. Specifically, in each month (May-August) before the closure, temperatures inside the Oyster Creek plume were warmer (3-8 ^{o}C) than after the closure (**Fig. 5a**). This pattern is unique to the Oyster Creek plume. It is also interesting to note that the May temperature differences decrease with distance from the Oyster Creek plume (i.e., versus outside the plume and at Forked River). In June, temperatures at all creek locations are warmer before the closure but these differences coincide with relatively cold June temperatures after the closure. It is interesting to note that the *extent* of the June temperature difference before versus after the OCNGS closure is greater inside the Oyster Creek plume (8 ^{o}C) than any other creek location (2-5 ^{o}C). A similar situation occurred in August, with warmer temperatures at both creek locations in Stratum I before the closure, coinciding with colder August temperatures after the closure. As in June, the extent of the August temperature difference before versus after the closure is greater within the Oyster Creek plume (4 ^{o}C) than anywhere else (0.1-2 ^{o}C) including nearby Forked River.

During adult blue crab sampling, salinity also differed inside the Oyster Creek plume compared with outside the plume (**Fig. 5b**). In May and June before the closure, salinities are lower inside the Oyster Creek plume than after the closure, however this pattern (with a few exceptions) also occurs at both creek locations in Stratum I. This pattern appeared to be driven by relatively wet conditions, particularly in May, before the closure. However, the extent of the salinity differences before versus after the closure is greater within the Oyster Creek plume (3 ppt) than outside the plume (1 ppt) and nearby Forked River (0.3-0.6 ppt).

During adult blue crab sampling, there were no monthly differences in dissolved oxygen inside the Oyster Creek plume before versus after the closure that did not also appear at most other creek locations (including nearby Forked River) (**Fig. 5c**).

Submerged aquatic vegetation (SAV, *Zostera* and *Ruppia*) was collected in otter trawls in all three strata (**Fig. 6**). SAV was most abundant in Stratum III (Impact) and was most abundant by an order of magnitude there in 2012. SAV was markedly less abundant in 2013, after Superstorm Sandy in fall 2012.

Within a given year, it was always least abundant in Stratum IV. At some sites, blades of SAV were collected in the trawl samples but no beds were evident.

Macroalgae was more abundant than SAV in all sample sites and years. It was most abundant in Stratum I in all years except 2019, when it was most abundant in Stratum III (**Fig. 7**). There was no evidence of a pattern related to before or after OCNGS closure consistent across strata and years including 2018 and present at all sampling stations (**Fig. 7**).

3.2.2 Ichthyoplankton

Ichthyoplankton data was collected in September 2018 before and during shutdown and in November and December 2018 after shutdown. Ichthyoplankton were also collected in October 2019 and 2021 after plant closure. Collections from 2012-2014 were also used for BACI comparison (**Table 1)**. Collections included 36,373 individuals of 75 nominal taxa, but 15 taxa were not identifiable to species and may have included species already represented in the list, (e. g. Clupeidae) (**Table 6)**. Atlantic menhaden dominated the catch with 18,626 individuals (51% of total), followed by bay anchovy with 7,196 individuals. The first 4 species made up 86.0% of the total catch and unidentifiable anchovies accounted for another 17%. Thirty-six taxa were represented by 3 or fewer individuals.

3.2.2.1 Response in Ichthyoplankton abundance

The sum abundance (standardized as CPUE) of ichthyoplankton among samples was highly skewed (Kolmogorov Smirnov KSstatic = 0.8587, p = 8.1025e-61). Therefore, CPUE response was tested using a log link and gamma distribution with the Laplace fit method, as maximum pseudoliklihood did not converge to desired tolerance after 100 iterations. It was very clear (p = 9.5199e-06) that there were more (effect coefficient = 2.0171) larval fish captured in the Control strata, but it was not at all indicated that this changed relative to the Impact zone after shutdown (interaction term coefficient -0.3434, p = 0.64183)(**Table 7, Fig. 8**).

3.2.2.2 Response in ichthyoplankton species composition

Unidentified and ambiguous taxa were removed from the species by sample matrix for the purpose of PCA. CPUE (individuals per 100 m^3) was log(y+1) transformed and centered. Rare species were retained. The first four principal components accounted for a cumulative 75.445% of the total variation (**Table 8)**. Plots of sample scores classified as Before or After on the first two principal components (**Fig. 9a**) and the same plot classified by Stratum (**Fig. 9b**), revealed little among-factor separation. There was a strong difference among sites along the principal component 1 (PC 1), with the Control Stratum I occasionally having much great density of numerous species, especially Atlantic croaker, northern pipefish, Atlantic menhaden, blue crab, and bay anchovy than the Impact Stratum III (**Fig. 10**). This variation was greater than among site variation within Stratum III (OCNGS intake canal, discharge canal, and Route 37 Bridge) (**Fig.9c**). Months segregated along PC 2 with October having considerable overlap with both September and November in the middle of the gradient, but the distribution among sites was balanced for this mode (**Fig. 9d**). Some monthly separation was also apparent along the third and fourth principal components (**Fig. 11, 12**). Scores for species and samples are provided in **Appendix 1**.

Tests of BACI differences in assemblage score on the first and second principal components yielded no basis for rejection of the null hypothesis. A decrease in scores (scores are arbitrary in sign but relate to positions on the plots and the corresponding turnover of species) for an effect of the Before*Control interaction was measured with low confidence (p = 0.17309) on the third principal component, and was clear for Control (p = 0.0921, score increase, **Table 9**) and very clear (p = 0.0398, score decrease) for Before*Control effects on the weakest (PC 4) axis. Therefore, we reject the null hypothesis that there was no effect of OCNGS closure on the larval fish assemblage of Barnegat Bay but note that these effects were weak compared to other trends.

3.2.3 Juvenile Fish and Crabs

Otter trawls from all years collected 54,099 individuals representing 101 taxa of fish, turtles, and crabs, although 11 of these taxa were for individuals not identifiable to species or even genus. These individuals are most likely specimens of otherwise identified taxa that are too young or small to have distinguishing characters (**Table 10**). Two of the taxa were turtles (common snapping turtle *Chelhydra serpentina* and Northern diamondback terrapin *Malaclemys terrapin*), and ten were crabs (portly spider crab *Libina emarginata,* longnose spider crab *L. dubia,* blue crab *Callinectes sapidus,* lesser blue crab *Callinectes similis,* Atlantic rock crab *Cancer irroratus,* European green crab *Cancer meanus,* lady crab *Ovalipes ocellatus*, iridescent swimming crab *Portunus gibessii,* blotched swimming crab *P. spinimanus*, and the chelicerate Atlantic horseshoe crab *Limulus polyphemus*). The bay anchovy (*Anchoa mitchilli*) was numerically dominant with 25,966 specimens, followed by blue crab with 7,971, and the Atlantic silverside (*Menidia menidia*) with 6,440. Seven taxa exceeded 1000 individuals, while 14 additional taxa had between 100 and 1000 individuals. Many were rare, with 36 taxa represented by 3 or fewer individuals (**Table 10)**.

Not counting partially identified taxa that were ambiguous but likely represented by identified individuals (e.g. ambiguous silversides *Menidia spp*.), but counting those that were represented by an unambiguous but unknown type (e.g. *Monacanthus spp*.), there were 16 taxa unique to the five years of pre-closure sampling and 13 unique to the two years of post-closure (**Table 11**). None of the unique species were abundant, with pollack (*Pollachius virens*, n = 10), fourspot butterfly fish (*Cheatodon ocellatus* n = 6), and white mullet (*Mugil curema*, n = 6) being the most numerous pre-closure and blotched swimming crab, n = 5) being the most numerous among post-closure unique species.

Because shutdown for decommissioning began in September 2018 and ran into November, the After sample set of October 2018 was imprinted by the recruitment pattern of April – June 2018, prior to shutdown and does not well represent an After case. Thus, 2019 represents the first year of sampling in which most specimens are juveniles resulting from spawning after the shutdown and October 2018 otter trawl collections are factored as Before samples for BACI comparison.

3.2.3.1 Response in juvenile fish and crab abundance

Fish CPUE was skewed based on the KS test and was therefore fit to GLMM with Log link and gamma distribution. The median CPUE of fish in otter trawls was between 0.1 and 0.2 fish/m^2 in all three strata both before and after closure (**Fig. 13**). CPUE was lowest in the Impact Stratum III before closure and both the median and maximum values increased after closure, but the variance was sufficient to swamp certainty even at alpha = 0.1 (**Table 12**). The Impact location factor main effect approached clarity at p = 0.18566, but other main effects did not. Therefore, we have low confidence in the null hypothesis that aggregate juvenile fish and crab abundance differed in the Impact sites relative to the Control sites, but strong confidence that there was no Before/After or interaction effect.

3.2.3.2 Response in juvenile fish and crab species composition

The two turtle species (which recruit differently than fishes and crabs) and eight unidentified or ambiguous fish taxa (*Anchoa* spp, *Brevoortia* spp. *Clupea* spp, unidentified Clupeidae, unidentified Gobiidae, *Libinea* spp, *Menidia* spp, *Monacanthus* spp. and *Prionotus* spp. And Unidentified fish) were removed for further analysis. Rare species and singletons were retained, because the accumulation of rare species along a gradient or in a class may be revealing. Compositional data of the trawl samples had a gradient length of 3.1 Standard Deviation units and so was suited to ordination by PCA, which assumes a linear model consistent with the fact that potential underlying environmental gradients are partial. The first four principal components cumulatively explained 49.16% of the total variation (**Table 13**). Plots of sample scores classified as Before or After on the first four principal components (**Fig. 14a, 15**) and the same plots classified by Stratum (**Fig. 14b, 15**), revealed little among-factor separation. These first two axes generally ordered seasonal variation and habitat variation, especially in the relative CPUE of bay anchovy, Atlantic menhaden, spot, and Atlantic croaker relative to Northern pipefish and fourspine stickleback on PC 1 and silver perch vs spider, lady, and rock crab on PC 2. (**Fig. 14, 15** and **Appendix 2**) as detailed in Valenti et al. (2015, 2017, 2022) and therefore not detailed further here. Sample score separation was strongest, but still marginal, among classified Before/After samples along principal component 3 (eigenvalue = 0.075) among the four examined components. Species distinguishing the third component gradient were especially striped anchovy, black sea bass, tautog (better represented in After samples). Oyster toadfish (*Opsanus tau*), naked goby (*Gobiosoma bosc*), and sheepshead (*Archosargus probatocephalus*), or alternately portly spider crab (*Libinia emarginata*), characterized endpoints of the weak fourth principal component (**Fig. 16, 17**, **Appendix 2**).

Robust testing by GLMM quantified the variation due to the factors of interest. None of the tested variables were clearly related to assemblage overturn along principal component 1, 2, or 4, but there was a clear ($p = 0.0899$) effect of Impact location as measured by principal component 3 scores and suggested along PC 4 ($p = 0.12005$), direction is arbitrary negative) (**Table 14, Appendix 2**). The direction is direction is arbitrarily positive along PC 3 for Impact site and arbitrarily negative along PC 4 for the Impact site, but these directions relate to the species composition trends and determining which responded with a relative increase or decrease. Therefore, we accept that the assemblage differed in the Impact vs Control locations, but not that it could be attributed to the closure, as the difference was manifest After the closure as well as Before closure.

3.2.3.3 Response in juvenile fish size

Species suitable for testing size response were those that were abundant enough and occurred in all periods and strata. Crabs were excluded. Testing included ten species (naked goby, northern pipefish, oyster toadfish, weakfish, silver perch, Atlantic silverside, bay anchovy, summer flounder, winter flounder, and black sea bass) that had differing life histories and habits (**Table 15, Appendix 2**). Anderson-Darling tests for all species independently showed significant skew in size distribution. Sizes were therefore fit to a GLMM with the same 4 fixed effects and 8 random effects as for assemblage using a gamma distribution with a Log link using the maximum pseudoliklihood method. Very clear effects were found for larger size of silver perch and summer flounder Before closure and for smaller size Before closure in bay anchovy. Summer flounder were also larger in the Impact location (Stratum 3) but smaller as an interaction of Before*Impact whereas bay anchovy increased in size as an interaction of Before*Impact. Additionally, northern pipefish were clearly larger in the Impact samples. **Fig. 18** shows the size distribution by species and **Appendix 2** details all test statistics. A larger size given two factors (e. g. Before and Impact) but a smaller size in the interaction term (Before*Impact) indicates that the fish were larger before closure and larger in the Impact Stratum (III) but that their size difference relative to the other strata decreased in that Impact zone after closure. We reject the null hypothesis based on a clear indication that there is a response in the size distribution of fish as a result of OCNGS closure. However, it is clear that the alternative hypothesis can be accepted for only four of the ten tested species (Northern pipefish, silver perch, bay anchovy, summer flounder) (**Table 15**). The first 3 of these were highly abundant with length sample sizes exceeding 1000 and this imparted power; however, Atlantic silverside, the second most abundant species, did not respond with a change in size and summer flounder were relatively much less abundant in the length sample size (n = 258). Length samples for species that responded to closure came from all sample habitats but Creek Mouth samples were particular abundant among these species in comparison to other habitats and in comparison to species that did not respond (**Fig. 19**). For example, Atlantic silverside lengths were represented mostly by samples from SAV habitat, where the species was most commonly found.

3.2.4 Adult fish

Gillnet data was collected in spring 2018 before the beginning of shutdown and in spring 2019 after the shutdown (**Table 3**). No night-time samples from earlier years from any locations in Barnegat Bay were available. These collected a total of 427 individuals of 18 species (11 fishes, 4 crabs including horseshoe crab, and one turtle species, **Table 16**). Atlantic menhaden (*Brevoortia tyrannus*) dominated the catch with 317 collected, followed by striped bass (*Morone saxatilis*, 41 collected), white perch (*M. americana*) with 14 collected, diamondback terrapin (*Malaclemys terrapin*) with 11 collected, and blue crab (*Callinectes sapidus*) with 11 collected. All other species were represented by less than 8 individuals. These were hickory shad (*Alosa mediocris*), alewife (*A. pseudoharengus*), American shad (*A. sapidissima*), gizzard shad (*Dorosoma cepedianum*), common and longnose spider crab (*Libinia emarginata* and *L. dubia*), horseshoe crab (*Limulus polyphemus*), summer flounder (*Paralichthys dentatus*), bluefish (*Pomatomus saltatrix*), butterfish (*Peprilus triacanthus*) and striped sea robin (*Prionotus evolans*). Soak time was 4,301 minutes from 60 completed net sets in 2018 and 3,974 minutes from 55 completed net sets in 2019. The total CPUE was 0.065 individuals per minute soak time in 2018 and 0.037 in 2019.

3.2.4.1 Response in the abundance of adult fish

The abundance of adult fish was highly skewed (KSstat = 0.4827, p = 5.6233e-23) and was thus log(Y+0.1) transformed and tested as a gamma distribution. An effect of period was clear (p = 0.1059), with fewer (-0.15726 effect coefficient) fish in 2019 After closure than in 2019 (**Table 17, Fig. 20**), but there was no discernable effect of location or BACI interaction, so we accept the Null hypothesis that the aggregate abundance of large adult fish was not affected by OCNGS plant closure. **Appendix 3** provides details of the BACI GLMM tests on CPUE data.

3.2.4.2 Response in the composition of adult fish

Northern diamondback turtles were removed from ordination analysis because they are non-migratory and aestivate during winter. The total variation of centered compositional gillnet data was 5.5 SD units; therefore, a unimodal model, detrended correspondence analysis, was appropriate for ordination (**Table 18**, **Figs. 21,22**). There was a clear score decrease with After effect on axis 2 (Explained variation = 14.2, p = 0.064) (**Table 19**). There was no clear interaction effect, meaning that the score compositional change indicated by the score decrease was similar in the Impact and control zones. **Appendix 3** provides details of the BACI GLMM tests on compositional data.

3.2.5 Crab Trap Sampling

The abundance (measured as CPUE) of blue crabs showed evidence of an OCNGS closure effect. Focusing on Strata I and III (see 4.1 Environmental Variables above), in July (Paired t=6.3, df=3, P=0.008) and August (Paired t=9.8, df=3, P=0.002) there were more males in the Oyster Creek plume before the closure than after the closure (**Fig. 23a**). However, the August differences are not unique to the Oyster Creek plume as they were also seen at most creek locations in Stratum I. Furthermore, the extent of the difference in the Oyster Creek plume appears consistent with most of the Stratum I creek locations. In contrast, in July the elevated CPUE of males in the Oyster Creek plume before the closure is: unique to the Oyster Creek plume; greater than the differences at any other creek location; and the differences decrease with distance from the Oyster Creek plume (i.e., versus outside the plume and at Forked River). In May (Paired t=4.9, df=3, P=0.016) and June (Paired t=5.4, df=3, P=0.013) there were more females in the Oyster Creek plume before the closure than after the closure (**Fig. 23b**) and these differences were unique to the Oyster Creek plume. Furthermore, the majority (May = 97%, June = 58%) of the females inside the plume were ovigerous suggesting elevated temperatures stimulate brood production earlier in the reproductive season. Thus, we reject the Null hypothesis of no response in the distribution of crabs as measured by a sex-specific abundance, to closure of the OCNGS.

4.0 Invertebrate Infauna

4.1 Methods

The study applied a Before-After-Gradient (BAG) design to assess the status of benthic invertebrates in Barnegat Bay in response to hydrographic changes associated with the cooling water shut down. The response variables are a) invertebrate abundance and b) invertebrate assemblage. Sampling (detailed below) funded for this for this project specifically commenced several months prior to shut down and continued afterwards to span a total of three years of sampling (four years total span including a one-year hiatus in response to the Covid-19 pandemic). By using some of the same sites sampled in a three-year (2012-214) study of the status of fishes and crabs relative to urbanization impacts in the Barnegat Bay (Valenti et al. 2017), the BAG design incorporated a longer "Before" component than would otherwise be allowed given the short notice on the plant's closure.

BAG designs incorporate both spatial and temporal elements (as repeated measures) to emulate a clinical trial with a "treatment dose", which is the varying over water distance (shortest measured path that does not cross land) from the impact location:

$Y_{(a,b)}$ = A*Period + B*Distance + (A*Period|B*Distance) + Random Effects

In the current case, Y is either (a) abundance, or (b) composition (assemblage), A is the effect of the period (Before or After), B is the coefficient of the distance, and the model contains an interaction term and random effects. The random effects are replicate sample transects which are common to all years, and years, which are not, and are thus blocked for randomization as categorical variables within the periods Before and After (i.e. they do not have numerical or sequential rank value). Period is a categorical variable, while distance is a numerical variable. The treatment, which defined the Impact site (Stratum III), was the restriction of warm effluent to 5% of its flow from the 47-year historical flow. Indirect effects of cooling flow reduction, such as change in salinity and sedimentation are possible. All sites were sampled several times before treatment began and again after cooling water shutdown was implemented. The sample sites are sufficiently close to the treatment so as to share a common ecosystem, mobile predators, climate and weather, and larval pool (Taghon et al. 2017). Replicates were sampled on the same schedule.

We used alpha = 0.1 as a "clear" indication of difference and alpha = 0.05 as "very clear", but in keeping with recommendation of Gelman and Stern (2006) and Dushoff et al. (2019), we discuss p levels more generally as approaching confidence that there was an effect, rather than as absolute thresholds of significance.

For the purpose of assessing assemblage change as a response, species abundance data for all included (unambiguous) species was expressed as catch-per-unit-effort (CPUE as individuals per m^2). Samples were ordered by principal components after log(Y+1) transformation following inspection of the overall gradient length of compositional (centered species) data. The first four principal components were tested as response variable.

4.2.1 Sample Selection

We used data collected from 97 stations during the years 2012 - 2014 from Taghon et al. (2017). We combined those data with data collected from 14 stations in 2016-2017, and from 25 stations during 2018-2019 and 2021. The initial spatial distribution of samples among years was biased due to goals of another project; therefore, we used created a boundary to include all stations across all years that were located south of the Toms River and north of the Barnegat Inlet for a total of 69 stations. Within this set, a subset of 20 or21 stations were sampled during 2012-14, 2 stations from 2016-17, 22 stations in 2018-19, and 25 stations in 2021 (**Table 20**, **Fig. 24**).

One station was 'upstream' of OCNGS, in the Forked River (Station 01) and one station was 'downstream,' in Oyster Creek (BB19-02). Twenty stations (Stations 03–22) were located along four linear transects (five stations per transect) extending away from the shoreline between Forked River and Oyster Creek. The first station of each transect was approximately 0.2 km offshore. Subsequent stations along each transect were at distances of 0.25, 0.5, 1, and 2 km from the previous station. A geometric length spacing pattern between stations was used, rather than constant spacing, on the assumption that any effects of the OCNGS will most likely be focused near shore. Three stations were at locations previously sampled in July of 2012, 2013, and 2014; these stations were designated Station BB19-26,BB10-40, and BB19-47 to maintain consistency with previous results (Taghon et al. 2015).

4.2.2 Field sampling standard operating procedures

At each station, three 0.04-m^2 Ted Young Modified Van Veen grabs were taken. Two grab samples were used for benthic invertebrate analysis. Each of these was processed separately; sediment was sieved over a 0.5-mm mesh screen using a gentle flow of surface seawater supplied by a submersible pump. Residue remaining on the screen was transferred to a jar and fixed with sodium-borate-buffered formaldehyde (3.7% solution in seawater) containing Rose Bengal to stain organisms.

All sediment sampling followed methods used during the USEPA's EMAP, REMAP, and NCA programs (US EPA 1995, 2001). The third grab sample was used for measurement of sediment properties (methods described below). For this sample, the top 2-cm layer of sediment was removed, transferred to a stainless-steel bowl, homogenized by stirring with a stainless steel spoon, placed in a Whirl-Pak bag, and stored on ice following collection and during transport to the laboratory.

4.2.3 Laboratory sample processing

Samples of benthic invertebrate analysis were delivered to Cove Corporation (Lusby, MD). Samples were transferred to ethanol and sorted under magnification to separate animals from residual sediment and detritus. Animals were identified to the lowest practical taxonomic unit, usually to the species level. A notable exception was oligochaetes (a difficult group to identify), which was only taken to the class level. Validity of species names was checked against the database in the World Register of Marine Species (www.marinespecies.org/aphia.php?p=webservice) to bring them up to date with current taxonomic status.

Sediment samples for analysis of chemical properties were air-dried and gently homogenized using an agate mortar and pestle. Any visible shell fragments, plant fragments, or obvious debris were removed. Total carbon and total nitrogen concentrations of sediment were measured by high-temperature combustion in a Carlo Erba Model NA-1500 Series 2 elemental analyzer (EPA Method 440.0, US EPA 1992). Two replicate subsamples were analyzed, and the average values reported here. Average recoveries for C and N based on concurrent analyses of standard reference material (Elemental Microanalysis High Organic Sediment B2150) were 95% for C and 99% for N. Total phosphorus was measured by colorimetric analysis (US EPA 2010, chapter 6). Two replicate subsamples were analyzed, and the average values reported here. Average recovery for P based on concurrent analyses of standard reference material (NIST 2702-Inorganics in Marine Sediment) was 90%. Total volatile solids were measured by Method 2540E Standard Methods for the Examination of Water and Wastewater (American Public Health Association 1992). Two replicate subsamples were analyzed, and the average values reported here.

Sediment grain size analysis followed methods described in detail in the EMAP-Estuaries Laboratory Methods Manual (US EPA 1995). Wet sediment was pre-treated with hydrogen peroxide to remove residual organic matter and disaggregate particles, then sieved through a 63µm-mesh screen using distilled water with sodium hexametaphosphate dispersant to separate the silt and clay fraction (<63 µm) from the sand-sized fraction (>63 µm). The silt plus clay fraction was transferred to a large graduated cylinder then brought to a final volume of 1000 mL. Following mixing, a 50-mL aliquot was removed to a pre-weighed beaker, dried at 70°, reweighed, then correcting the mass to the total 1000 mL volume. The sand fraction was dried, then sieved into the following size fractions: <63 µm (silt), 63-

125 µm (very fine sand), 125-250 µm (fine sand), 250-500 µm (medium sand), 500-1000 µm (coarse sand), 1000-2000 µm (very coarse sand), 2000-4000 µm (granules) for 10 minutes on a rotary shaker. Each fraction was weighed. Sediment particle size statistics were calculated using the GSSTAT software program (Poppe et al. 2004).

Although sediment grain size and organic content and water quality were sampled, these data could not be recovered from Dr. Taghon's computer following his passing due to privacy laws. Instead, results are presented here from the 2019 Annual report of this project so that findings on invertebrate distribution may be interpreted without accessing that report. The distribution of sediment and infauna is more stable seasonally than for water and mobile fauna. The distribution on these factors is further examined in detail in Taghon et al. (2015). Although it aids in interpretation, it is not a necessary component of BAG testing when sample sizes are sufficiently large and well distributed that these factors can be assumed to be randomized relative to the main effects.

4.2.4. Data preparation

Most site occupations included two grabs. Since these are likely to be autocorrelated, we treated them as psuedo-replicates and used the mean abundance for each species at each station to calculate count per unit effort (CPUE) as individuals per 0.04 m^2. CPUE was used for all subsequent data analysis. We treated all years 2012-2018 as the "Before" condition and 2019-2021 as the "After" condition. We conducted a PCA analysis and classified the latent sample distribution as "Before/After" and year to visualize the resulting sample similarities by factor and also the trend of species' abundance through them. Total invertebrate abundance (standardized as CPUE) and principal component sample scores were used as the response variables in a generalized linear mixed model (GMM) analysis to test the null hypotheses

4.3 Results

4.3.1 Environmental properties

The average bottom water temperature during 2018 grab sampling was 25.4 °C (range 19.9 to 31.7) (**Table 21**). In order to visualize spatial variations, possibly due to the thermal plume from OCNGS, temperature anomalies were calculated for each station (value at station – average of all stations). Bottom water at BB02, downstream of the facility, had the largest positive temperature anomaly, and the second largest positive anomaly was at the mouth of Oyster Creek (**Fig. 25**). Within the bay, water temperatures were above average at stations closest to shore. Temperature decreased from southwest to northeast and from west to east into the bay.

Average bottom water salinity was 27.6, and was less variable among stations (range 25.9 to 30.9) than temperature (**Table 21**). Spatial variation – higher salinity at the central and eastern locations – was likely due to the influence of ocean water entering through Barnegat Inlet (**Fig. 26**).

Bottom water dissolved oxygen concentration averaged 7.15 mg/L and varied from 6.13 to 8.58 (**Table 21**). Most nearshore locations between Forked River and Oyster Creek had above-average DO concentration (**Fig. 27**).

The average silt content of sediment at all locations was 38% by mass, but varied over a wide range, 3–91% (Table 3). Eastern-most stations tended to have the lowest silt content, but there were notable exceptions (**Fig. 28**). For example, Station BB02 sediment, just downstream from the generating station, had one of the lowest silt contents. Curiously, all stations along transect 2 had lower than average silt content, while stations along transects to the north and south tended to have higher than average silt content.

Sediment C, N, and P concentrations were tightly correlated with each other, and with the percent silt content (**Table 22, Fig. 29**). Therefore, sediment C concentration was chosen to illustrate spatial pattern in elemental concentrations (**Fig. 30**). By far, sediment at station BB01 had the highest total carbon concentration, while station BB02 sediment had one of the lowest. These carbon concentrations mirrored the differences in silt content of sediment upstream and downstream of the generating station. Within the bay, sediment carbon concentration tended to decrease toward the east.

4.3.2 Infaunal invertebrates

A total of 301 taxa were collected among the subset of stations. The average species richness per station was 61, and the range for all stations was 21 to 95 across all years (**Table 23**). Station BB49 and had the highest species richness during the years 2012 and 2013. BB48 had the highest species richness in 2014. BB18-01 had the highest species richness in 2018 (72 species), but the lowest species richness of all stations the following year (31 species). In 2019, BB19-08 had the highest species richness. In 2021, BB21-20 had the highest species richness and BB21-01 had the lowest.

A total of 78,735 individuals were collected. The average abundance per station was 583.3 (**Fig. 31**). Following closure of the power plant, there was a slight increase in abundance near the plant in 2019, followed by a slight decrease in 2021. Shannon diversity was higher with more high and fewer low values After than Before closure and decreased with distance from the discharge (**Fig. 32**). Under testing by GLMM, the total CPUE of infaunal invertebrates was very clearly higher Before closure (coefficient = 13331, p = 0.0501) and there was a suggestion (p = 0.1286) that Before negatively (coefficient = -1279.5) interacted with distance, meaning that the effect weakened (**Table 24, Appendix 5**). This negative response to closing response may have been due to dominance of one or more species prior to closing (as seen in the decreased Shannon diversity Before closing), either through a predatory or conditioning effect.

The first four axes of multivariate analysis of species compositional data cumulatively explained 38.24% of the variance in composition (**Table 25, Appendix 5**). Composition varied with PC 1 scores declining (sign is arbitrary but relates to species gradient direction in the scatter plots) with distance from the discharge (p =0.043398). There is weak confidence in a Before*Impact interaction (p = 0.13605) on the same axis (**Fig. 33 - 36**). There was a very clear difference in scores along PC 3 by period (p = 0.0006, score decrease Before) and a clear difference with distance (p = 0.0862, scores decreasing with distance) and in their interaction, p = 0.07217) with distance Before shutdown. Period and Before*Impact, but not distance, were also clear along PC 4 (**Table 26**). Therefore, we reject the null hypothesis that OCGN closure had no effect on assemblage. **Appendix 5** provides detailed results of the statistical models.

5.0 Discussion

Closure of the OCNGS allowed a retrospective examination of the effects of plant operation, including larval loss to pumps and indirect distributional response to changes in flow, temperature and salinity, and temperature effects on growth and aerobic scope, as an empirical study. The specific individual mechanisms through which these drivers can act are well studied in the laboratory, but natural systems allow for confounding effects, such as favoring among competing predators, that redirect responses among species in biological community. These confounding mechanisms are very difficult to either observe, measure or predict, and are usually revealed only by large scale manipulations of the environment, as was the case with operation of the plant. This study also provides a model for the sensitivity of the local fish and invertebrate community to climate change. Empirical observations are quantified in the narrative as directions (positive or negative coefficients) and confidence (p-values), but this report also serves as a repository (in the Appendices) for important information on covariance and species-specific measures of fit and statistical weight. These can serve as input to models that synthesize data with a knowledge base of mechanisms (e.g. Ecopath with EcoSim) to extend our understanding of ecology.

This study leveraged previously collected samples of fish, crabs, and invertebrates from as far back as 2012 for comparison with recent sampling (2018, 2019, 2021) in a Before/After Control/Impact design (for fishes and crabs) or a Before/After/Gradient design (for benthic infauna) to challenge the null hypothesis that there was no effect of closure and to quantify any noted effects relative to natural variation. Measures included abundance/distribution (for fishes, crabs and benthic infauna) assemblage change/beta diversity (for fishes and invertebrates) and size (for fishes) at different life stages as sampled by plankton net, otter trawl, crab traps, and gillnets. The strength of effects and the confidence in their measure was dependent on species and life stage, and for some there were no measurable effects. In all cases, BACI/BAG interactions (effects measured as different after closure in the Impact sites relative to their measure in the Control sites) were secondary to other sources of variation, including habitat, seasonal, and interannual variation, and spatial variation among the control sites. It is apparent that control site choice, as a function of measurement scale, affects the answer, pointing to a recognized and fundamental challenge in ecology: the scale at which measurement is made can determine the answer to the null hypothesis challenge (a consequence of the Rashomon effect, Levin 1992, Brieman 2001, Mashintonio et al. 2014). For example, focusing a given sampling effort over the few hundred to one thousand meters around the intake versus discharge canal is much more likely to produce observations of stark changes with a high level of confidence than spreading the same sampling effort over a wider area. Our studies on fish, crabs and invertebrates sought to frame the question of effects on a scale that speaks to resource management needs for a bay-wide understanding of ecology and change, and this reflects public interest in the plant operation. The scale, bay-wide for mobile and migratory fish, stratum wide for less mobile crabs, and somewhat more than plume wide for immobile infauna, is sensitive to this need.

The blue crab sampling campaign includes sampling inside and directly outside the Oyster Creek plume before and after the OCNGS closure. Sampling at this spatial scale provides a unique opportunity to test the effect of the OCNGS closure. Differences in environmental variables (especially temperature) and biological metrics (e.g., blue crab abundance) before versus after OCNGS closure that are unique to inside the Oyster Creek plume strongly implicate a closure effect. However, differences that also occur at other locations suggest alternative factors (e.g., annual variation) may contribute to those differences. In addition, sampling at this spatial scale also provides the opportunity to examine a decreasing closure effect associated with increasing distance from the Oyster Creek plume by comparing response variables inside the plume, outside the plume and nearby Forked River. In each month (May-August), temperatures inside the Oyster Creek plume were warmer before the closure than after the closure. In May, this difference was unique to the Oyster Creek plume indicating a closure effect. This interpretation is also supported by decreasing differences before versus after OCNGS closure with increasing distance from the Oyster Creek plume. However, in June, temperatures at all creek locations were warmer before the closure than after and these differences coincide with relatively cold June temperatures after the closure suggesting annual variation helps explain these differences. The suggested closure effect on temperatures in May inside the Oyster Creek plume are presumably a key factor in the numerous ovigerous female blue crabs found inside the Oyster Creek plume in May suggesting that the warmer waters of the plume allow adult female blue crabs to spawn earlier in spring than outside the plume.

In retrospect, the OCNGS was well sited because the spatial extent and persistence of the plume effects were dampened by regular tidal exchange with the ocean through Barnegat Inlet. Measured effects on sex-specific crab distribution and benthic invertebrate distribution and abundance decreased rapidly with distance from the discharge. Abundance was never seriously depressed (and was increased for adult fish) in the Impact site, most likely because it was never source limited. Fish, benthic infauna, and many of the crabs utilizing the bay arrive from distance spawning sites as larvae, and many of the adult stages arrive as migrants; thus, local consumption by the plant was mitigated. Further, the life history of these species are adapted to and experience (individually and as populations) a greater seasonal and range-wide thermal variation (~38 ^{o}C, Kennish 2001, Ng, 2007, Able and Fahay 2010) than that produced by the plant (change of 0 -10 ^{o}C from ambient, depending on distance from the discharge). This is a function of the station's location near the apex of the Middle Atlantic Bight, and should be expected to differ from similar power-plant disturbances elsewhere in the country or world.

6.0 Recommendations

A previous trophic-bases ecosystem model using Ecopath with Ecosim (EwW) model (Christensen and Walters 2004) specifically modeled the effect of OCNGS closure as the closure of a fishery (Vasslides et al. 2017). That model included 12 fish species and predicted a minor change in biomass, approaching 3% maximum for the most effected species, as complex interactions unfolded among different level consumers. For example, it predicted a counterintuitive decrease with closure for Atlantic croaker, a species that suffers high impingement mortality in early stages, due to a concomitant increase of 1.5% in its predator, weakfish, with decrease in that specie's impingement mortality. Numerous (but small) species-specific abundance changes are documented for fish species and invertebrates in this report. It would be useful to work a similar EwE model backwards to understand the parameter estimates needed to replicate the scale of results that were found here and then to determine what these new values would suggest for the future.

7.0 List of Appendices

Appendix 1. Results of significance testing and supporting figures for ichthyoplankton sampling

Appendix 2. Results of significance testing and supporting figures for otter trawl sampling

Appendix 3. Results of significance testing and supporting figures for gillnet sampling

Appendix 4. Results of significance testing and supporting figures for crab trap sampling

Appendix 5. Results of significance testing and supporting figures for grab sampling

8.0 References

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Table 1. Ichthyoplankton sampling effort indicating the number of tows completed each month and year of sampling.

Site and Year	Sept	Oct	Nov	Total sets
Little Sheepshead Creek (Control)	13	26	15	54
2012		4	3	7
2013	4	5	4	13
2014	5	4	4	13
2018	4	5	4	13
2019		4		4
2021		4		4
Oyster Creek Inlet	2	10	1	13
2013		1		1
2014		1		1
2018	2		1	3
2019		4		4
2021		4		4
Oyster Creek Outflow	2	10	1	13
2013		1		1
2014		1		1
2018	2		1	3
2019		4		4
2021		4		4
Route 37 Bridge	2	9	1	12
2014		1		1
2018	2		1	3
2019		4		4
2021		4		4
Grand Total	19	55	18	92

Table 2. Otter trawl sampling effort combined for all locations, indicating the number of tows completed for each month of each year.

	Months						
Years	April	May	June	Aug	Sep	Oct	Grand Total
2012	72		70	72		72	286
2013	60	12	71	72		72	287
2014		72	71	71		71	285
2018		69	72	72		72	285
2019	71		72	72	24	47	286
2021	72		72	72	33	39	288
Grand Total	275	153	428	431	57	373	1,717

Table 3. Gillet sampling effort combined for all locations, indicating the number of sets completed for each month of each year.

Year	April	May	Grand Total
2018	44	9	53
2019	20	36	56
Grand Total	64	45	109

Table 4. Blue crab trap sampling effort combined for all locations, indicating the number of sets completed for each month of each year.

	Months				
Years	May	June	July	Aug	Grand Total
2012	72	72	72	72	288
2013	48	47	81	72	248
2014	96	96	96	94	382
2018	128	128	128	128	512
2019	128	128	128	128	512
2021	96	128	128	128	480
Grand Total	568	599	633	622	2422

Table 5. Environmental characterization of sampling sites by stratum from trawling (top panel) and blue crab trap sampling (bottom panel). OCNGS is located in Stratum III. This characterization averages surface and bottom values from data collected during otter trawling. 2012, 2013, 2014, and 2018 represent the years before the closure of OCNGS. 2019 and 2021 represent the years post closure.

Strata	Year	Average Temperature (°C)	Average Salinity (ppt)	Average Dissolved Oxygen (mg/L)	Average pH	Average Depth (m)
		Trawling				
I (Control)	2012	19.2	28.7	7	7.7	1.6
	2013	18.4	27.7	7	7.6	1.8
	2014	20.7	26.2	8.4	7.7	1.5
	2018	23.3	26.6	6.6	7.6	1.5
	2019	21.7	27.3	7.4	7.7	1.6
	2021	21.3	26.7	7.7	7.7	1.5
III	2012	21	28.1	7.3	7.9	2.0
	2013	20	26.8	7.2	7.8	2.1
	2014	21.1	25.8	7.2	7.8	2.0
	2018	23.4	26	6.7	7.9	2.1
	2019	21.2	25.1	6.9	7.8	2.1
	2021	19.9	25	7.7	7.6	2.1
IV	2012	20.3	21.7	6.8	7.9	1.6
	2013	19.3	21	7.5	7.8	1.5
	2014	21.3	19.3	7	7.7	1.5
	2018	22.7	19.2	6.9	7.6	1.6
	2019	22.1	20.5	7.4	7.8	1.6
	2021	20.4	19.6	7.2	7.8	1.5
		Blue Crab Trap Sampling				
I (Control)	2012	24	29.6	6.9	N/A	N/A
	2013	21.8	28.9	7.3	N/A	N/A
	2014	23	28.1	7.7	N/A	N/A
	2018	24.7	27.9	7.3	N/A	N/A
	2019	22.9	27.6	7.1	N/A	N/A
	2021	24.8	29.1	6.6	N/A	N/A
III	2012	24.1	28.3	5.9	N/A	N/A
	2013	22.6	27.9	6.6	N/A	N/A
	2014	23.5	26.1	7.1	N/A	N/A
	2018	24.7	26	7.1	N/A	N/A

	2019	22.2	25.7	6.9	N/A	N/A
	2021	23.8	27.4	6.1	N/A	N/A
IV	2012	23.8	22.6	6.6	N/A	N/A
	2013	23.7	21.5	6.6	N/A	N/A
	2014	23.1	20.6	6.7	N/A	N/A
	2018	24.4	20.1	6.7	N/A	N/A
	2019	23.2	19.2	7.1	N/A	N/A
	2021	24.7	21.5	6.2	N/A	N/A

Table 6. Species abundance from ichthyoplankton net collections of larval and juvenile fish and crabs collected from September 2012 to December 2021 across four sites and all three sampling periods (before, during and after station shutdown) combined and listed in descending order of abundance (right) and alphabetical order (left). See Figure 1 for sampling locations. Note that sampling did not occur in 2015, 2016, 2017, and 2020. Combined totals represent those collected during September through December. Sorting is alphabetically by genus in first 3 columns, and by abundance in last 2 columns.

Common Name	Species (ranked alphabetical)	Total	Species (ranked abundance)	Total
Striped anchovy	Anchoa hepsetus	43	Brevoortia tyrannus	18,626
Bay anchovy	Anchoa mitchilli	7,196	Anchoa mitchilli	7,196
Anchoa species	Anchoa sp.	632	Micropogonias undulatus	6,111
American eel	Anguilla rostrata	5	Microgobius thalassinus	679
Northern stargazer	Astroscopus guttatus	4	Anchoa sp.	632
American silver perch	Bairdiella chrysoura	2	Callinectes sapidus	580
Atlantic menhaden	Brevoortia tyrannus	18,626	Clupeiformes sp.	413
Blue crab	Callinectes sapidus	580	Menidia menidia	393
Callinectes species	Callinectes sp.	3	Paralichthys dentatus	342
Rock crab	Cancer irroratus	2	Ctenogobius boleosoma	242
Cancer species	Cancer sp.	2	Syngnathus fuscus	207
Crevalle jack	Caranx hippos	1	Sciaenidae_sp.	108
Caranx species	Caranx sp.	1	Gobiosoma bosc	89
Black sea bass	Centropristis striata	9	Ovalipes ocellatus	88
Striped blenny	Chasmodes bosquianus	3	Gobiosoma ginsburgi	77
Bay whiff	Citharichthys spilopterus	1	Symphurus plagiusa	68
Clupeidae species	Clupeidae sp.	64	Clupeidae sp.	64
Clupeiformes species	Clupeiformes_sp.	413	Gobionellus oceanicus	64
Darter goby	Ctenogobius boleosoma	242	Syngnathus floridae	55
Ctenogobius species	Ctenogobius sp.	3	Anchoa hepsetus	43
Weakfish	Cynoscion regalis	1	Menidia beryllina	30
Sheepshead minnow	Cyprinodon variegatus	7	Hippocampus erectus	28
Fat sleeper	Dormitator maculatus	6	Menidia sp.	26
Ladyfish	Elops saurus	3	Urophycis regia	24

Emerald sleeper	Erotelis smaragdus	5
Smallmouth flounder	Etropus microstomus	11
Mummichog	Fundulus heteroclitus	10
Striped killifish	Fundulus majalis	6
Gerreidae species	Gerreidae sp.	2
Skilletfish	Gobiesox strumosus	5
Gobiidae species	Gobiidae sp.	7
Gobioides species	Gobioides sp.	1
Highfin goby	Gobionellus oceanicus	64
Naked goby	Gobiosoma bosc	89
Seaboard goby	Gobiosoma ginsburgi	77
Gobiosoma species	Gobiosoma sp.	23
Lined seahorse	Hippocampus erectus	28
Feather blenny	Hypsoblennius hentz	8
Libinia species	Libinia sp.	1
Horseshoe crab	Limulus polyphemus	9
Rainwater killifish	Lucania parva	1
Atlantic tarpon	Megalops atlanticus	3
Inland silverside	Menidia beryllina	30
Atlantic silverside	Menidia menidia	393
Menidia species	Menidia_sp.	26
Green goby	Microgobius thalassinus	679
Atlantic croaker	Micropogonias undulatus	6,111
White perch	Morone americana	1
Speckled worm eel	Myrophis punctatus	1
Margined snake eel	Ophichthus cruentifer	1
Atlantic thread herring	Opisthonema oglinum	2
Oyster toadfish	Opsanus tau	1
Lady crab	Ovalipes ocellatus	88
Summer flounder	Paralichthys dentatus	342
Bluefish	Pomatomus saltatrix	3

Gobiosoma sp.	23
Prionotus evolans	14
Etropus microstomus	11
Fundulus heteroclitus	10
Centropristis striata	9
Limulus polyphemus	9
Hypsoblennius hentz	8
Cyprinodon variegatus	7
Gobiidae sp.	7
Dormitator maculatus	6
Fundulus majalis	6
Anguilla rostrata	5
Erotelis smaragdus	5
Gobiesox strumosus	5
Astroscopus guttatus	4
Prionotus carolinus	4
Callinectes sp.	3
Chasmodes bosquianus	3
Ctenogobius sp.	3
Elops saurus	3
Megalops atlanticus	3
Pomatomus saltatrix	3
Bairdiella chrysoura	2
Cancer irroratus	2
Cancer sp.	2
Gerreidae sp.	2
Opisthonema oglinum	2
Portunus gibbesii	2
Unidentified crab	2
Caranx hippos	1
Caranx sp.	1

Iridescent swimming crab	Portunus gibbesii	2	Citharichthys spilopterus	1
Northern searobin	Prionotus carolinus	4	Cynoscion regalis	1
Striped searobin	Prionotus evolans	14	Gobioides sp.	1
Prionotus species	Prionotus sp.	1	Libinia sp.	1
Cobia	Rachycentron canadum	1	Lucania parva	1
Sciaenidae species	Sciaenidae_sp.	108	Morone americana	1
Red drum	Sciaenops ocellatus	1	Myrophis punctatus	1
Moonfish	Selene setapinnis	1	Ophichthus cruentifer	1
Lookdown	Selene vomer	1	Opsanus tau	1
Blackcheek tonguefish	Symphurus plagiusa	68	Prionotus sp.	1
Dusky pipefish	Syngnathus floridae	55	Rachycentron canadum	1
Northern pipefish	Syngnathus fuscus	207	Sciaenops ocellatus	1
Syngnathus species	Syngnathus sp.	1	Selene setapinnis	1
Inshore lizardfish	Synodus foetens	1	Selene vomer	1
Cunner	Tautogolabrus adspersus	1	Syngnathus sp.	1
Hogchoker	Trinectes maculatus	1	Synodus foetens	1
Houndfish	Tylosurus acus	1	Tautogolabrus adspersus	1
Unidentified crab	Unidentified crab	2	Trinectes maculatus	1
Unidentified fish	Unidentified fish	1	Tylosurus acus	1
Red hake	Urophycis chuss	1	Unidentified fish	1
Spotted hake	Urophycis regia	24	Urophycis chuss	1
	Grand Total	36,373	Grand Total	36,373

Table 7. Fixed effects coefficients from GLMM on ichthyoplankton abundance with 92 observations and 88 degrees of freedom. Full results are in Appendix 1.

Name	Estimate	SE	p value
Intercept	4.2648	0.32801	3.4104e-22
Before	-0.2971	0.73337	0.68638
Control	**2.0171**	**0.42908**	**9.5199e-06**
Before:Control	-0.34134	0.73132	0.64183

Table 8. PCA results summary for ichthyoplankton with 92 samples and 60 species. Total sum of squares in response data = 1776.26553, total standard deviation TAU = 0.567263.

Axes	1	2	3	4	Total variance
Eigenvalues:	0.390	0.184	0.112	0.068	1.000
Cumulative percentage variance	39.0	57.4	68.6	75.4	

Table 9. Fixed effects coefficients from GLMM on ichthyoplankton compositional data as PC 1-4 scores with 92 observations and 88 degrees of freedom

Name	Estimate	SE	p value
PC 1			
Intercept	-0.11525	0.20137	0.56856
Before	-0.57862	0.42497	0.17681
Control	0.25692	0.46762	0.5841
Before:Control	0.044779	0.43734	0.91868
PC 2			
Intercept	-0.32469	0.26807	0.22906
Before	0.2799	0.4629	0.54696
Control	0.059213	0.27811	0.83189
Before:Control	0.33951	0.44465	0.44717
PC 3			
Intercept	-0.059793	0.24099	0.80462
Before	0.23309	0.51049	0.64908
Control	0.26591	0.26967	0.32682
Before:Control	-0.60395	0.43972	0.17309
PC 4	4		
Intercept	0.029929	0.30301	0.92154
Before	0.12448	0.43076	0.77328
Control	**0.48661**	**0.2857**	**0.092056**
Before:Control	**-0.95855**	**0.45926**	**0.039765**

Table 10. Species abundance from otter trawl collections of juvenile and adult fish, turtles, and crabs from April 2012 to October 2021 in all three sample strata combined listed in descending order of abundance (left) and alphabetical order (right). See Figure 1 for sampling locations. Note that sampling did not occur in 2015, 2016, 2017, and 2020. Combined totals represent those collected during spring, summer, and fall sampling.

Common Name	Species (ranked by abundance)	Total	Species (ranked alphabetically)	Total
Bay anchovy	Anchoa mitchilli	25,966	Acanthostracion quadricornis	1
Chesapeake blue crab	Callinectes sapidus	7,971	Alosa aestivalis	1
Atlantic silverside	Menidia menidia	6,440	Anchoa hepsetus	266
American silver perch	Bairdiella chrysoura	2,875	Anchoa lyolepis	3
Four-spine stickleback	Apeltes quadracus	2,667	Anchoa mitchilli	25,966
Northern pipefish	Syngnathus fuscus	1,806	Anchoa sp.	18
Atlantic menhaden	Brevoortia tyrannus	1,518	Anguilla rostrata	42
Spot	Leiostomus xanthurus	708	Apeltes quadracus	2,667
Winter flounder	Pseudopleuronectes americanus	563	Archosargus probatocephalus	3
Northern puffer	Sphoeroides maculatus	307	Astroscopus guttatus	1
Broad-striped anchovy	Anchoa hepsetus	266	Bairdiella chrysoura	2,875
Summer flounder	Paralichthys dentatus	258	Brevoortia sp.	1
Portly spider crab	Libinia emarginata	240	Brevoortia tyrannus	1,518
Naked goby	Gobiosoma bosc	209	Callinectes sapidus	7,971
Oyster toadfish	Opsanus tau	203	Callinectes similis	7
Atlantic croaker	Micropogonias undulatus	177	Cancer irroratus	54
Mummichog	Fundulus heteroclitus	163	Caranx hippos	5
Black sea bass	Centropristis striata	162	Carcinus maenas	2
Tautog	Tautoga onitis	144	Centropristis striata	162
Weakfish	Cynoscion regalis	108	Chaetodon ocellatus	6
Inland silverside	Menidia beryllina	100	Chasmodes bosquianus	26
Atlantic herring	Clupea harengus	98	Chelydra serpentina	1
Lady crab	Ovalipes ocellatus	79	Chilomycterus schoepfi	17
Dusky pipefish	Syngnathus floridae	79	Clupea harengus	98
Longnose spider crab	Libinia dubia	66	Clupeidae sp.	1

Bluefish	Pomatomus saltatrix	57
Lined seahorse	Hippocampus erectus	55
Atlantic rock crab	Cancer irroratus	54
Seaboard goby	Gobiosoma ginsburgi	51
Northern kingfish	Menticirrhus saxatilis	48
Pinfish	Lagodon rhomboides	47
Diamondback terrapin	Malaclemys terrapin	46
Spotted hake	Urophycis regia	43
American eel	Anguilla rostrata	42
Black drum	Pogonias cromis	41
Smallmouth flounder	Etropus microstomus	39
Cunner	Tautogolabrus adspersus	37
Hogchoker	Trinectes maculatus	27
Striped blenny	Chasmodes bosquianus	26
Skilletfish	Gobiesox strumosus	23
Feathered blenny	Hypsoblennius hentz	20
Anchoa species	Anchoa sp.	18
Striped burrfish	Chilomycterus schoepfi	17
Rainwater killifish	Lucania parva	16
Striped searobin	Prionotus evolans	15
Menidia species	Menidia sp.	13
Northern searobin	Prionotus carolinus	11
Pollock	Pollachius virens	10
Lookdown	Selene vomer	10
Scup	Stenotomus chrysops	10
Atlantic horseshoe crab	Limulus polyphemus	9
Atlantic moonfish	Selene setapinnis	9
Libinia species	Libinia sp.	8
Lesser blue crab	Callinectes similis	7
American butterfish	Peprilus triacanthus	7
Inshore lizardfish	Synodus foetens	7

Clupeiformes sp.	6
Conger oceanicus	2
Cynoscion regalis	108
Dasyatis say	2
Engraulis eurystole	1
Etropus microstomus	39
Fistularia tabacaria	1
Fundulus heteroclitus	163
Fundulus luciae	1
Fundulus majalis	2
Gasterosteus aculeatus	1
Gobiesox strumosus	23
Gobiosoma bosc	209
Gobiosoma ginsburgi	51
Gobiosoma sp.	4
Haemulon aurolineatum	1
Hippocampus erectus	55
Hypsoblennius hentz	20
Lagodon rhomboides	47
Leiostomus xanthurus	708
Libinia dubia	66
Libinia emarginata	240
Libinia sp.	8
Limulus polyphemus	9
Lucania parva	16
Lutjanus griseus	2
Malaclemys terrapin	46
Menidia beryllina	100
Menidia menidia	6440
Menidia sp.	13
Menticirrhus americanus	2

Spotfin butterflyfish	Chaetodon ocellatus	6
Clupeiformes species	Clupeiformes sp.	6
Green goby	Microgobius thalassinus	6
White perch	Morone americana	6
White mullet	Mugil curema	6
Crevalle jack	Caranx hippos	5
Smooth dogfish	Mustelus canis	5
Blotched swimming crab	Portunus spinimanus	5
Gobiosoma species	Gobiosoma sp.	4
Shortfinger anchovy	Anchoa lyolepis	3
Sheepshead	Archosargus probatocephalus	3
Iridescent swimming crab	Portunus gibbesii	3
Clearnose skate	Raja eglanteria	3
Atlantic needlefish	Strongylura marina	3
European green crab	Carcinus maenas	2
American conger	Conger oceanicus	2
Bluntnose stingray	Dasyatis say	2
Striped killifish	Fundulus majalis	2
Gray snapper	Lutjanus griseus	2
Southern kingfish	Menticirrhus americanus	2
Flathead gray mullet	Mugil cephalus	2
Sciaenidae species	Sciaenidae sp.	2
Scrawled cowfish	Acanthostracion quadricornis	1
Blueback herring	Alosa aestivalis	1
Northern stargazer	Astroscopus guttatus	1
Brevoortia species	Brevoortia sp.	1
Common snapping turtle	Chelydra serpentina	1
Clupeidae species	Clupeidae sp.	1
Silver anchovy	Engraulis eurystole	1
Cornetfish	Fistularia tabacaria	1
Spotfin killifish	Fundulus luciae	1

Menticirrhus saxatilis	48
Microgobius thalassinus	6
Micropogonias undulatus	177
Monacanthidae sp.	1
Morone americana	6
Morone saxatilis	1
Morone sp.	1
Mugil cephalus	2
Mugil curema	6
Mullus auratus	1
Mustelus canis	5
Mycteroperca microlepis	1
Ophidion marginatum	1
Opsanus tau	203
Ovalipes ocellatus	79
Paralichthys dentatus	258
Peprilus triacanthus	7
Pogonias cromis	41
Pollachius virens	10
Pomatomus saltatrix	57
Portunus gibbesii	3
Portunus spinimanus	5
Prionotus carolinus	11
Prionotus evolans	15
Prionotus sp.	1
Pseudopleuronectes americanus	563
Raja eglanteria	3
Raja erinacea	1
Rhinoptera bonasus	1
Sciaenidae sp.	2
Scophthalmus aquosus	1

Three-spined stickleback	Gasterosteus aculeatus	1
Tomtate grunt	Haemulon aurolineatum	1
Monacanthidae species	Monacanthidae sp.	1
Striped bass	Morone saxatilis	1
Morone species	Morone sp.	1
Red goatfish	Mullus auratus	1
Gag grouper	Mycteroperca microlepis	1
Striped cusk eel	Ophidion marginatum	1
Prionotus species	Prionotus sp.	1
Little skate	Raja erinacea	1
Cownose ray	Rhinoptera bonasus	1
Windowpane flounder	Scophthalmus aquosus	1
Largehead hairtail	Trichiurus lepturus	1
Unidentified fish	Unidentified fish	1
	Grand Total	54,099

Selene setapinnis	9
Selene vomer	10
Sphoeroides maculatus	307
Stenotomus chrysops	10
Strongylura marina	3
Syngnathus floridae	79
Syngnathus fuscus	1806
Synodus foetens	7
Tautoga onitis	144
Tautogolabrus adspersus	37
Trichiurus lepturus	1
Trinectes maculatus	27
Unidentified fish	1
Urophycis regia	43
Grand Total	54,099

Table 11. Species collected from otter trawl unique to pre-closure (2012, 2013, 2014, 2018) and post-closure (2019, 2021). Refer to table 9 for species common names.

Species	Unique to Pre-Closure	Species	Unique to Post-Closure
Astroscopus guttatus	1	Acanthostracion quadricornis	1
Brevoortia sp.	1	Alosa aestivalis	1
Carcinus maenas	2	Anchoa lyolepis	3
Chaetodon ocellatus	6	Engraulis eurystole	1
Chelydra serpentina	1	Fistularia tabacaria	1
Dasyatis say	2	Gasterosteus aculeatus	1
Fundulus luciae	1	Monacanthidae sp.	1
Haemulon aurolineatum	1	Mugil cephalus	2
Menticirrhus americanus	2	Mullus auratus	1
Mugil curema	6	Portunus gibbesii	3
Mycteroperca microlepis	1	Portunus spinimanus	5
Ophidion marginatum	1	Rhinoptera bonasus	1
Pollachius virens	10	Trichiurus lepturus	1
Raja erinacea	1		
Scophthalmus aquosus	1		
Strongylura marina	3		

Table 12. Fixed effects coefficients from GLMM on otter trawl CPUE data with 144 observations and 104 degrees of freedom

Name	Estimate	SE	p value
Intercept	-1.5298	0.23939	2.2922e-09
Before	0.0697	0.35876	0.84624
Impact	0.55149	0.41463	0.18566
Before:Impact	-0.45062	0.50782	0.37641

Table 13. Summary of PCA on otter trawl compositional data with 144 active cases. Total sum of squares in response data = 12290.21782. Total standard deviation TAU = 0.984821

Axes	1	2	3	4	Total variance
Eigenvalues:	0.242	0.121	0.075	0.054	1.000
Cumulative percentage variance:	24.2	36.3	43.8	49.2	

Table 14. Fixed effects coefficients from GLMM on otter trawl compositional data as PC 1-4 scores with 144 observations and 88 degrees of freedom

Name	Estimate	SE	p value
PC 1			
Intercept	0.070959	0.46538	0.87903
Before	-0.24053	0.19541	0.22041
Impact	-0.022616	0.24595	0.92687
Before: Impact	0.43621	0.18156	0.017593
PC 2			
Intercept	0.29136	0.30882	0.34708
Before	-0.30375	0.22581	0.18074
Impact	-0.070494	0.23314	0.76283
Before:Impact	-0.29412	0.28554	0.30477
PC 3			
Name	Estimate	SE	
Intercept	0.11054	0.43003	0.79752
Before	-0.30523	0.26884	0.25816
Impact	**0.51144**	**0.29957**	**0.089999**
Before: Impact	-0.34887	0.27426	0.20546
PC4			
Intercept	0.10547	0.2873	0.7141
Before	0.20152	0.25536	0.43135
Impact	**-0.47273**	**0.30223**	**0.12005**
Before: Impact	-0.3701	0.33211	0.26702

Table 15. Summary results of tests for difference in length of selected fishes as a response to closure of OCNGS as sampled by otter trawl using the model: response ~ 1 + BA*Impact + 1 | Hab + 1 + Impact | clusterNum + 1 + BA | year. The default Intercept state is when After is True and Control is True. The model asks if fish length responded with positive or negative change in size when factor "Before", in which years 2012-2014 and 2018 were randomly mixed was True, and/or when factor Impact, with only cluster 3 was True, and/or when the interaction of Before and Impact was added. All samples included habitats as replicates. Intercepts were always highly significant at $p << 0.05$, but are not shown. If an effect was very clear, it is also clear, therefore the $p > 0.1$ columns are marked as empty "—" for those terms. BAY = Open bay, CKM = Creek mouth, CKU = upper creek, SAV = submerged aquatic vegetation.

Species	Sample size	Habit	Primary Habitat	Length Min/Med/Max (mm)	P<0.05	P<0.1	Change in Size	Interpretation
Naked goby	203	Benthic brooder	CKM, CKU	21/36/68	none	none		No change
Northern Pipefish	1430	Benthopelagic pouch brooder	SAV	24/50/248	none	Impact 0.0797	Increase	Fish were larger in the Impact area than in Controls throughout the study
Oyster toadfish	202	benthic brooder	CKM, CKU, SAV	13/64/213	none	none		No change
Weakfish	104	pelagic broadcast spawner	CKM, CKU	28/69/308	none	none		No change
Silver perch	1832	pelagic broadcast spawner	CKM, SAV	11/66/171	**Before 0.0038**	--	increase	Fish were larger Before impact, regardless of site
Atl. silverside	1706	Pelagic, substrate spawner	SAV	17/65/119	none	none		No change
Bay anchovy	6015	pelagic broadcast spawner	Bay, CKM, CKU	17/46/98	**Before 0.0001**	--	Decrease	Fish were larger After impact, and this happened in in the Impact site
					Before*Impact 7.733e-06	--	Increase	
Summer flounder	258	benthic broadcast spawner	CKM, CKU	22/136/577	**Before 1.2986e-06**	--	Increase	Fish were larger before impact.
					Impact 0.0478	--	Increase	Fish were larger in the impact site.
					Before*Impact 0.048051	--	decrease	Fish were smaller in the Impact site Before the impact than after the impact
Winter flounder	558	benthic benthic spawner	SAV	22/63/395	none	none		No change
Black sea bass	162	benthic broadcast spawner	Bay, CKM, SAV	23/86/205	none	none		No change

Table 16. Species collected by gillnet

Common name	Species	2018	2019	Total
Hickory shad	Alosa mediocris	1		1
Alewife	Alosa pseudoharengus	1	3	4
American shad	Alosa sapidissima	1		1
Atlantic menhaden	Brevoortia tyrannus	232	85	317
Chesapeake blue crab	Callinectes sapidus	6	5	11
American gizzard shad	Dorosoma cepedianum	2	4	6
Longnose spider crab	Libinia dubia		1	1
Portly spider crab	Libinia emarginata	1	4	5
Atlantic horseshoe crab	Limulus polyphemus	2	5	7
Diamondback terrapin	Malaclemys terrapin	5	6	11
White perch	Morone americana	3	11	14
Striped bass	Morone saxatilis	21	20	41
Summer flounder	Paralichthys dentatus	1		1
American butterfish	Peprilus triacanthus	1	1	2
Bluefish	Pomatomus saltatrix		2	2
Striped searobin	Prionotus evolans	2	1	3
Grand Total		279	148	427

Table 17. Fixed effects coefficients from GLMM with log link and gamma distribution on gillnet CPUE data with 109 observations and 105 degrees of freedom

Name	Estimate	SE	p value
Intercept	-1.9257	0.072729	2.8109e-48
After	**-0.15726**	**0.096443**	**0.10597**
Control	0.099327	0.084626	0.24316
After:Control	-0.056065	0.11705	0.63296

Table 18. Summary of DCA on gillnet compositional data with 88 active cases (nets with no catch are dropped from compositional analysis). Total inertia in response data = 4.76896. Sum of all eigenvalues = 4.7690

Axes	1	2	3	4	Total inertia
Eigenvalues:	0.843	0.677	0.502	0.217	4.769
Lengths of gradient:	4.231	4.014	5.169	3.661	
Cumulative percentage variance:	17.7	31.9	42.4	47.0	

Table 19. Fixed effects coefficients from GLMM on gillnet compositional data as PC 1-4 scores with 88 observations and 84 degrees of freedom

Name	Estimate	SE	p value
Intercept	0.50466	0.15651	0.0017985
After	0.32797	0.22222	0.14371
Impact	-0.11969	0.20865	0.56775
After:Impact	-0.17605	0.27038	0.51674
CA 2			
Intercept	0.41398	0.12936	0.0019381
After	**0.34278**	**0.18984**	**0.074563**
Impact	-0.086463	0.15843	0.58668
After:Impact	-0.23096	0.22973	0.31761
CA 3			
Intercept	2.3151	0.17629	4.6034e-22
After	0.28608	0.25461	0.26437
Impact	-0.14009	0.25776	0.58821
After:Impact	-0.22284	0.30919	0.47307
CA 4			
Intercept	1.5612	0.15175	1.5447e-16
After	0.20467	0.22271	0.36071
Impact	0.18249	0.19347	0.34825
After:Impact	-0.016765	0.26956	0.95055

Table 20. Infauna grab sample station locations

Station	Latitude Decimal degrees	Longitude Decimal degrees
BB12-23	39.84285	74.13262
BB12-26	39.86073	74.12255
BB12-27	39.83200	74.09752
BB12-34	39.86782	74.09247
BB12-35	39.82833	74.11758
BB12-36	39.85262	74.10208
BB12-38	39.81407	74.13748
BB12-40	39.79262	74.15318
BB12-43	39.79237	74.17273
BB12-44	39.77447	74.15252
BB12-45	39.78142	74.15757
BB12-46	39.77058	74.15755
BB12-47	39.82472	74.14760
BB12-48	39.80313	74.15272
BB12-49	39.80683	74.11778
BB12-50	39.78873	74.13247
BB12-53	39.82487	74.11243
BB12-54	39.81398	74.10738
BB12-57	39.77807	74.13243
BB12-58	39.81028	74.11270
BB12-A48	39.78148	74.17260
BB13-23	39.84302	74.13253
BB13-26	39.86047	74.12227
BB13-27	39.83203	74.09772
BB13-34	39.86795	74.09238
BB13-35	39.82847	74.11745
BB13-36	39.85265	74.10197
BB13-38	39.81413	74.13767
BB13-40	39.79282	74.15295
BB13-43	39.79248	74.17298
BB13-44	39.77448	74.15242
BB13-45	39.78192	74.15757
BB13-46	39.77050	74.15740
BB13-47	39.82467	74.14762
BB13-48	39.80338	74.15240
BB13-49	39.80683	74.11768
BB13-50	39.78883	74.13223
BB13-53	39.82503	74.11218
BB13-54	39.81423	74.10720
BB13-55	39.78145	74.17227
BB13-57	39.77672	74.13315
BB13-58	39.81028	74.11275
BB14-23	39.84285	74.13262
BB14-26	39.86073	74.12255
BB14-27	39.83200	74.09752
BB14-34	39.86782	74.09247
BB14-35	39.82833	74.11758

BB14-36	39.85262	74.10208
BB14-38	39.81407	74.13748
BB14-40	39.79262	74.15318
BB14-43	39.79237	74.17273
BB14-44	39.77447	74.15252
BB14-45	39.78142	74.15757
BB14-46	39.77058	74.15755
BB14-47	39.82472	74.14760
BB14-48	39.80313	74.15272
BB14-49	39.80683	74.11778
BB14-50	39.78873	74.13247
BB14-53	39.82487	74.11243
BB14-54	39.81398	74.10738
BB14-57	39.77807	74.13243
BB14-58	39.81028	74.11270
BB16-05	39.85262	74.10208
BB16-06	39.80128	74.10208
BB17-05	39.85262	74.10208
BB17-06	39.80128	74.10208
BB18-01	39.82503	74.17955
BB18-02	39.80960	74.15978
BB18-03	39.82557	74.15698
BB18-04	39.82687	74.15198
BB18-05	39.82910	74.14188
BB18-06	39.83363	74.12137
BB18-07	39.84246	74.15931
BB18-08	39.82017	74.15657
BB18-09	39.82078	74.15053
BB18-10	39.82183	74.13910
BB18-11	39.82395	74.11645
BB18-12	39.82647	74.16252
BB18-13	39.81573	74.15968
BB18-14	39.81548	74.15420
BB18-15	39.81502	74.14255
BB18-16	39.81348	74.11987
BB18-17	39.81027	74.16810
BB18-18	39.81108	74.16512
BB18-19	39.81028	74.15952
BB18-20	39.80867	74.14868
BB18-21	39.80565	74.12505
BB18-22	39.80552	74.12355
BB18-26	39.85967	74.15302
BB18-40	39.79228	74.14747
BB18-47	39.82473	74.14747
BB19-01	39.82503	74.17955
BB19-02	39.80960	74.15978
BB19-03	39.82557	74.15698
BB19-04	39.82687	74.15198
BB19-05	39.82910	74.14188
BB19-06	39.83363	74.12137

BB19-07	39.84246	74.15931
BB19-08	39.82017	74.15657
BB19-09	39.82078	74.15053
BB19-10	39.82183	74.13910
BB19-11	39.82395	74.11645
BB19-12	39.82647	74.16252
BB19-13	39.81573	74.15968
BB19-14	39.81548	74.15420
BB19-15	39.81502	74.14255
BB19-16	39.81348	74.11987
BB19-17	39.81027	74.16810
BB19-18	39.81108	74.16512
BB19-19	39.81028	74.15952
BB19-20	39.80867	74.14868
BB19-21	39.80565	74.12505
BB19-22	39.80552	74.12355
BB19-26	39.85967	74.15302
BB19-40	39.79228	74.14747
BB19-47	39.82473	74.14747
BB21-01	39.82502	74.17957
BB21-02	39.80997	74.18532
BB21-03	39.82552	74.15988
BB21-04	39.82672	74.15728
BB21-05	39.82893	74.15217
BB21-06	39.83340	74.14177
BB21-07	39.84202	74.12127
BB21-08	39.82013	74.15953
BB21-09	39.82077	74.15662
BB21-10	39.82168	74.15077
BB21-11	39.82380	74.13932
BB21-12	39.82785	74.11642
BB21-13	39.81567	74.16268
BB21-14	39.81530	74.15993
BB21-15	39.81480	74.15413
BB21-16	39.81348	74.14255
BB21-17	39.81090	74.11940
BB21-18	39.81097	74.16797
BB21-19	39.81017	74.16513
BB21-20	39.80865	74.15945
BB21-21	39.80563	74.14845
BB21-22	39.79987	74.12638
BB21-23	39.85952	74.12340
BB21-24	39.82467	74.14762
BB21-25	39.79228	74.15307

Table 21. Water column properties

Station	Temp		Salinity		DO, mg L^{-1}		pH	
	Surface	Bottom	Surface	Bottom	Surface	Bottom	Surface	Bottom
01	26.7	26.7	26.53	26.84	7.19	7.26	7.94	7.95
02	31.6	31.7	26.37	26.40	6.66	6.99	7.93	7.93
03	25.8	25.8	26.63	26.64	7.30	7.34	7.97	7.97
04	25.6	25.5	26.62	26.91	7.08	7.12	7.96	7.96
05	25.5	25.1	26.66	27.61	7.04	6.17	7.97	7.89
06	25.6	24.3	26.65	28.44	7.17	6.13	7.98	7.88
07	25.2	24.5	24.96	27.21	7.13	6.72	7.98	7.95
08	26.1	26.1	26.73	26.78	7.43	7.52	8.00	8.00
09	25.9	25.9	26.87	26.98	7.38	7.33	7.99	7.98
10	25.6	25.4	26.56	26.88	7.32	7.34	7.99	7.98
11	25.2	23.9	26.81	28.71	7.28	6.88	8.00	7.95
12	24.9	24.9	25.44	27.26	7.43	7.45	7.99	8.06
13	27.0	27.1	26.95	27.05	7.37	7.09	7.99	7.99
14	26.1	26.0	26.72	26.74	7.33	7.58	8.00	8.00
15	25.8	25.7	26.65	26.82	7.36	7.54	8.01	8.00
16	25.4	23.1	26.92	29.59	7.46	6.82	8.03	7.94
17	24.4	23.9	28.57	28.72	7.10	6.63	8.00	7.95
18	31.1	30.9	26.4	26.44	6.98	6.92	7.94	7.95
19	31.0	27.6	26.37	27.51	6.86	7.29	7.93	7.98
20	25.9	25.9	26.71	26.73	7.53	7.67	8.02	8.01
21	24.5	24.2	27.63	28.57	7.36	7.05	7.98	7.96
22	24.2	20.2	28.69	30.89	6.62	8.58	7.94	7.97
26	25.8	25.1	24.11	25.88	6.89	6.28	7.94	7.88
40	19.9	19.9	30.74	30.73	8.05	7.95	7.94	7.90
47	25.4	25.1	26.33	27.14	7.22	7.07	7.99	7.96

Table 22. Sediment chemical and physical properties. Units are percent of the sample total by mass. TVS is total volatile solids.

Station	Total C	Total N	Total P	TVS	Silt
1	4.74	0.42	0.08	12.40	88.30
2	0.52	0.04	0.02	1.46	11.10
3	1.36	0.12	0.06	3.81	85.00
4	1.19	0.10	0.06	3.85	78.10
5	0.74	0.07	0.06	2.55	63.20
6	1.08	0.10	0.06	3.56	72.30
7	0.33	0.03	0.03	1.18	11.10
8	0.60	0.06	0.02	1.43	8.77
9	0.16	0.02	0.01	0.72	14.50
10	0.43	0.04	0.02	1.26	19.80
11	0.74	0.07	0.03	1.83	20.10
12	0.49	0.05	0.04	1.69	15.50
13	2.35	0.22	0.06	6.93	91.10
14	0.59	0.05	0.03	1.76	27.30
15	0.80	0.08	0.05	2.77	44.40
16	0.86	0.08	0.06	2.85	49.80
17	0.59	0.07	0.03	2.23	13.60
18	2.11	0.18	0.05	5.33	43.00
19	0.87	0.08	0.04	2.59	32.70
20	0.54	0.05	0.04	1.67	27.10
21	0.15	0.02	0.02	0.77	3.31
22	0.58	0.06	0.04	2.07	15.80
26	1.06	0.09	0.06	3.26	62.90
40	0.07	0.01	0.01	0.59	2.58
47	0.67	0.06	0.05	2.37	42.40

Table 23. Infaunal invertebrates collected during grab sampling in Barnegat Bay 2012 -2021. Values are the average of (usually two) psuedoreplicate grabs collected at each station occupation, actual numbers were slightly more than twice the average grand total at 78,735. The last two columns are resorted in descending order of abundance.

Genus	species	Type or stage	Species Code	Species Total	Species Code (ranked by abundance)	Species Total
Acanthohautorius	millsi		Acan-mill	1750	Spir-corr	38250
Acteocina	canaliculata		Acte-cana	912.5	Medi-ambi	18662.5
Agriopoma	morrhuanum		Agri-morr	12.5	Ampe-abdi	9987.5
Aligena	elevata		Alig-elev	37.5	Thar-sp.	8612.5
Alitta	succinea		Alit-succ	87.5	Ampe-verr	7800
Amastigos	caperatus		Amas-cape	562.5	Ampi-long	7275
Americamysis	bahia		Amer-bahi	112.5	Micr-gryl	7112.5
Americhelidium	americanum		Amer-amer	100	Pygo-eleg	6037.5
Ameritella	agilis		Amer-agil	1475	Exog-disp	5325
Ameroculodes	spp.	complex	Amer-spp.	187.5	Elas-levi	5275
Ampelisca	abdita		Ampe-abdi	9987.5	Olig-sp.	5237.5
Ampelisca	vadorum		Ampe-vado	4025	Eobr-spin	5025
Ampelisca	verrilli		Ampe-verr	7800	Clym-zona	4500
Ampharete	oculata		Amph-ocul	262.5	Muli-late	4225
Amphibalanus	sp.	juvenile	Amph-sp.	100	Ampe-vado	4025
Amphiporus	bioculatus		Amph-bioc	437.5	Tubi-sp.	3800
Amphiporus	caecus		Amph-caec	25	Nucu-prox	3687.5
Amphiporus	ochraceus		Amph-ochr	87.5	Aric-cath	3600
Amphitrite	ornata		Amph-orna	25	Gamm-mucr	3312.5
Ampithoe	longimana		Ampi-long	7275	Stre-bene	3237.5
Anadara	transversa		Anad-tran	37.5	Noto-sp.	3112.5
Angulus	agilis		Angu-agil	1825	Prio-hete	2937.5
Anoplodactylus	petiolatus		Anop-peti	187.5	Hete-fili	2912.5
Apocorophium	acutum		Apoc-acut	1037.5	Gemm-gemm	2587.5
Apoprionospio	pygmaea		Apop-pygm	375	Rhep-huds	2587.5
Arabella	iricolor		Arab-iric	125	Pent-pulc	2450
Arenicola	cristata		Aren-cris	12.5	Lysia-alba	2250
Aricidea	catherinae		Aric-cath	3600	Poly-exim	2237.5
Asabellides	oculata		Asab-ocul	62.5	Clym-torq	2150
Ascidiacea	sp.	juv.	Asci-sp.	37.5	Capi-capi	2125
Astyris	lunata		Asty-luna	75	Japo-punc	2062.5
Batea	catharinensis		Bate-cath	587.5	Idot-balt	1975
Bittiolum	alternatum		Bitt-alte	1087.5	Rudi-nagl	1937.5
Bivalia	sp.	indeterminate	Biva-sp.	25	Spio-ocul	1912.5
Boccardiella	ligerica		Bocc-lige	12.5	Angu-agil	1825
Bostrichobranchus	pilularis		Bost-pilu	200	Dipo-soci	1800

Brania	wellfleetensis		Bran-well	700
Cabira	incerta		Cabi-ince	87.5
Callinectes	sapidus		Call-sapi	25
Callipallene	brevirostris		Call-brev	375
Cancer	irroratus		Canc-irro	25
Capitella	capitata		Capi-capi	2125
Capitella	teleta		Capi-tele	312.5
Caprella	penantis		Capr-pena	1237.5
Carazziella	hobsonae		Cara-hobs	37.5
Carinomella	lactea		Cari-lact	150
Caulleriella	venefica		Caul-vene	25
Cerapus	sp.	C	Cera-sp.	837.5
Cerebratulus	lacteus		Cere-lact	12.5
Ceriantheopsis	americana		Ceri-amer	72.5
Chiridotea	coeca		Chir-coec	187.5
Cirratulus	grandis		Cirra-gran	12.5
Cirriformia	grandis		Cirri-gran	12.5
Cirrophorus	sp.	B	Cirr-sp.	12.5
Clymenella	sp.	indeterminate	Clym-sp.ind	525
Clymenella	sp.	juvenile	Clym-sp.juv	50
Clymenella	torquata		Clym-torq	2150
Clymenella	zonalis		Clym-zona	4500
Corambe	obscura		Cora-obsc	100
Corophiidae	spp.	juvenile	Coro-spp.	12.5
Cossura	sp.	A	Coss-sp.	225
Costoanachis	avara		Cost-avar	12.5
Crangon	septemspinosa		Cran-sept	37.5
Cratena	pilata		Crat-pila	125
Crepidula	fornicata		Crep-forn	225
Crepidula	plana		Crep-plan	25
Crepidula	sp.	juv.	Crep-sp.	200
Cyathura	burbancki		Cyat-burb	625
Cyclaspis	varians		Cycl-vari	12.5
Cymadusa	compta		Cyma-comp	637.5
Diadumene	leucolena		Diad-leuc	150
Diopatra	cuprea		Diop-cupr	150
Dipolydora	commensalis		Dipo-comm	37.5
Dipolydora	socialis		Dipo-soci	1800
Donax	variabilis		Dona-vari	12.5
Dorvillea	rudolphii		Dorv-rudo	25
Drilonereis	longa		Dril-long	12.5
Dyspanopeus	sayi		Dysp-sayi	112.5
Edotia	triloba		Edot-tril	262.5

Poly-corn	1800
Acan-mill	1750
Eric-fili	1750
Myti-edul	1675
Scol-tenu	1550
Turb-inte	1500
Amer-agil	1475
Spio-cost	1450
Para-tenu	1425
Capr-pena	1237.5
Merc-merc	1200
Salv-clav	1200
Glyc-sp.	1112.5
Prot-cf.	1112.5
Bitt-alte	1087.5
Lept-tenu	1075
Tell-agil	1075
Apoc-acut	1037.5
Spis-soli	1037.5
Spio-bomb	950
Glyc-mult	937.5
Acte-cana	912.5
Pect-goul	912.5
Sole-velu	912.5
Cera-sp.	837.5
Mono-ache	725
Bran-well	700
Para-alat	687.5
Gast-sp.	675
Para-micr	675
Para-trea	650
Cyma-comp	637.5
Cyat-burb	625
Micr-rane	625
Bate-cath	587.5
Meli-macu	575
Opis-long	575
Amas-cape	562.5
Saba-elon	537.5
Spha-brev	537.5
Clym-sp.ind	525
Tage-divi	525
Leit-robu	500

Edwardsia	elegans		Edwa-eleg	150
Elasmopus	levis		Elas-levi	5275
Ennucula	tenuis		Ennu-tenu	12.5
Ensis	directus		Ensi-dire	62.5
Ensis	leei		Ensi-leei	50
Eobrolgus	spinosus		Eobr-spin	5025
Epitonium	rupicola		Epit-rupi	12.5
Epitonium	sp.	juvenile	Epit-sp.	50
Erichsonella	attenuata		Eric-atte	412.5
Erichsonella	filiformis		Eric-fili	1750
Ericthonius	brasiliensis		Eric-bras	12.5
Ericthonius	sp.	B	Eric-sp.	37.5
Erinaceusyllis	erinaceus		Erin-erin	300
Eteone	foliosa		Eteo-foli	12.5
Eteone	heteropoda		Eteo-hete	212.5
Eulimastoma	engonium		Euli-engo	262.5
Eumida	sanguinea		Eumi-sang	462.5
Eunicidae	sp.	juvenile	Euni-sp.	25
Euplana	gracilis		Eupl-grac	150
Eupleura	caudata		Eupl-caud	75
Eurypanopeus	depressus		Eury-depr	12.5
Exogone	dispar		Exog-disp	5325
Gammarus	mucronatus		Gamm-mucr	3312.5
Gastropoda	sp.	indeter.	Gast-sp.	675
Gemma	gemma		Gemm-gemm	2587.5
Glycera	americana		Glyc-amer	237.5
Glycera	dibranchiata		Glyc-dibr	100
Glycera	sp.	juvenile	Glyc-sp.	1112.5
Glycinde	multidens		Glyc-mult	937.5
Grandidierella	japonica		Gran-japo	212.5
Gyroscala	rupicola		Gyro-rupi	12.5
Haloclava	producta		Halo-prod	137.5
Haminella	solitaria		Hami-soli	337.5
Hargeria	rapax		Harg-rapa	12.5
Harmothoe	extenuata		Harm-exte	75
Harmothoe	imbricata		Harm-imbr	12.5
Havelockia	scabra		Have-scab	37.5
Heteromastus	(Heteromysis)	formosa	Hete-(Het	25
Heteromastus	filiformis		Hete-fili	2912.5
Hexapanopeus	angustifrons		Hexa-angu	37.5
Hippolyte	zostericola		Hipp-zost	75
Hobsonia	florida		Hobs-flor	12.5
Hydroides	dianthus		Hydr-dian	25

Plat-dume	500
Idun-barn	487.5
List-barn	487.5
Eumi-sang	462.5
Amph-bioc	437.5
Iani-nr.	437.5
Eric-atte	412.5
Mono-tube	400
Para-pinn	400
Micr-atra	387.5
Syll-alte	387.5
Apop-pygm	375
Call-brev	375
Leuc-amer	362.5
Oers-dors	362.5
Oxyu-smit	350
Hami-soli	337.5
Para-long	325
Sabe-sp.	325
Capi-tele	312.5
Maco-tent	312.5
Erin-erin	300
Molg-manh	300
Neom-amer	300
Poda-levi	300
Lyon-hyal	287.5
Unci-diss	275
Amph-ocul	262.5
Edot-tril	262.5
Euli-engo	262.5
Iani-serr	262.5
Glyc-amer	237.5
Coss-sp.	225
Crep-forn	225
Eteo-hete	212.5
Gran-japo	212.5
Phol-minu	212.5
Bost-pilu	200
Crep-sp.	200
Pist-cris	200
Amer-spp.	187.5
Anop-peti	187.5
Chir-coec	187.5

Hydroides	protulicola		Hydr-prot	12.5
Hypereteone	foliosa		Hype-foli	12.5
Hypereteone	heteropoda		Hype-hete	25
Ianiropsis	nr.	tridens	Iani-nr.	437.5
Ianiropsis	serricaudis		Iani-serr	262.5
Idotea	balthica		Idot-balt	1975
Idunella	barnardi		Idun-barn	487.5
Idunella	smithi		Idun-smit	12.5
Ilyanassa	obsoleta		Ilya-obso	50
Japonactaeon	punctostriatus		Japo-punc	2062.5
Jassa	marmorata		Jass-marm	12.5
Kelliopsis	elevata		Kell-elev	125
Kurtiella	planulata		Kurt-plan	12.5
Laeonereis	culveri		Laeo-culv	12.5
Laevicardium	mortoni		Laev-mort	12.5
Leitoscoloplos	fragilis		Leit-frag	12.5
Leitoscoloplos	robustus		Leit-robu	500
Lepidametria	commensalis		Lepi-comm	12.5
Leptochelia	rapax		Lept-rapa	12.5
Leptosynapta	tenuis		Lept-tenu	1075
Leucon	americanus		Leuc-amer	362.5
Lineus	pallidus		Line-pall	50
Lineus	ruber		Line-rube	12.5
Listriella	barnardi		List-barn	487.5
Listriella	smithi		List-smit	25
Littoridinops	tenuipes		Litt-tenu	25
Littorina	littorea		Litt-litt	25
Loimia	medusa		Loim-medu	125
Loimia	viridis		Loim-viri	12.5
Lyonsia	hyalina		Lyon-hyal	287.5
Lysianopsis	alba		Lysia-alba	2250
Lysilla	alba		Lysi-alba	75
Macoma	petalum		Maco-peta	12.5
Macoploma	tenta		Maco-tent	312.5
Magelona	sp.	A	Mage-sp.	25
Maldanidae	sp.	indeter.	Mald-sp.	175
Marphysa	sanguinea		Marp-sang	12.5
Mediomastus	ambiseta		Medi-ambi	18662.5
Melinna	maculata		Meli-macu	575
Melita	nitida		Meli-niti	12.5
Mercenaria	mercenaria		Merc-merc	1200
Microdeutopus	gryllotalpa		Micr-gryl	7112.5
Microphiopholis	atra		Micr-atra	387.5

Neph-pict	187.5
Scol-tex	187.5
Mald-sp.	175
Owen-fusi	175
Poda-obsc	175
Trit-obso	175
Zygo-vire	175
Prio-pygm	162.5
Cari-lact	150
Diad-leuc	150
Diop-cupr	150
Edwa-eleg	150
Eupl-grac	150
Scol-bous	150
Halo-prod	137.5
Unci-irro	137.5
Arab-iric	125
Crat-pila	125
Kell-elev	125
Loim-medu	125
Tetr-eleg	125
Amer-bahi	112.5
Dysp-sayi	112.5
Pist-palm	112.5
Tetr-sp.	112.5
Amer-amer	100
Amph-sp.	100
Cora-obsc	100
Glyc-dibr	100
Neoa-figu	100
Proc-corn	100
Pseu-caro	100
Sacc-kowa	100
Sthe-boa	100
Alit-succ	87.5
Amph-ochr	87.5
Cabi-ince	87.5
Molg-aren	87.5
Oxyd-obsc	87.5
Pano-sp.	87.5
Styl-elli	87.5
Tana-psam	87.5
Asty-luna	75

Microphthalmus	sczelkowii		Micr-scze	75	Eupl-caud	75
Microprotopus	raneyi		Micr-rane	625	Harm-exte	75
Micrura	sp.		Micr-sp.	75	Hipp-zost	75
Molgula	arenata		Molg-aren	87.5	Lysi-alba	75
Molgula	manhattensis		Molg-manh	300	Micr-scze	75
Monocorophium	acherusicum		Mono-ache	725	Micr-sp.	75
Monocorophium	insidiosum		Mono-insi	12.5	Neme-sp.	75
Monocorophium	tuberculatum		Mono-tube	400	Phor-psam	75
Mulinia	lateralis		Muli-late	4225	Phyl-aren	75
Mya	arenaria		Mya-aren	12.5	Pseu-minu	75
Mysella	planulata		Myse-plan	62.5	Syll-verr	75
Mytilus	edulis		Myti-edul	1675	Ceri-amer	72.5
Nassariidae	sp.	juvenile	Nass-sp.	12.5	Asab-ocul	62.5
Nassarius	vibex		Nass-vibe	37.5	Ensi-dire	62.5
Naticidae	sp.	juv./indeter.	Nati-sp.	12.5	Myse-plan	62.5
Neanthes	arenaceodentata		Nean-aren	50	Nudi-sp.	62.5
Nemertea	sp.	2	Neme-sp.	75	Para-spec	62.5
Neoamphitrite	figulus		Neoa-figu	100	Para-fulg	62.5
Neomysis	americana		Neom-amer	300	Phas-stro	62.5
Nephtyidae	sp.	juvenile	Neph-sp.	12.5	Stre-verr	62.5
Nephtys	incisa		Neph-inci	25	Clym-sp.juv	50
Nephtys	picta		Neph-pict	187.5	Ensi-leei	50
Nereididae	sp.	juvenile	Nere-sp.	12.5	Epit-sp.	50
Neverita	duplicata		Neve-dupl	12.5	Ilya-obso	50
Notomastus	sp.	A	Noto-sp.	3112.5	Line-pall	50
Nucula	proxima		Nucu-prox	3687.5	Nean-aren	50
Nuculanidae	sp.	juvenile	Nucu-sp.	25	Odos-sp.juv	50
Nudibranchia	sp.		Nudi-sp.	62.5	Petr-phol	50
Odostomia	sp.	indeter.	Odos-sp.ind	25	Pinn-sp.	50
Odostomia	sp.	juvenile	Odos-sp.juv	50	Spio-seto	50
Oerstedia	dorsalis		Oers-dors	362.5	Syll-sp.	50
Oligochaeta	sp.		Olig-sp.	5237.5	Syll-conv	50
Opisthodonta	longocirrata		Opis-long	575	Alig-elev	37.5
Owenia	artifex		Owen-arti	25	Anad-tran	37.5
Owenia	fusiformis		Owen-fusi	175	Asci-sp.	37.5
Oxydromus	obscurus		Oxyd-obsc	87.5	Cara-hobs	37.5
Oxyurostylis	smithi		Oxyu-smit	350	Cran-sept	37.5
Pagurus	longicarpus		Pagu-long	25	Dipo-comm	37.5
Palaemon	vulgaris		Pala-vulg	37.5	Eric-sp.	37.5
Panopeidae	sp.	juv.	Pano-sp.	87.5	Have-scab	37.5
Paracaprella	tenuis		Para-tenu	1425	Hexa-angu	37.5
Paradoneis	sp.	C	Para-sp.	25	Nass-vibe	37.5
Parahaustorius	longimerus		Para-long	325	Pala-vulg	37.5

Parahesione	luteola		Para-lute	37.5	Para-lute	37.5
Parametopella	cypris		Para-cypr	37.5	Para-cypr	37.5
Paranaitis	speciosa		Para-spec	62.5	Phro-vibe	37.5
Paraonis	fulgens		Para-fulg	62.5	Poly-joui	37.5
Paraprionospio	alata		Para-alat	687.5	Sabe-vulg	37.5
Paraprionospio	pinnata		Para-pinn	400	Upog-affi	37.5
Paraprionospio	treadwelli		Para-trea	650	Yold-lima	37.5
Parasabella	microphthalma		Para-micr	675	Amph-caec	25
Pectinaria	gouldii		Pect-goul	912.5	Amph-orna	25
Pentamera	pulcherrima		Pent-pulc	2450	Biva-sp.	25
Periploma	fragile		Peri-frag	12.5	Call-sapi	25
Petricolaria	pholadiformis		Petr-phol	50	Canc-irro	25
Phascolion	strombus		Phas-stro	62.5	Caul-vene	25
Pholoe	minuta		Phol-minu	212.5	Crep-plan	25
Phoronis	psammophila		Phor-psam	75	Dorv-rudo	25
Phrontis	vibex		Phro-vibe	37.5	Euni-sp.	25
Phyllodoce	arenae		Phyl-aren	75	Hete-(Het	25
Pinnixa	chaetopterana		Pinn-chae	12.5	Hydr-dian	25
Pinnixa	sp.	indeter.	Pinn-sp.	50	Hype-hete	25
Pionosyllis	longocirrata		Pion-long	12.5	List-smit	25
Pista	cristata		Pist-cris	200	Litt-tenu	25
Pista	palmata		Pist-palm	112.5	Litt-litt	25
Pista	spp.	juvenile	Pist-spp.	25	Mage-sp.	25
Pitar	morrhuanus		Pita-morr	25	Neph-inci	25
Platynereis	dumerilii		Plat-dume	500	Nucu-sp.	25
Podarke	obscura		Poda-obsc	175	Odos-sp.ind	25
Podarkeopsis	levifuscina		Poda-levi	300	Owen-arti	25
Polycirrus	eximius		Poly-exim	2237.5	Pagu-long	25
Polycladida	sp.	A	Poly-sp.	25	Para-sp.	25
Polydora	cornuta		Poly-corn	1800	Pist-spp.	25
Polygordius	jouinae		Poly-joui	37.5	Pita-morr	25
Polynoidae	(Lepidonotinae)	sp.	Poly-Lep	12.5	Poly-sp.	25
Prionospio	heterobranchia		Prio-hete	2937.5	Ptil-tenu	25
Prionospio	pygmaeus		Prio-pygm	162.5	Sten-minu	25
Proceraea	cornuta		Proc-corn	100	Tetr-verm	25
Protohaustorius	cf.	deichmannae	Prot-cf.	1112.5	Agri-morr	12.5
Pseudohautorius	caroliniensis		Pseu-caro	100	Aren-cris	12.5
Pseudoleptocuma	minus		Pseu-minu	75	Bocc-lige	12.5
Ptilanthura	tenuis		Ptil-tenu	25	Cere-lact	12.5
Pygospio	elegans		Pygo-eleg	6037.5	Cirra-gran	12.5
Rhepoxynius	hudsoni		Rhep-huds	2587.5	Cirri-gran	12.5
Rudilemboides	naglei		Rudi-nagl	1937.5	Cirr-sp.	12.5
Sabaco	elongatus		Saba-elon	537.5	Coro-spp.	12.5

Sabellaria	vulgaris		Sabe-vulg	37.5
Sabellidae	sp.	indeterminate	Sabe-sp.	325
Saccoglossus	kowalevskii		Sacc-kowa	100
Salvatoria	clavata		Salv-clav	1200
Scolelepis	(P.)	spp.	Scol-sp.	12.5
Scolelepis	(Parascolelepis)	bousfieldi	Scol-bous	150
Scolelepis	(Parascolelepis)	texana	Scol-tex	187.5
Scoletoma	tenuis		Scol-tenu	1550
Scoloplos	(Leodamas)	rubra	Scol-rubr	12.5
Scoloplos	sp.	juvenile	Scolo-sp.	12.5
Solemya	velum		Sole-velu	912.5
Sphaerosyllis	brevidentata		Spha-brev	537.5
Spio	setosa		Spio-seto	50
Spiochaetopterus	costarum	oculatus	Spio-cost	1450
Spiochaetopterus	oculatus		Spio-ocul	1912.5
Spiophanes	bombyx		Spio-bomb	950
Spirorbis	corrugatus		Spir-corr	38250
Spisula	solidissima		Spis-soli	1037.5
Stenothoe	minuta		Sten-minu	25
Sthenelais	boa		Sthe-boa	100
Streblospio	benedicti		Stre-bene	3237.5
Streptosyllis	verrilli		Stre-verr	62.5
Streptosyllis	websteri		Stre-webs	12.5
Stylochus	ellipticus		Styl-elli	87.5
Syllidae	sp.	indeterminate	Syll-sp.	50
Syllides	convolutus		Syll-conv	50
Syllides	verrilli		Syll-verr	75
Syllis	alternata		Syll-alte	387.5
Tagelus	divisus		Tage-divi	525
Tanaissus	psammophilus		Tana-psam	87.5
Tellina	agilis		Tell-agil	1075
Tetrastemma	elegans		Tetr-eleg	125
Tetrastemma	sp.	A	Tetr-sp.	112.5
Tetrastemma	vermiculus		Tetr-verm	25
Tharyx	sp.	A	Thar-sp.	8612.5
Tornidae	sp.	indeter.	Torn-sp.ind	12.5
Tornidae	sp.	juvenile	Torn-sp.juv	12.5
Tricladida	sp.	B	Tric-sp.	12.5
Tritia	obsoleta		Trit-obso	175
Tubificoides	sp.		Tubi-sp.	3800
Turbellaria	sp.	A	Turb-sp.	12.5
Turbonilla	interrupta		Turb-inte	1500
Unciola	dissimilis		Unci-diss	275

Cost-avar	12.5
Cycl-vari	12.5
Dona-vari	12.5
Dril-long	12.5
Ennu-tenu	12.5
Epit-rupi	12.5
Eric-bras	12.5
Eteo-foli	12.5
Eury-depr	12.5
Gyro-rupi	12.5
Harg-rapa	12.5
Harm-imbr	12.5
Hobs-flor	12.5
Hydr-prot	12.5
Hype-foli	12.5
Idun-smit	12.5
Jass-marm	12.5
Kurt-plan	12.5
Laeo-culv	12.5
Laev-mort	12.5
Leit-frag	12.5
Lepi-comm	12.5
Lept-rapa	12.5
Line-rube	12.5
Loim-viri	12.5
Maco-peta	12.5
Marp-sang	12.5
Meli-niti	12.5
Mono-insi	12.5
Mya-aren	12.5
Nass-sp.	12.5
Nati-sp.	12.5
Neph-sp.	12.5
Nere-sp.	12.5
Neve-dupl	12.5
Peri-frag	12.5
Pinn-chae	12.5
Pion-long	12.5
Poly-Lep	12.5
Scol-sp.	12.5
Scol-rubr	12.5
Scolo-sp.	12.5
Stre-webs	12.5

Unciola	irrorata		Unci-irro	137.5	Torn-sp.ind	12.5
Unciola	serrata		Unci-serr	12.5	Torn-sp.juv	12.5
Upogebia	affinis		Upog-affi	37.5	Tric-sp.	12.5
Urosalpinx	cinerea		Uros-cine	12.5	Turb-sp.	12.5
Yoldia	limatula		Yold-lima	37.5	Unci-serr	12.5
Yoldia	sp.	juvenile	Yold-sp.	12.5	Uros-cine	12.5
Zygonemertes	virescens		Zygo-vire	175	Yold-sp.	12.5
Grand Total				38,250		38,250

Table 24. Fixed effects coefficients from GLMM on grab sample total CPUE data with 134 observations and 130 degrees of freedom using a normal distribution and identity link with maximal pseudoliklihood method.

Name	Estimate	SE	pValue
Intercept	6904.1	5036.8	0.17282
Before	13331	6742.5	0.050146
Distance	967.78	685.35	0.16031
Before:Distance	-1279.5	836.08	0.12836

Table 25. Summary of PCA on grab sample compositional data with 134 active cases. Total sum of squares in response data = 69848.63388. Total standard deviation TAU = 1.315962

Statistic	Axis 1	Axis 2	Axis 3	Axis 4
Eigenvalues	0.1291	0.1173	0.0771	0.0588
Explained variation (cumulative)	12.91	24.65	32.36	38.24

Table 25. Fixed effects coefficients from GLMM on grab sample compositional data with 134 observations and 130 degrees of freedom using a normal distribution and identity link with maximal pseudoliklihood method.

Name	Estimate	SE	p value
PC 1			
Intercept	0.42065	0.47492	0.37741
Before	-0.19085	0.66746	0.77539
Distance	**-0.14956**	**0.073319**	**0.043398**
'Before:Distanc'	0.13394	0.089296	0.13605
PC 2			
Intercept	-0.43019	0.4878	0.37946
Before	-0.45806	0.62578	0.4655
Distance	0.021471	0.080314	0.78963
Before:Distance	0.11446	0.094013	0.22563
PC 3			
Intercept	1.3023	0.38037	0.00082648
Before	**-1.9762**	**0.56036**	**0.000582**
Distance	-0.095748	0.055389	0.086246
Before:Distance	**0.12336**	**0.068047**	**0.07217**
PC 4			
Intercept	-0.16874	0.58928	0.77506
Before	**1.4474**	**0.75909**	**0.058761**
Distance	0.033635	0.066414	0.61341
Before:Distance	**-0.20701**	**0.081482**	**0.012243**

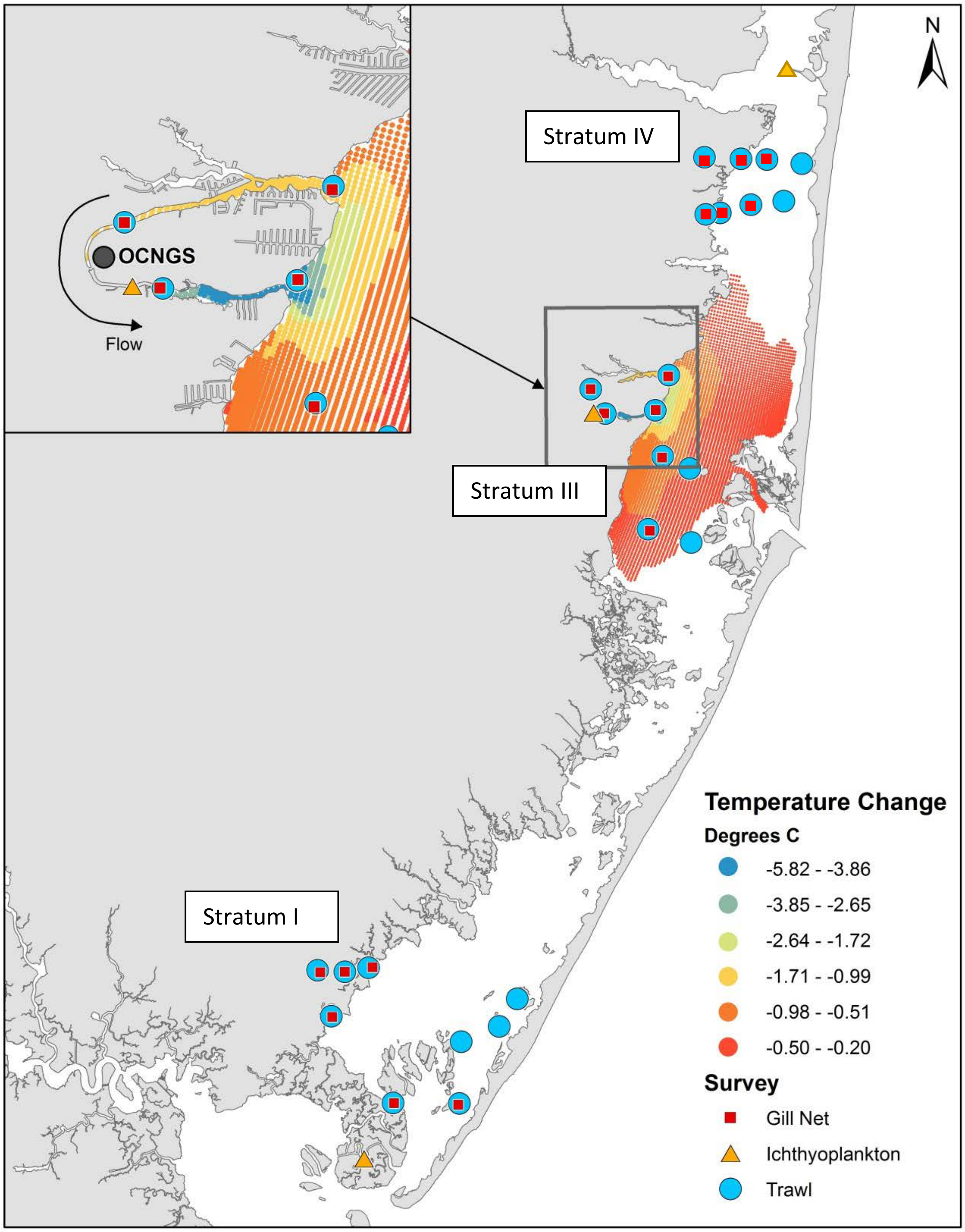


Figure 1. Location of Oyster Creek Nuclear Generating Station OCNGS in Barnegat Bay. Colored gradients, in large maps and inset, depict the change in water temperature cooling as a result of the decrease off thermal discharge. Prediction is based on USGS simulation using input from moored Hobo Temp Loggers. Courtesy of Helen Pang. See http://www.nj.gov/dep/barnegatbay/bbmapviewer.htm.

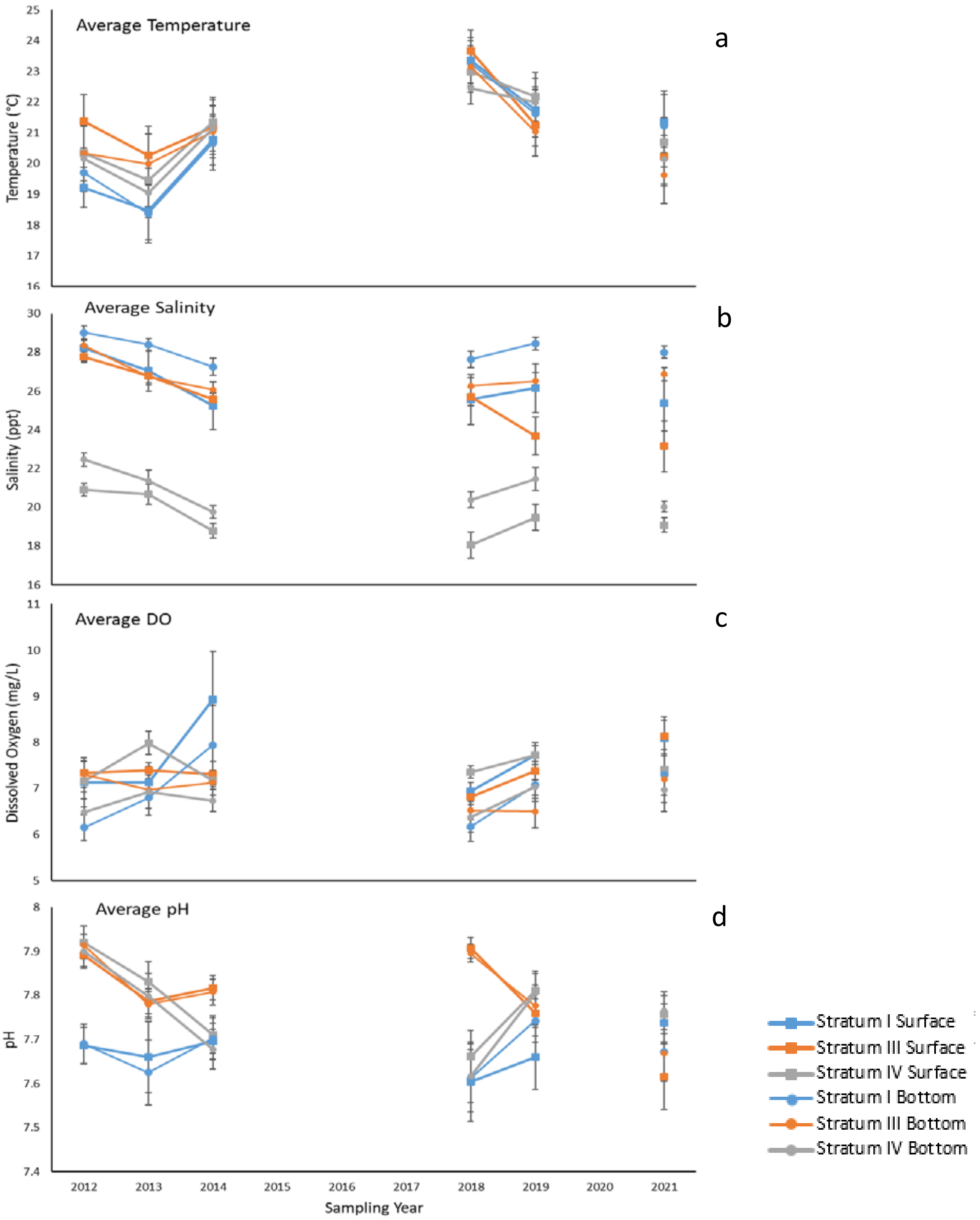


Figure 2. Average environmental parameters collected during otter trawl sampling from surface and bottom water samples over the years. See Figure 1 for Strata locations. The years 2012, 2013, 2014 and 2018 represent the years before the closure of the power plant. 2019 and 2021 represent the years post-closure.

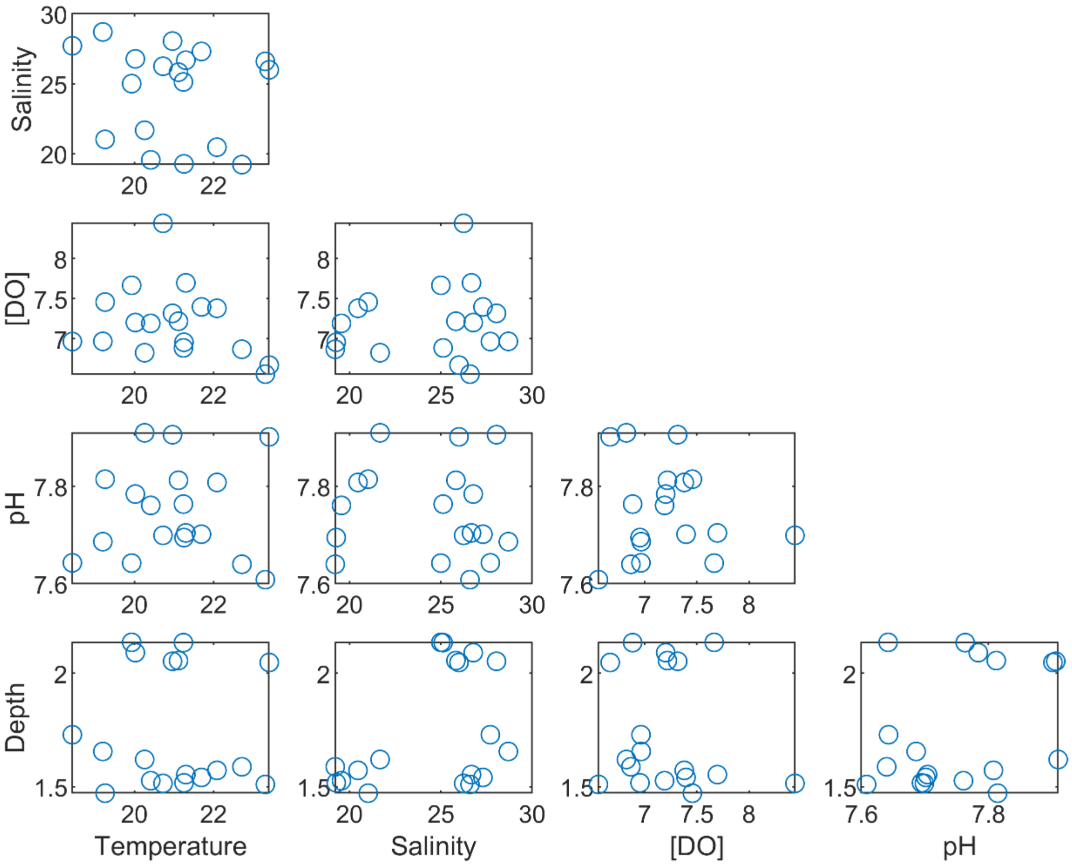


Figure 3. Plots showing the relationship between each pair-wise combination of water column characters measured during otter trawling.

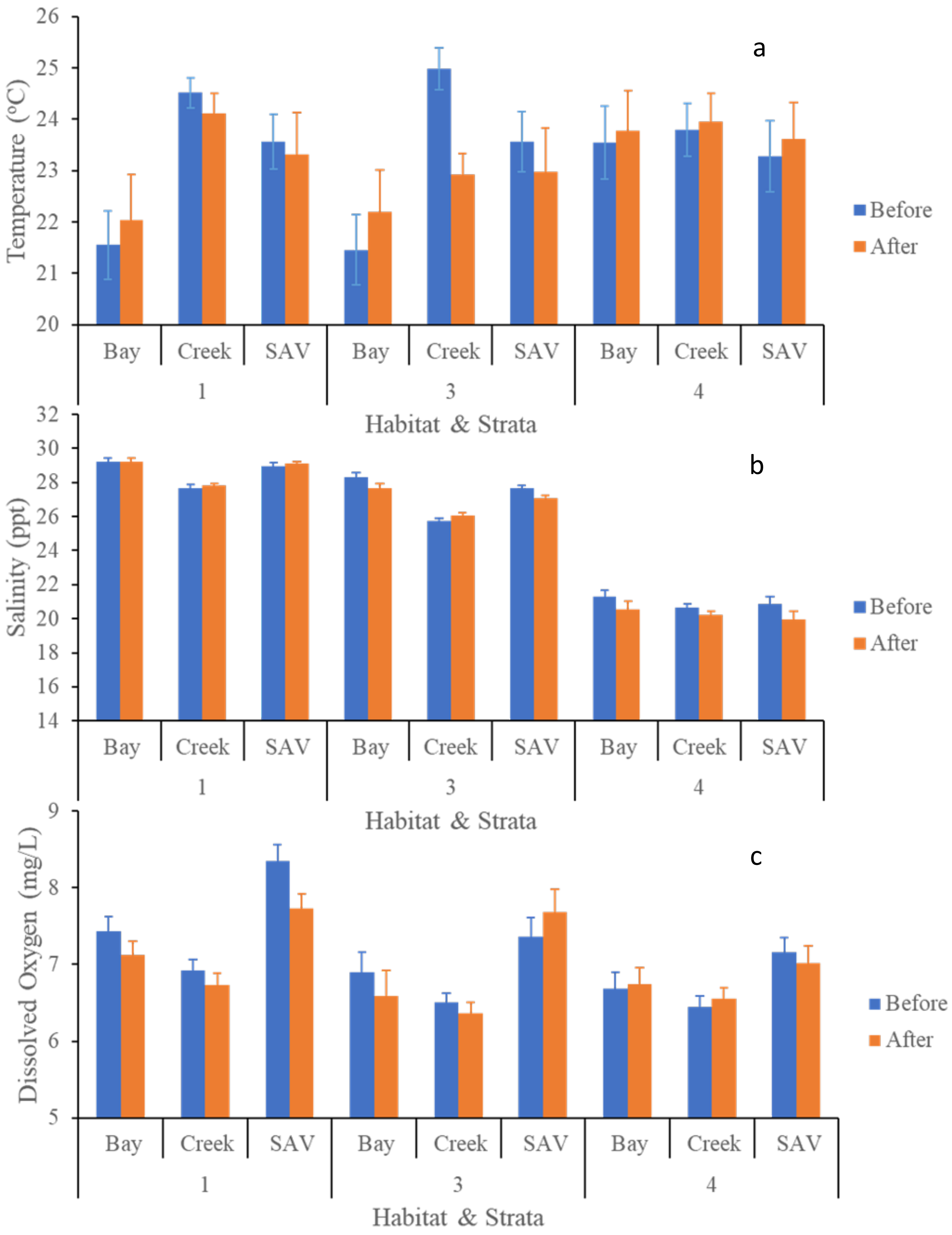


Figure 4. Average (+ 1 standard error) temperature (a) salinity (b) and dissolved oxygen (c) before and after the OCNGS closure in each habitat within each strata from adult blue crab sampling.

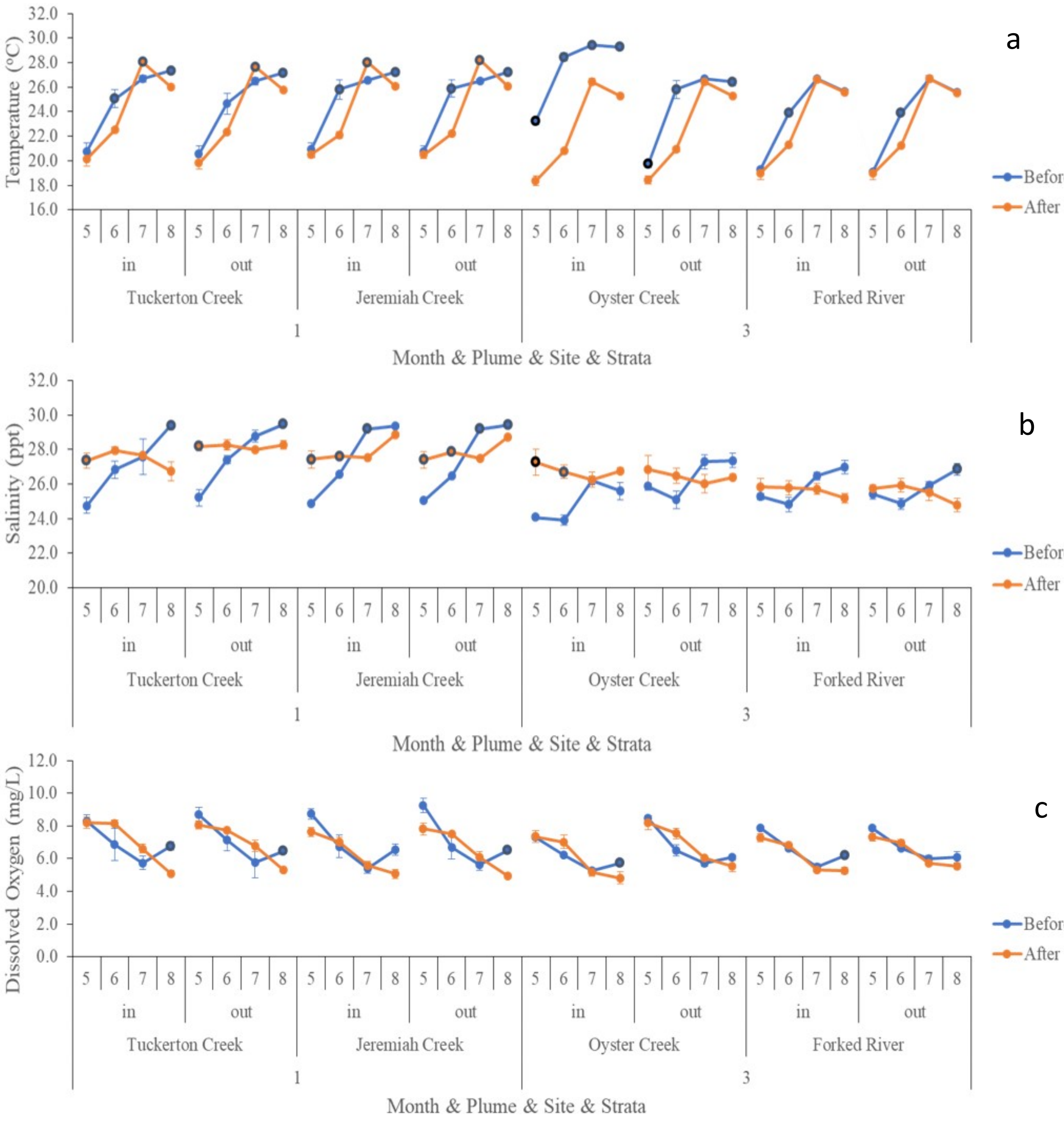


Figure 5. Average (+1 standard error) (a) temperature, (b) salinity, and (c) and dissolved oxygen before and after the OCNGS closure across months (5-8), inside and outside the plumes of each creek habitat in strata 1 and 3 from adult blue crab sampling.

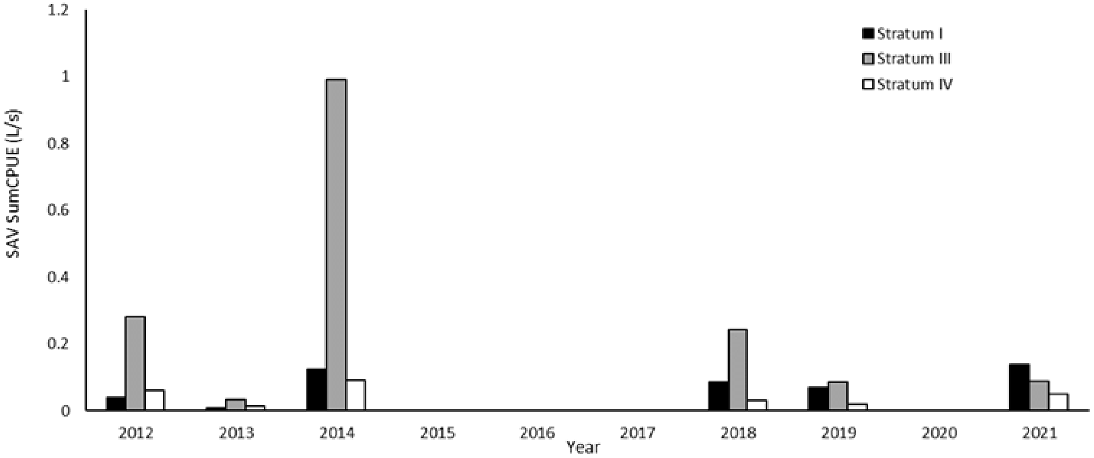


Figure 6. Abundance of submerged aquatic vegetation by year as collected in otter trawls

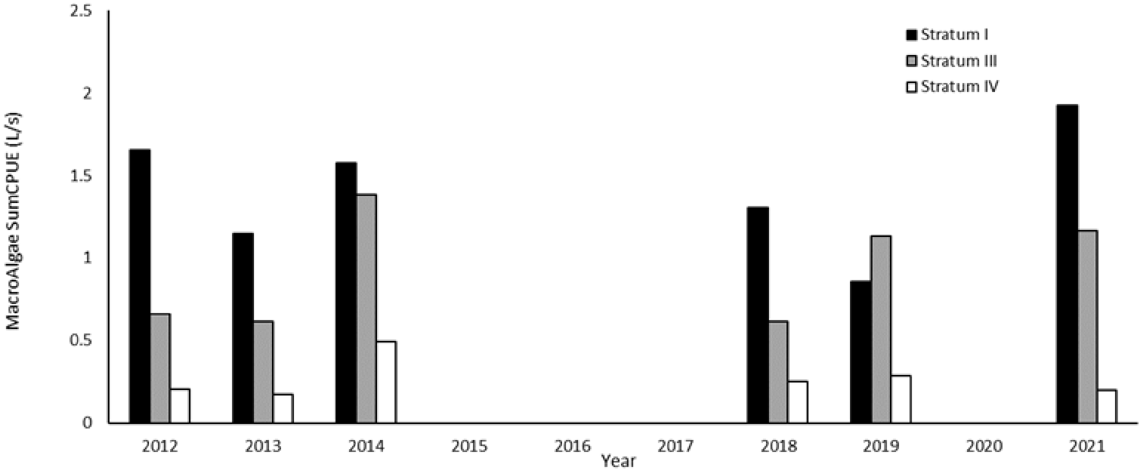


Figure 7. Abundance of macroalgae by year as collected in otter trawls

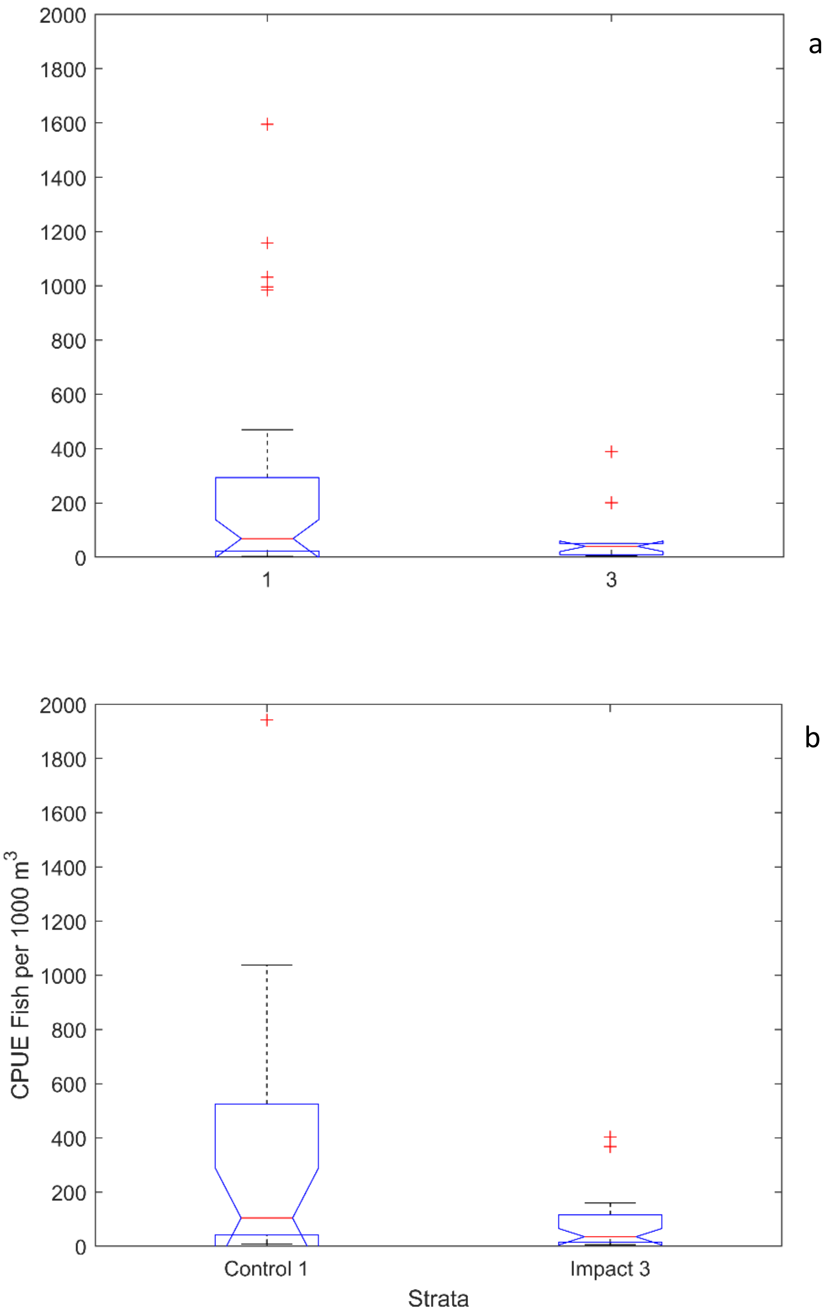


Figure 8. Box-whisker plot of CPUE of larval fish collected by plankton net Before (a) and After (b) in Control and Impact samples. The central red mark indicates the median, and the bottom and top edges of the box indicate the 25th and 75th percentiles, respectively. The whiskers extend to the most extreme data points not considered outliers, and the outliers are plotted individually using the `'+'` symbol. When the sample size is small, notches may extend beyond the end of the box. Outliers for Impact at 3.7812 and for Control at 5329.98 and 4006.01 in the Before panel for Control at 10,739.015 in the After panel are not shown to expand lower axis limits panel. It was very clear that there were more larval fish captured in the Control strata, but it was not at all indicated that this changed relative to the Impact zone after shutdown (see **Table 7** for test results).

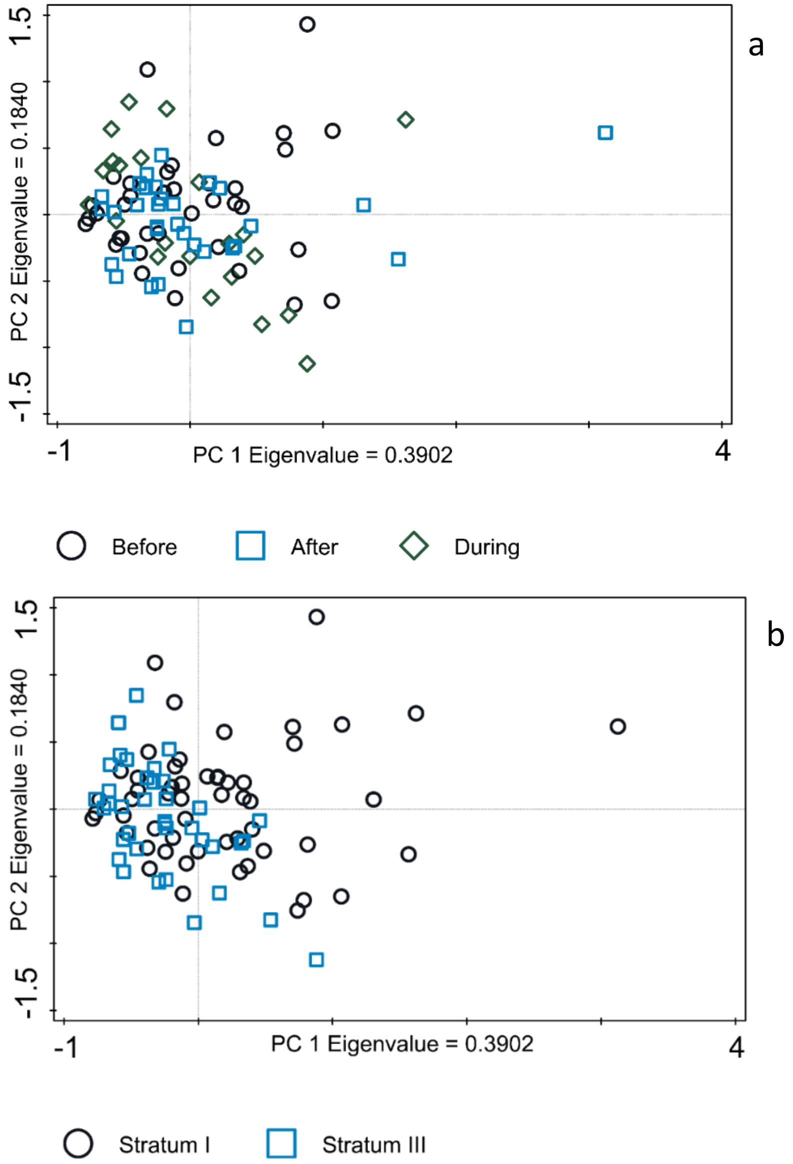


Figure 9. Scatter plots of ichthyoplankton sample ordination scores on the first and second principal component axes. Each plot point represents a sample. Since each sample differs from others in the abundance of many species, it is not possible or justifiable to quantify their similarity on a single species. PCA (and DCA) find the four most important trends in all the species at the same time as (Eigenaxes or components 1-4) and space sample plots by similarity along these. Inter-sample distance is χ^2 and indicates similarity in species composition. The trends in composition that account for this spacing are shown in the same plot space in **Figure 10**, but are separated for legibility. Sample symbols in panel (a) show that there is no clear separation of Before, During, or After samples. Sample symbols in panel (b) show the sample stratum. Dissimilarity in the composition of larva fish in many of the LSHC samples (all from Stratum 1) from those in locations in locations from Stratum III is apparent as a right (positive) shift in sample scores but overlap is sufficient in the remaining samples that confidence in an effect is low (see **Table 9** for test statistics).

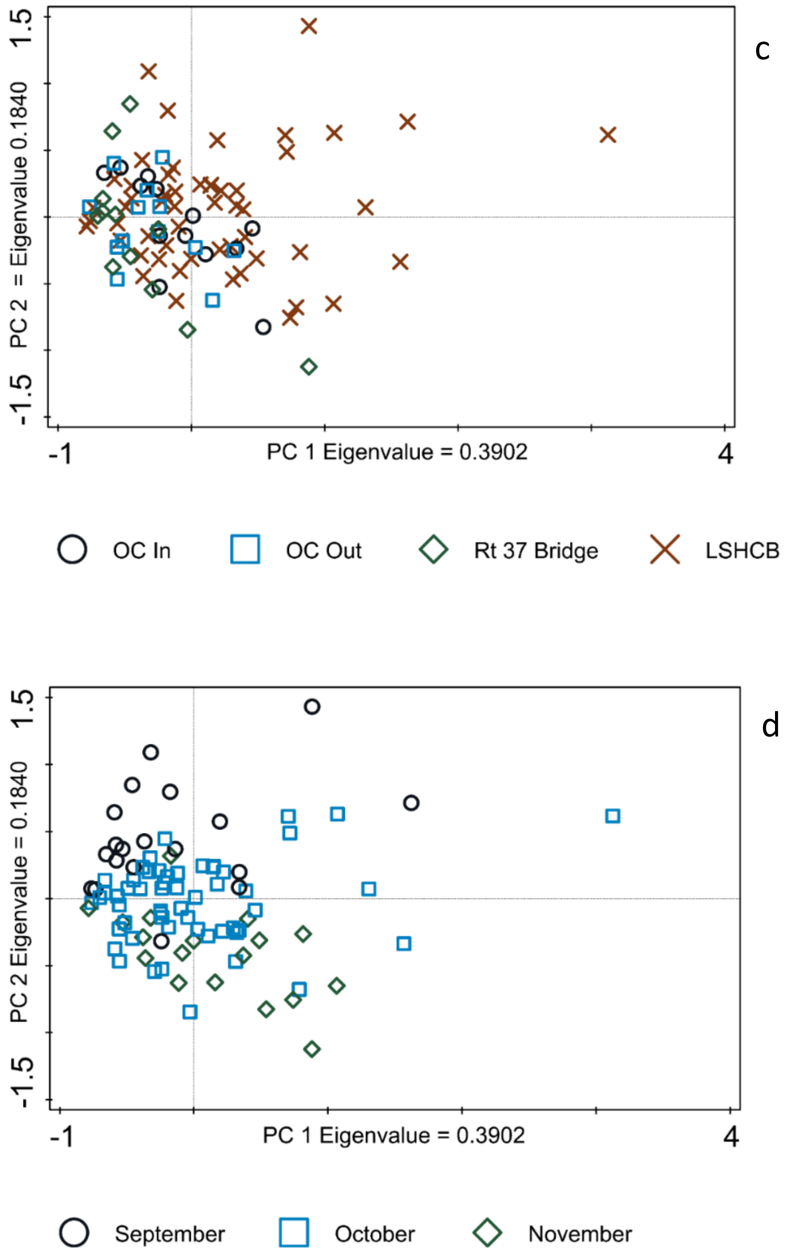


Figure 9. Scatter plots of ichthyoplankton sample ordination scores on the first and second principal component axes. Each plot point represents a sample. Inter-sample distance is χ^2 and indicates similarity in species composition. The trends in composition that account for this spacing are shown in the same plot space in **Figure 10**, but are separated for legibility. Samples symbols in panel (c) show location of collection. Sample symbols in panel (d) show t show month of collection. A gradual right (positive) shift in the scores by month indicates a gradual change in the composition of larval species from September to November (See **Table 9** for test statistics).

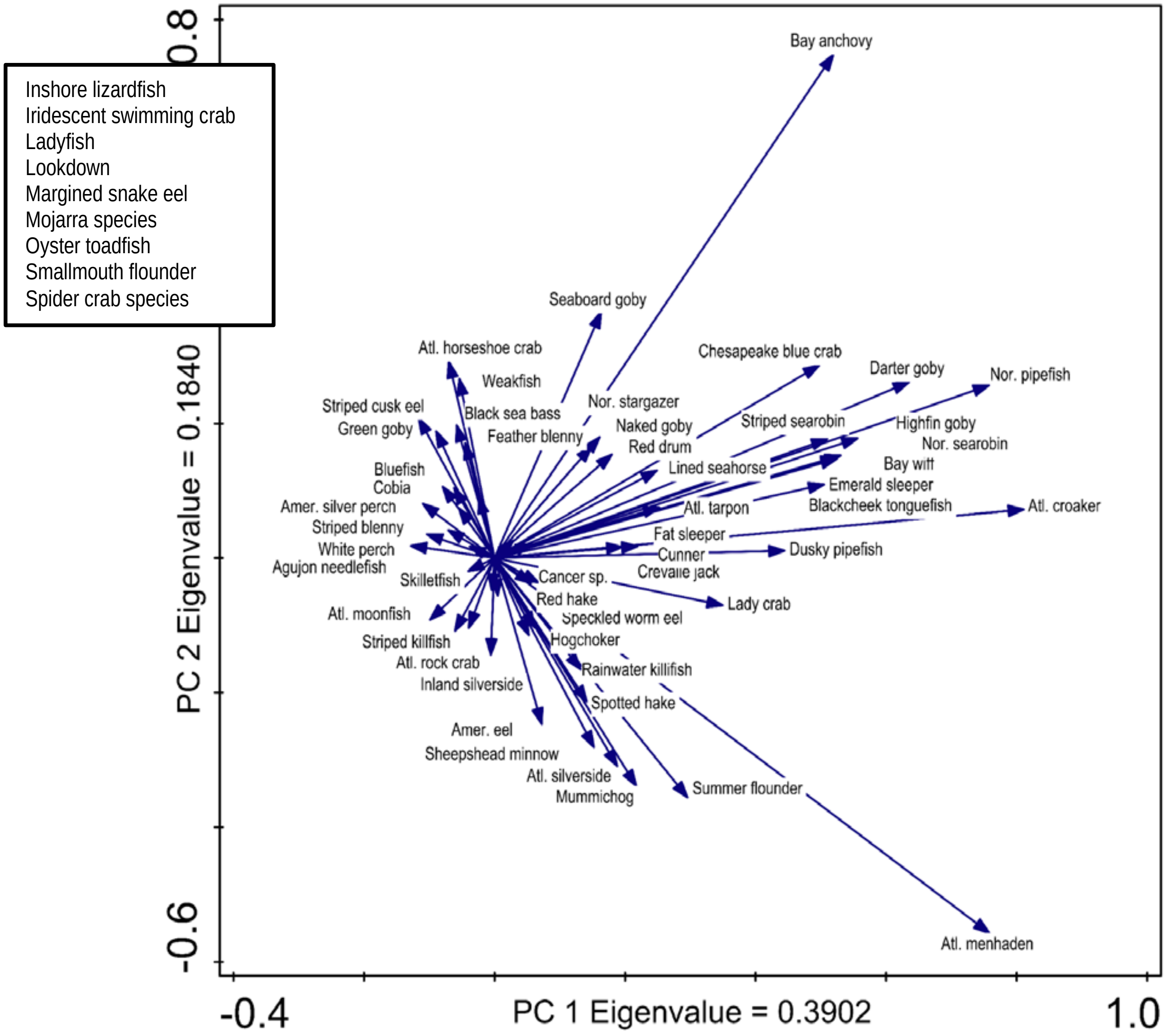


Figure 10. Scatter plot of species abundance trends along the first and second principal components through the ichthyoplankton samples. Figure is in the same plot space as **Figure 8**, but separated for legibility. Samples in **Figure 8** are more likely to contain more of the species for which vectors point towards them. Vector length is proportional to the strength of that species abundance gradient. Some species labels are moved or cut for legibility. Cut species labels are generally towards the plot middle and are less important in defining the ordination gradient. Cut species labels are shown inset. Coefficients, Frequency fitted values, and weights for all species are provided in **Appendix 1**.

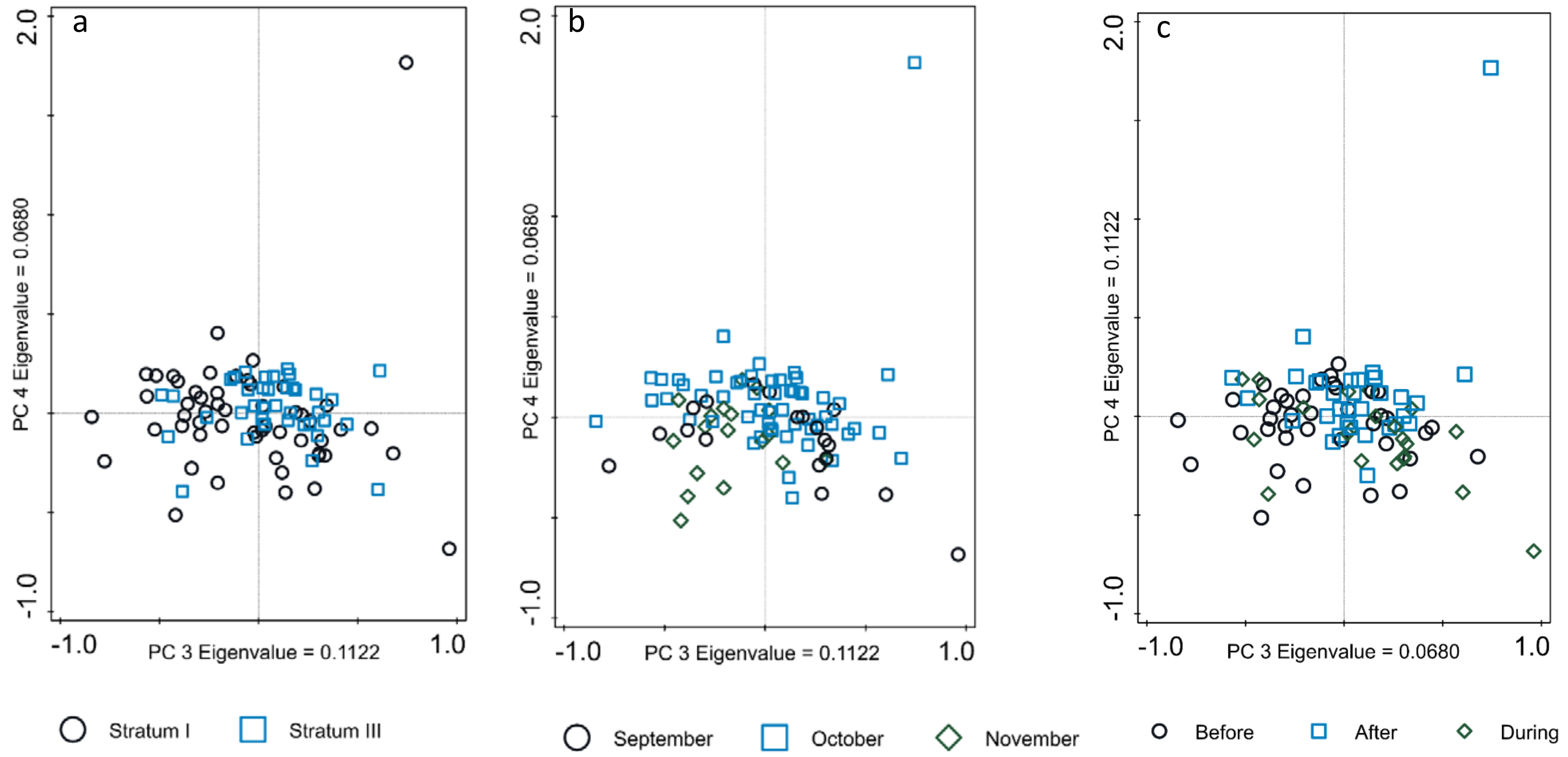


Figure 11. Scatter plots of ichthyoplankton sample ordination scores on the third and fourth principal component axes. Inter-sample distance is χ^2 and indicates similarity in species composition. The trends in composition that account for this spacing are shown in the same plot space in **Figure 12**, but are separated for legibility. Samples symbols in panel (a) show sample stratum, (b), month of collection and (c) show the sample test period. An upward (positive) shift in the scores for Stratum III also reflected in Before/After are sufficient for concluding that there was a difference in species composition (See **Table 9** for test statistics). A shift in sample composition by month is also apparent, but season was treated as a random factor in testing.

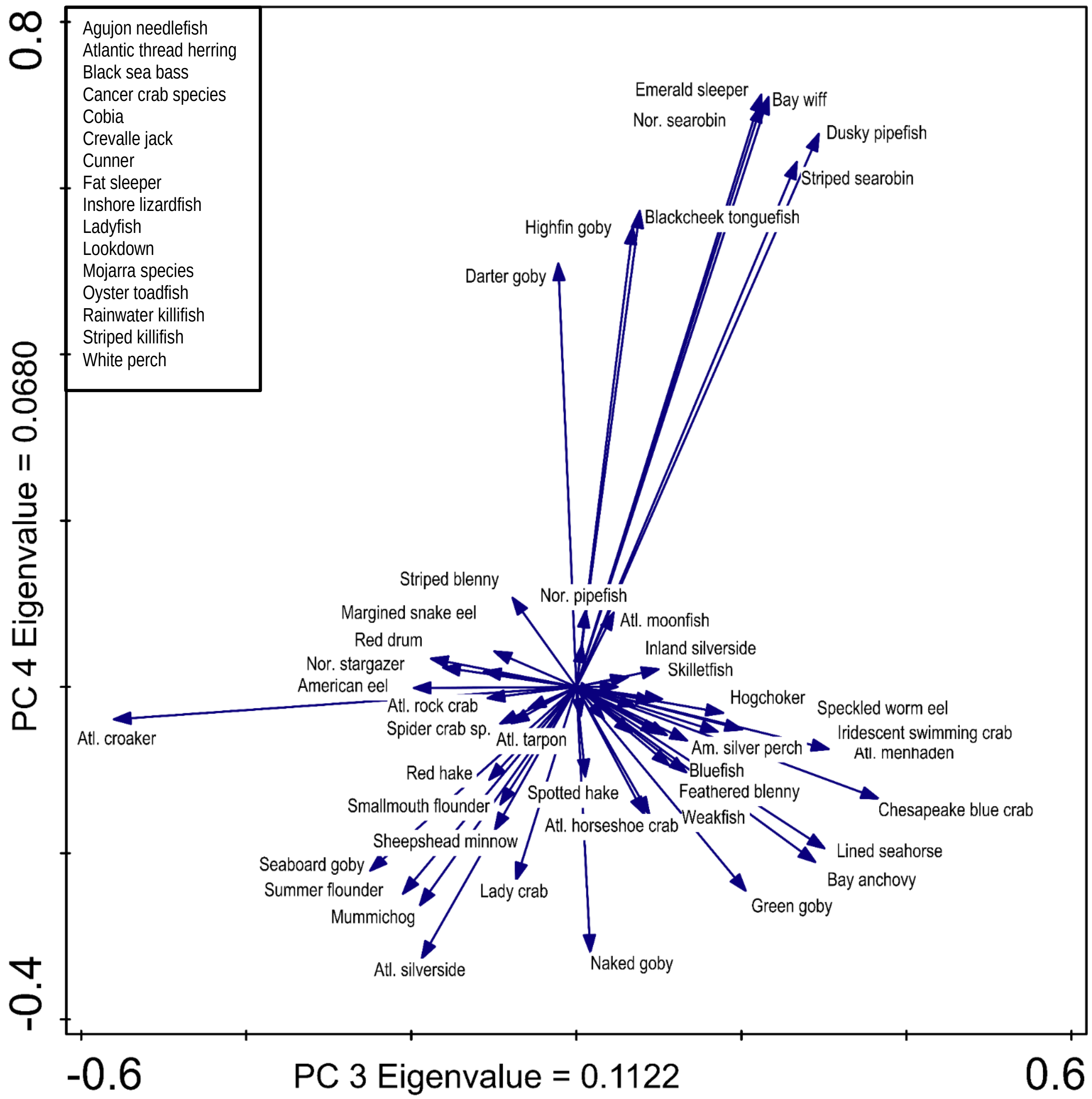


Figure 12. Scatter plot of species abundance trends along third and fourth principal components through the ichthyoplankton samples. Figure is in the same plot space as **Figure 11**, but separated for legibility. Samples in **Figure 11** are more likely to contain more of the species for which vectors point towards them. Vector length is proportional to the strength of that species abundance gradient. Some species labels are moved or cut for legibility. Cut species labels are generally towards the plot middle and are less important in defining the ordination gradient. Cut species labels are shown inset. Coefficients, Frequency fitted values, and weights for all species are provided in **Appendix 1**.

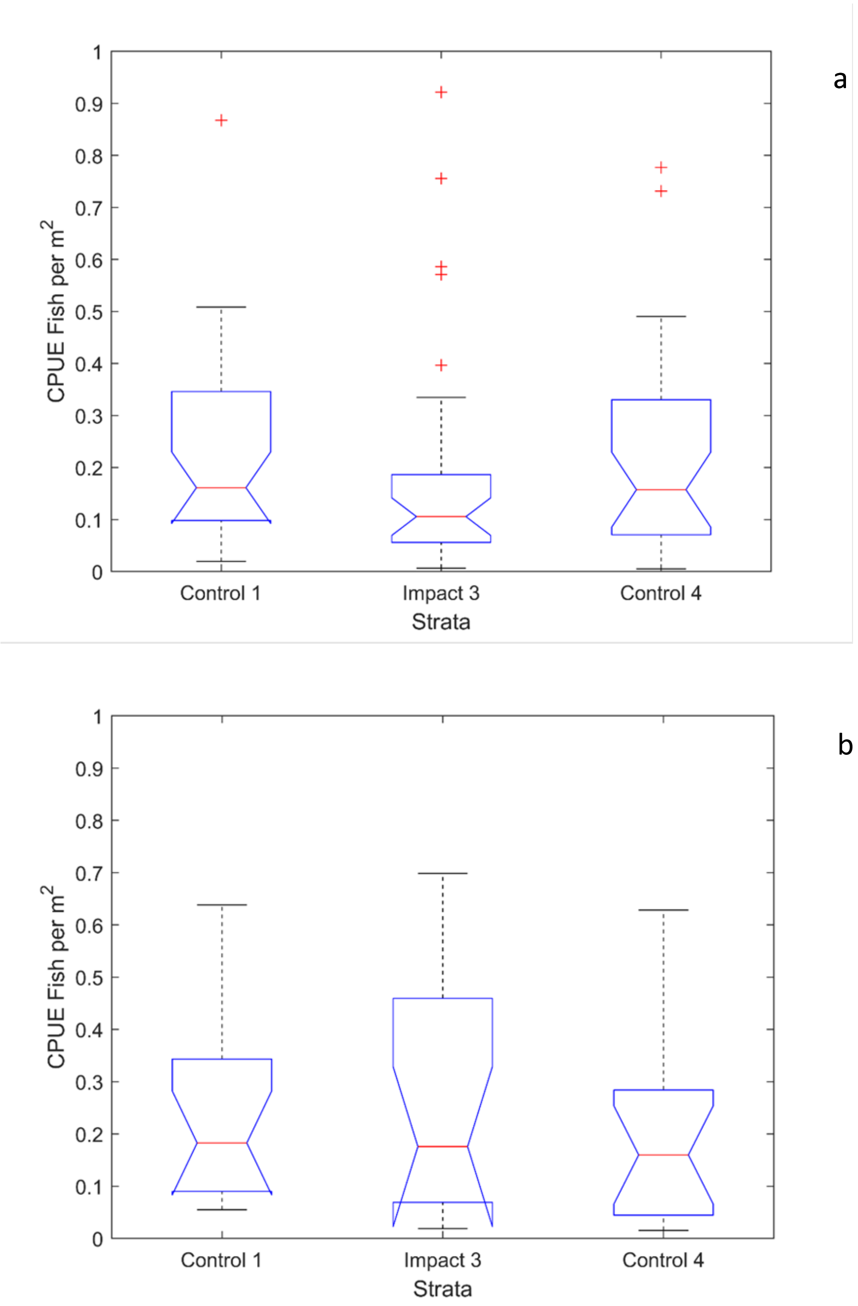


Figure 13. Box-whisker plot of fish abundance as Catch-per-Unit-Effort CPUE in otter trawls Before (al) and After (bl) OCNGS closure. The central red mark indicates the median, and the bottom and top edges of the box indicate the 25th and 75th percentiles, respectively. The whiskers extend to the most extreme data points not considered outliers, and the outliers are plotted individually using the `'+'` symbol. When the sample size is small, notches may extend beyond the end of the box. In the Before panel, outliers for Impact at 3.7812 and for Control 1 at 2.2806 are not shown to expand lower axis limits. In the After panel An Outlier for Impact at 2.4118 not shown to expand lower axis limits. While there are some more samples with more fish in the Impact site After closure, the variance is high and there is no confidence in this difference as a real increase (see **Table 12** for test statistics).

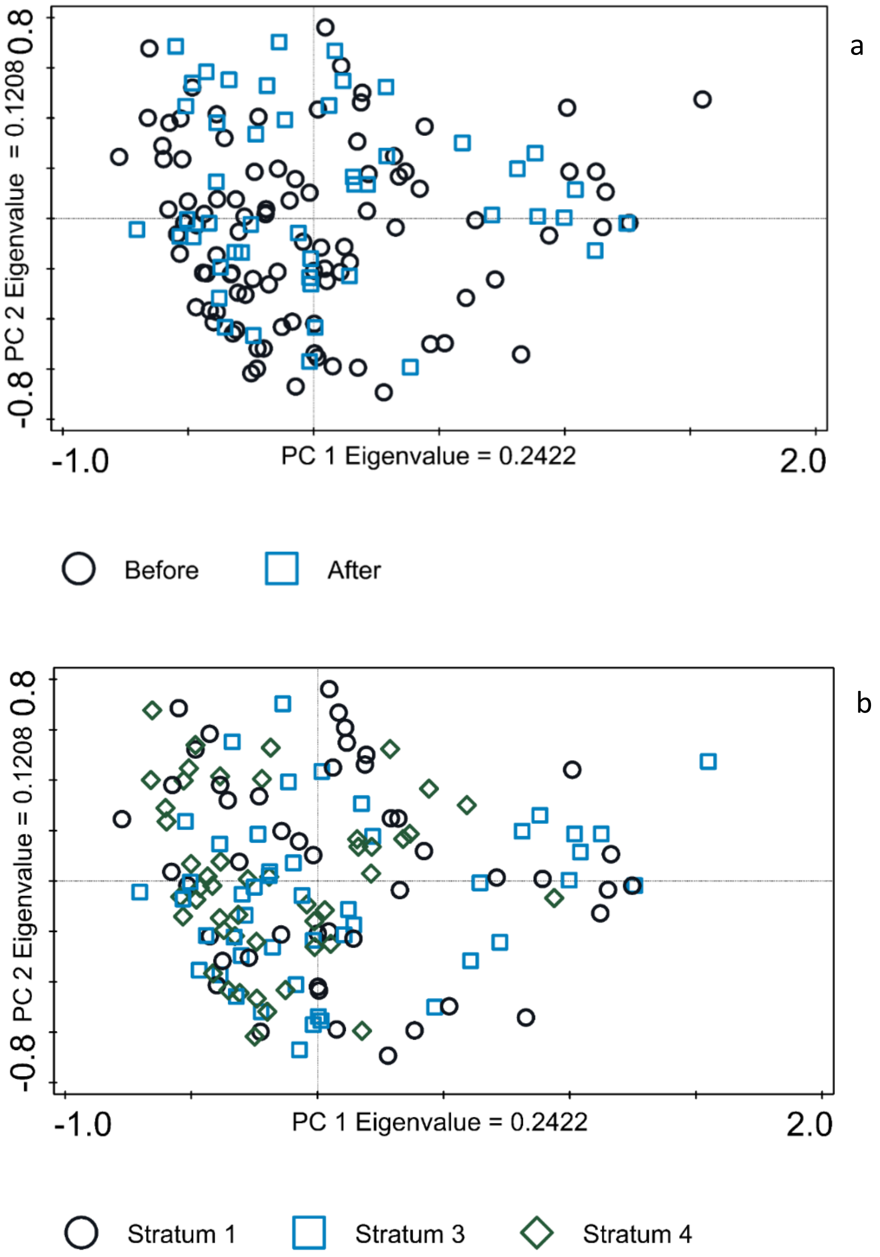


Figure 14. Scatter plots of otter trawl sample ordination scores on the first and second principal component axes. Inter-sample distance is χ^2 and indicates similarity in species composition. The trends in composition that account for this spacing are shown in the species plot in the same plot space in **Figure 15**, but are separated for legibility. Overlaying the sample and species plots shows which species drove sample differentiation and to what extent along either of the two principal component axes. Sample symbols in panel (a) show the sample test period and panel (b) shows sample stratum. There is no clear separation of samples on the basis of Before/After or by Stratum that would indicate a change in the composition of species as a result of these factors (see **Table 14** for test statistics).

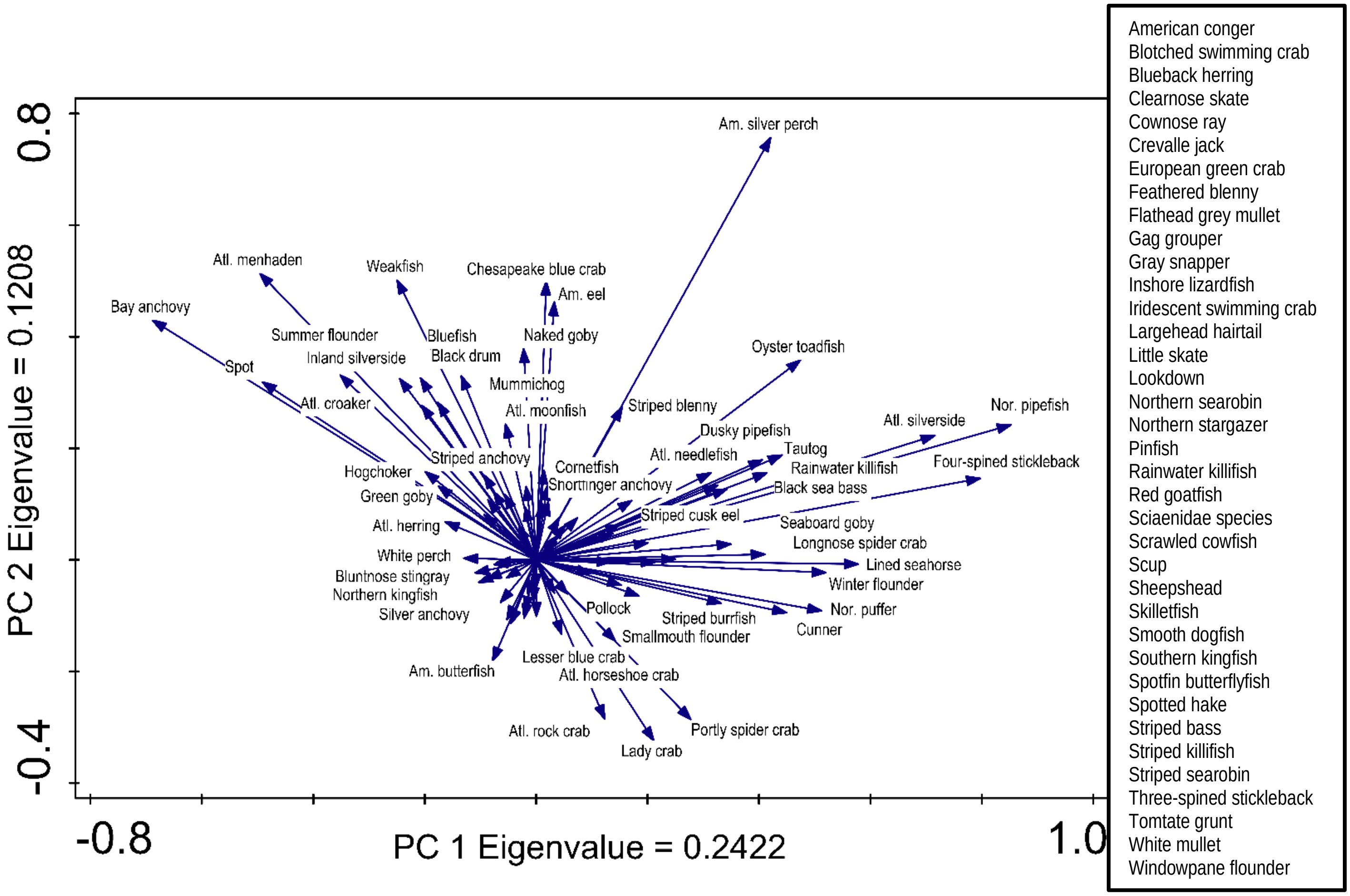


Figure 15. Scatter plot of species abundance trends along first and second principal components through the otter trawl samples. Figure is in the same plot space as **Figure 15**, but separated for legibility. Samples in **Figure 15** are more likely to contain more of the species for which vectors point towards them. Vector length is proportional to the strength of that species abundance gradient. Some species labels are moved or cut for legibility. Cut species labels are generally towards the plot middle and are less important in defining the ordination gradient. Cut species labels are shown inset. Coefficients, Frequency fitted values, and weights for all species are provided in **Appendix 2**.

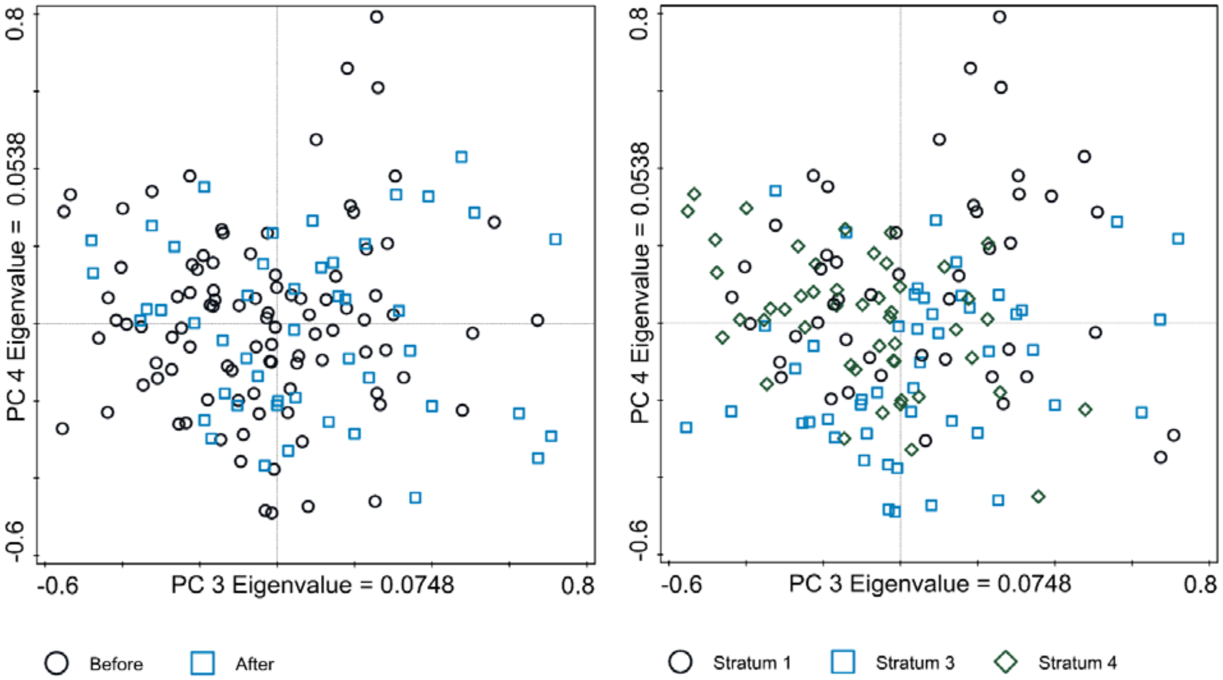


Figure 16. Scatter plots of otter trawl sample ordination scores on the third and fourth principal component axes. Each plot point is a sample. Inter-sample distance is χ^2 and indicates similarity in species composition. The trends in species composition that account for this spacing are shown in the same plot space in **Figure 18**, but are separated for legibility. Sample symbols in panel (a) show the sample test period and panel (b) shows sample stratum. There is a no apparent difference in the distribution of samples from Before closure relative to After along either principal component axis, but there is a weak right (positive) shift in the distribution of Impact stratum sample relative to Control samples along the third principal component axis and a weak positive negative shift for Impact samples on the fourth axis, and these are sufficient for confidence that the composition of species in these samples differed (see **Table 14** for test statistics).

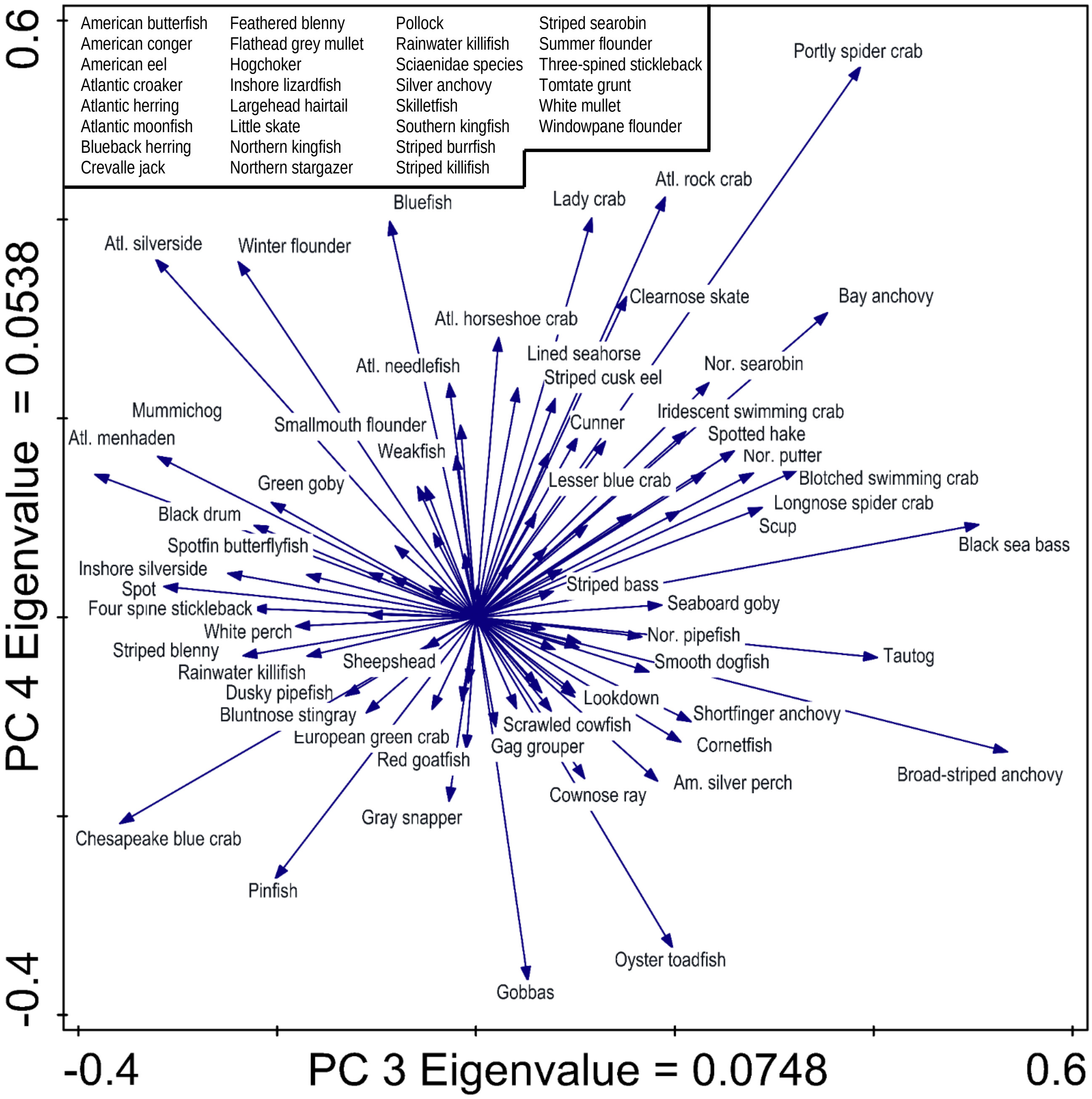
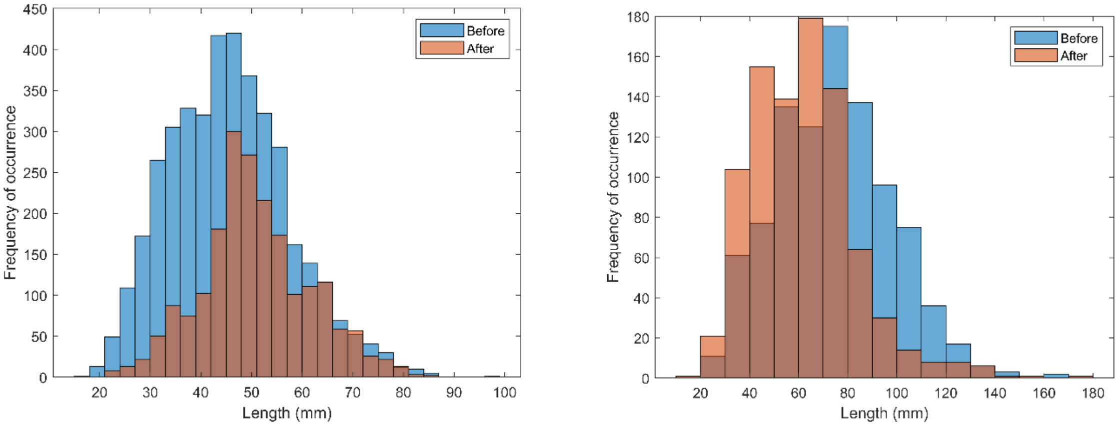
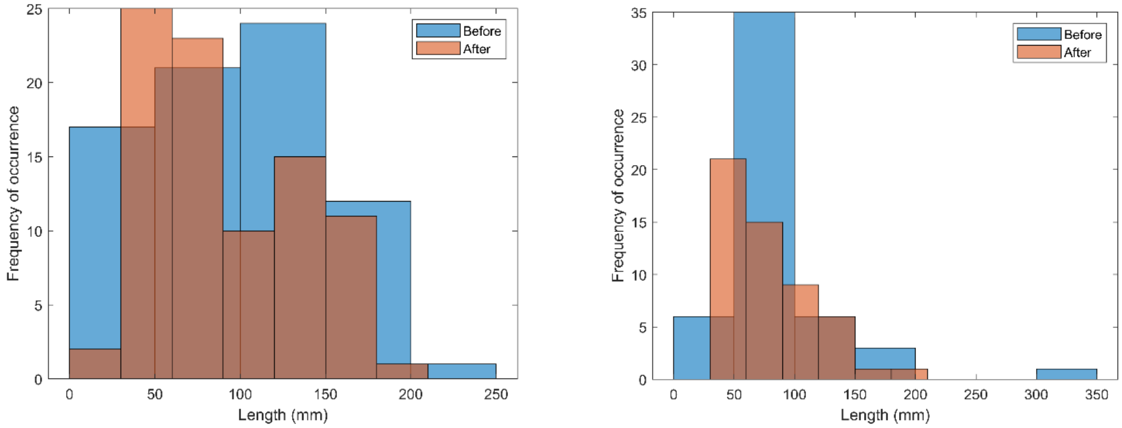


Figure 17. Scatter plot of species abundance trends along the third and fourth principal components through the otter trawl samples. Figure is in the same plot space as **Figure 16**, but separated for legibility. Samples in **Figure 16** are more likely to contain more of the species for which vectors point towards them. Vector length is proportional to the strength of that species abundance gradient. Some species labels are moved or cut for legibility. Cut species labels are generally towards the plot middle and are less important in defining the ordination gradient. Cut species labels are shown inset. Coefficients, Frequency fitted values, and weights for all species are provided in **Appendix 2**.



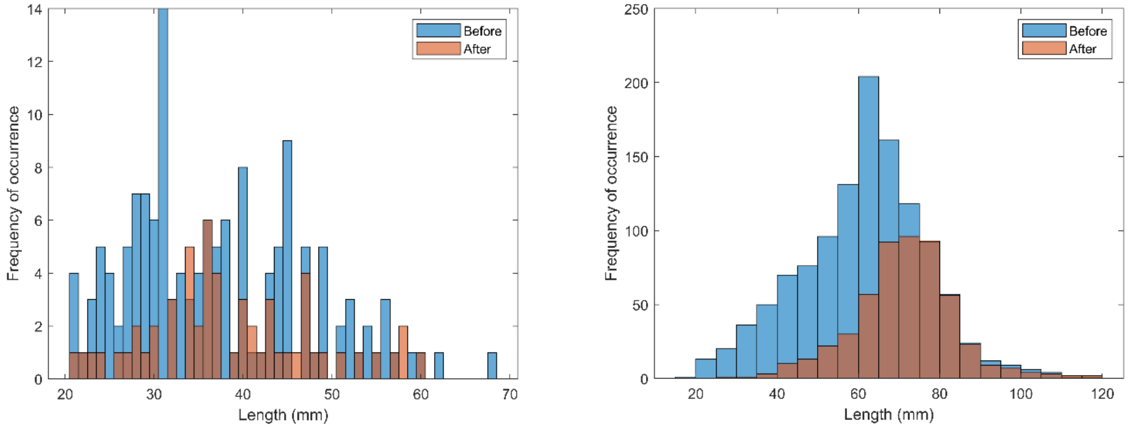
Anchoa mitchilli

Bairdiella chrysoura



Centropristis striata

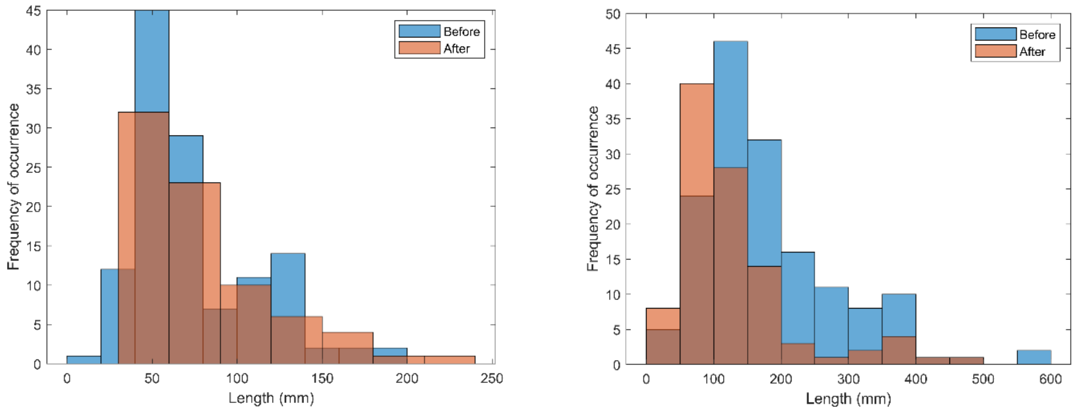
Cynoscion regalis



Gobiosoma bosc

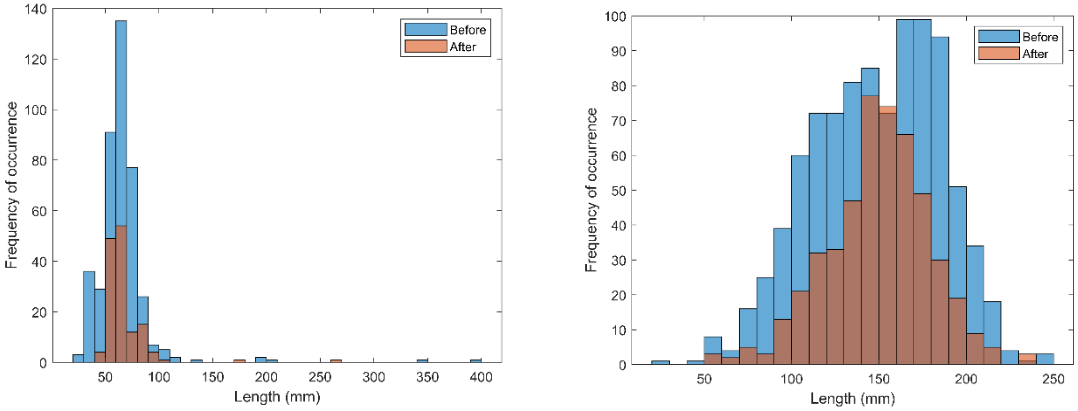
Menidia menidia

Figure 18. Length frequency distribution of select species of fish as sampled by otter trawl before and after closure of the OCNGS. Continued on next page.



Opsanus tau

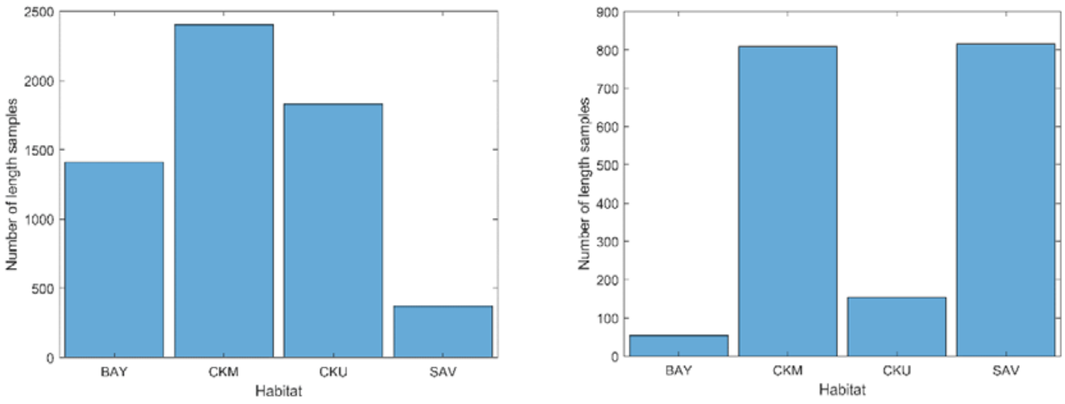
Paralichthys dentatus



Pseudopleuronectes americanus

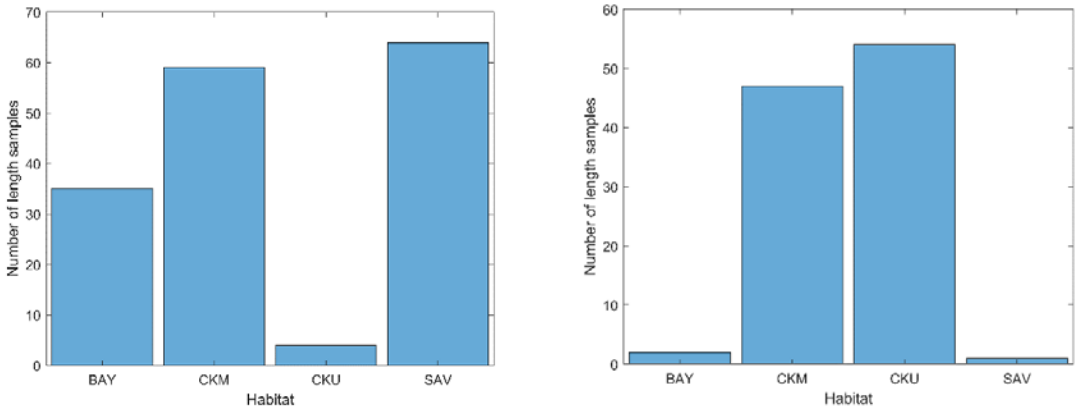
Syngnathus fuscus

Figure 18 Continued. Length frequency distribution of select species of fish as sampled by otter trawl before and after closure of the OCNGS.



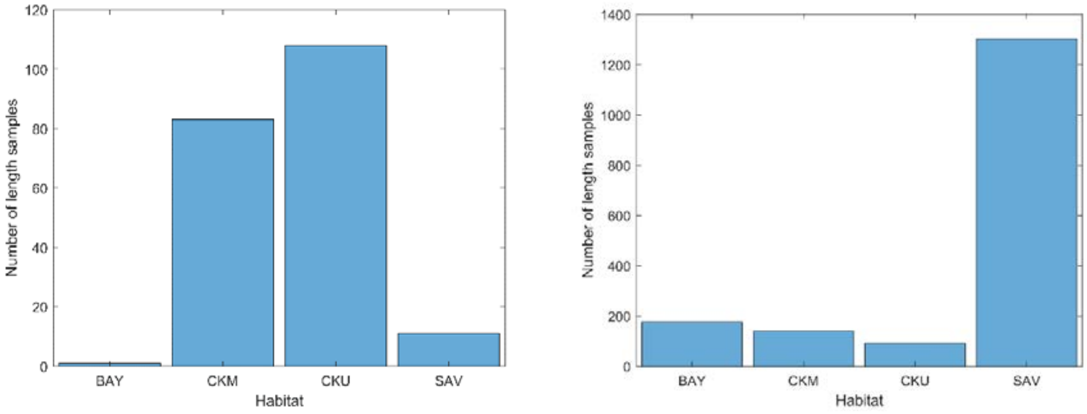
Anchoa mitchilli

Bairdiella chrysoura



Centroprist1s striata

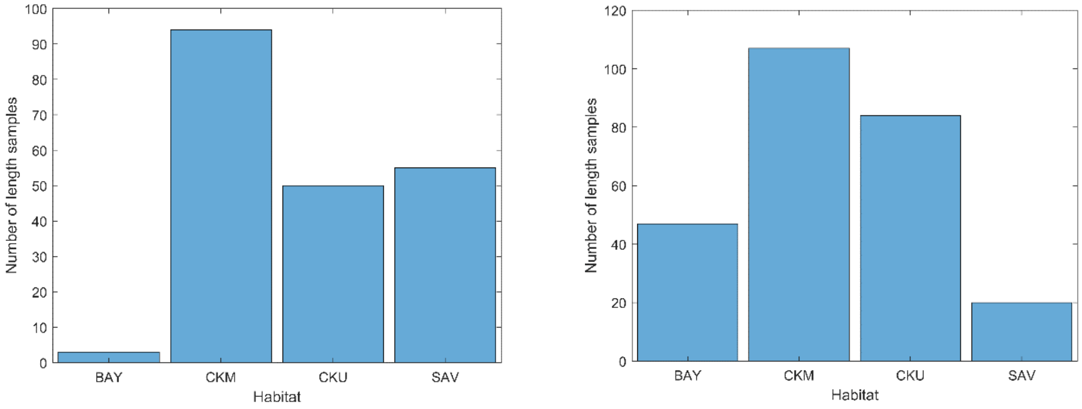
Cynoscion regalis



Gobiosoma bosc

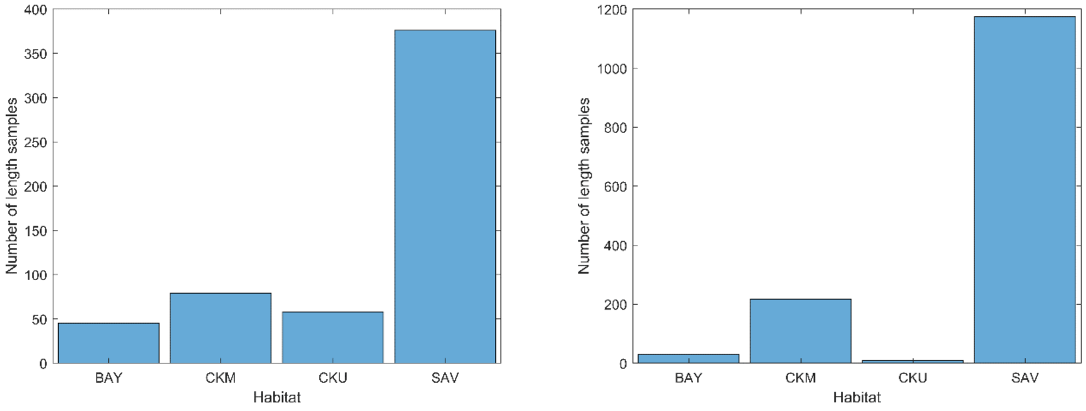
Menidia menidia

Figure 19. Distribution of length measurement samples of select fish among habitats as sampled by otter trawl. BAY = Open bay, CKM = Creek mouth, CKU = upper creek, SAV = submerged aquatic vegetation. An understanding of habitat use is helpful to interpreting which species may be impacted by closure through exposure to altered salinity, temperature, or food regimes. Continued on next page.



Opsanus tau

Paralichthys dentatus



Pseudopleuronectes americanus

Syngnathus fuscus

Figure 19 continued. Distribution of length measurement samples of select fish among habitats as sampled by otter trawl. BAY = Open bay, CKM = Creek mouth, CKU = upper creek, SAV = submerged aquatic vegetation. An understanding of habitat use is helpful to interpreting which species may be impacted by closure through exposure to altered salinity, temperature, or food regimes.

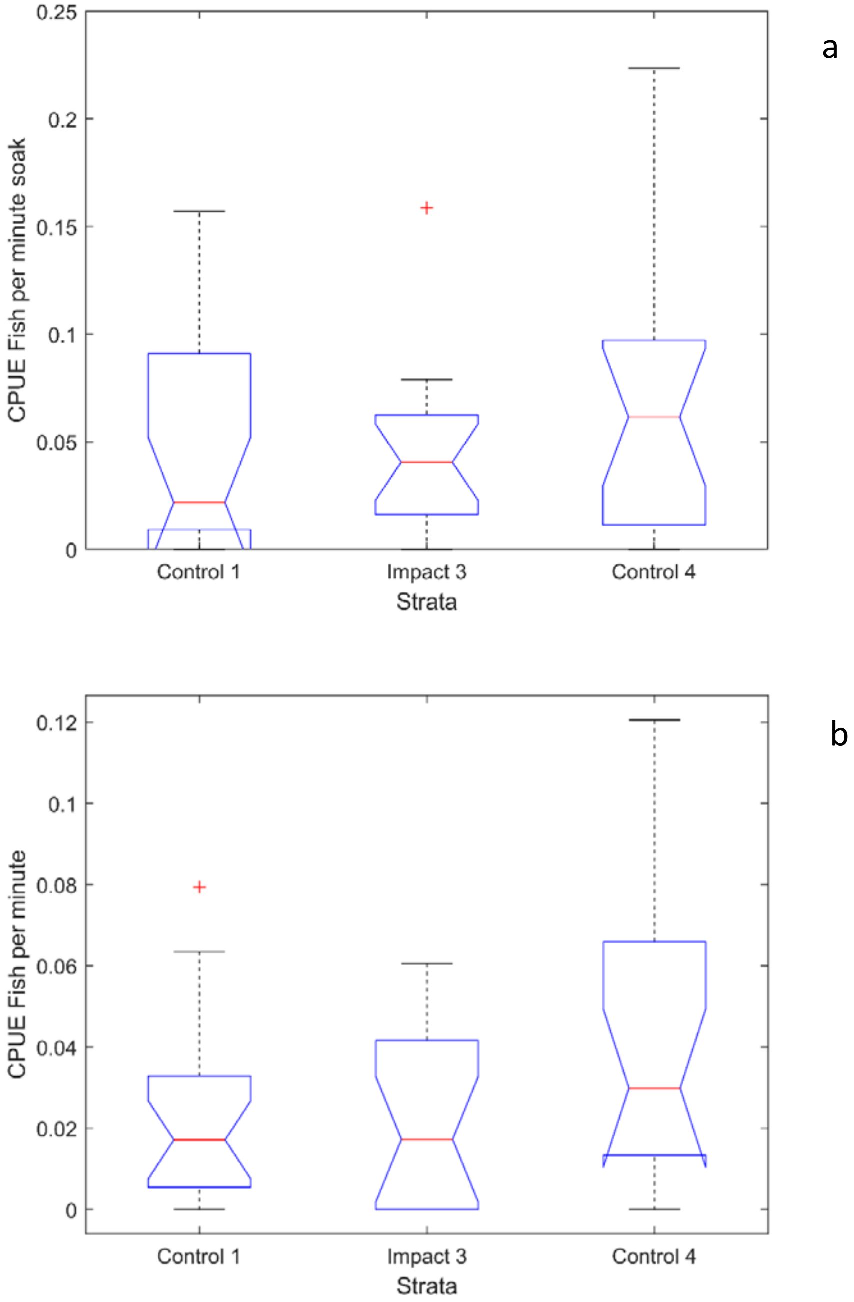


Figure 20. Box-whisker plot of fish abundance as Catch-per-Unit-Effort (CPUE, minute of soak time) in gillnet sets Before (a) and After (b) OCNGS closure. The central red mark indicates the median, and the bottom and top edges of the box indicate the 25th and 75th percentiles, respectively. The whiskers extend to the most extreme data points not considered outliers, and the outliers are plotted individually using the `'+'` symbol. When the sample size is small, notches may extend beyond the end of the box. In the Before panel, an outlier for Control 1 at 0.41975 not shown to expand lower axis limits. An effect of period was clear with fewer fish After closure (note the Y-axis scale difference), but there was no discernable change in the relative differenced among Impact or Control sites that changes after this closure (see **Table 17** for test statistics**).**

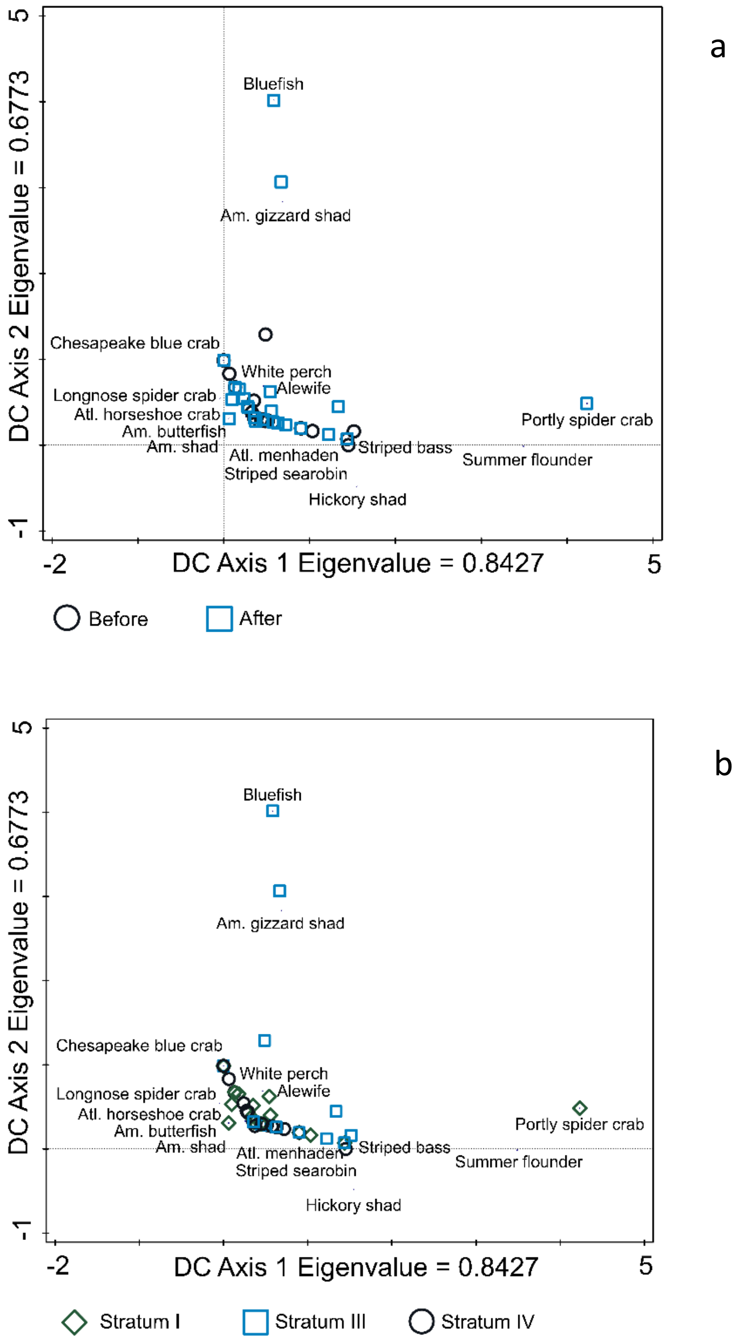


Figure 21. Scatter plot of gillnet samples and the species that characterize them along first and second detrended correspondence axes. Species labels are shown as their center of distribution relative to the sample spacing, and decline in all directions from that center. Species that occurred in only one sample are thus centered on that sample, although the species label may be adjusted for legibility. Coefficients, Frequency fitted values, and weights for all species are provided in **Appendix 3**.

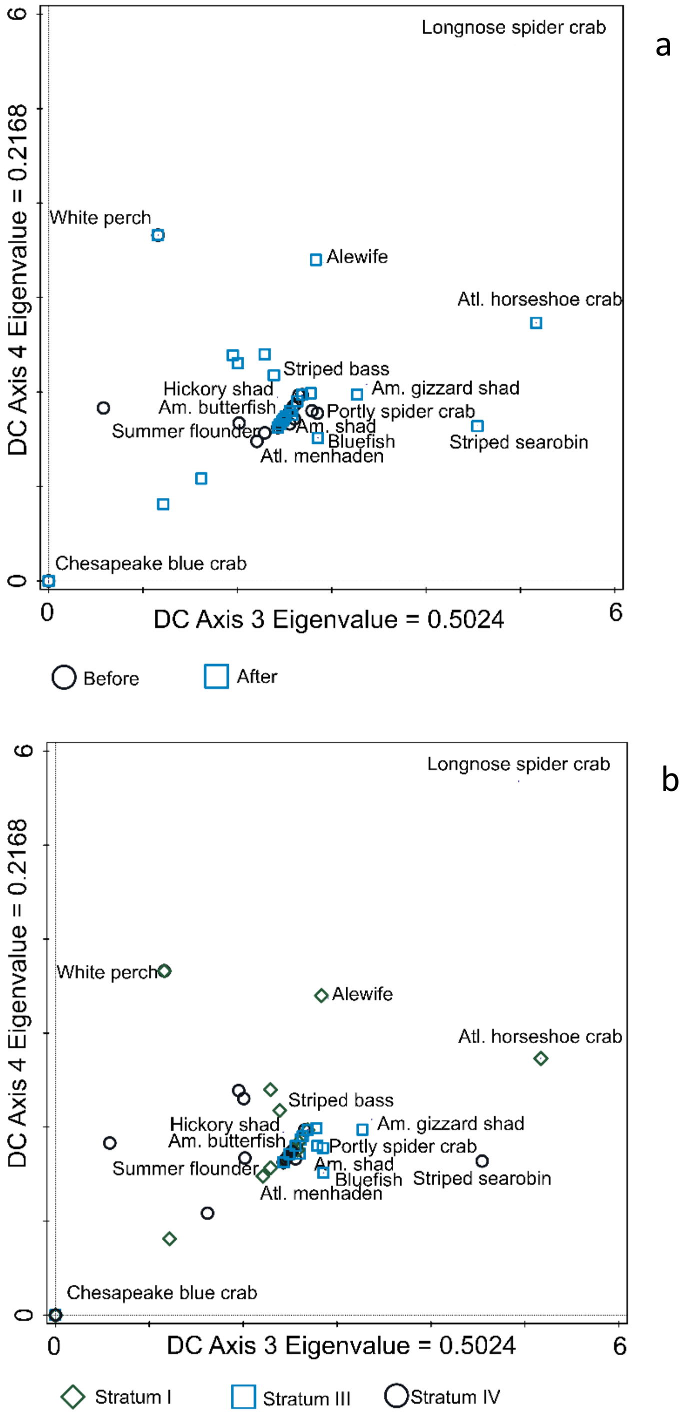


Figure 22. Scatter plots of gillnet samples and the species that characterize them along third and fourth detrended correspondence axes, classified by sample period (a) or stratum (b). Species labels are shown as their center of distribution relative to the sample spacing, and decline in all directions from that center. Species that occurred in only one sample are thus centered on that sample, although the species label may be adjusted for legibility. Coefficients, Frequency fitted values, and weights for all species are provided in **Appendix 3**.

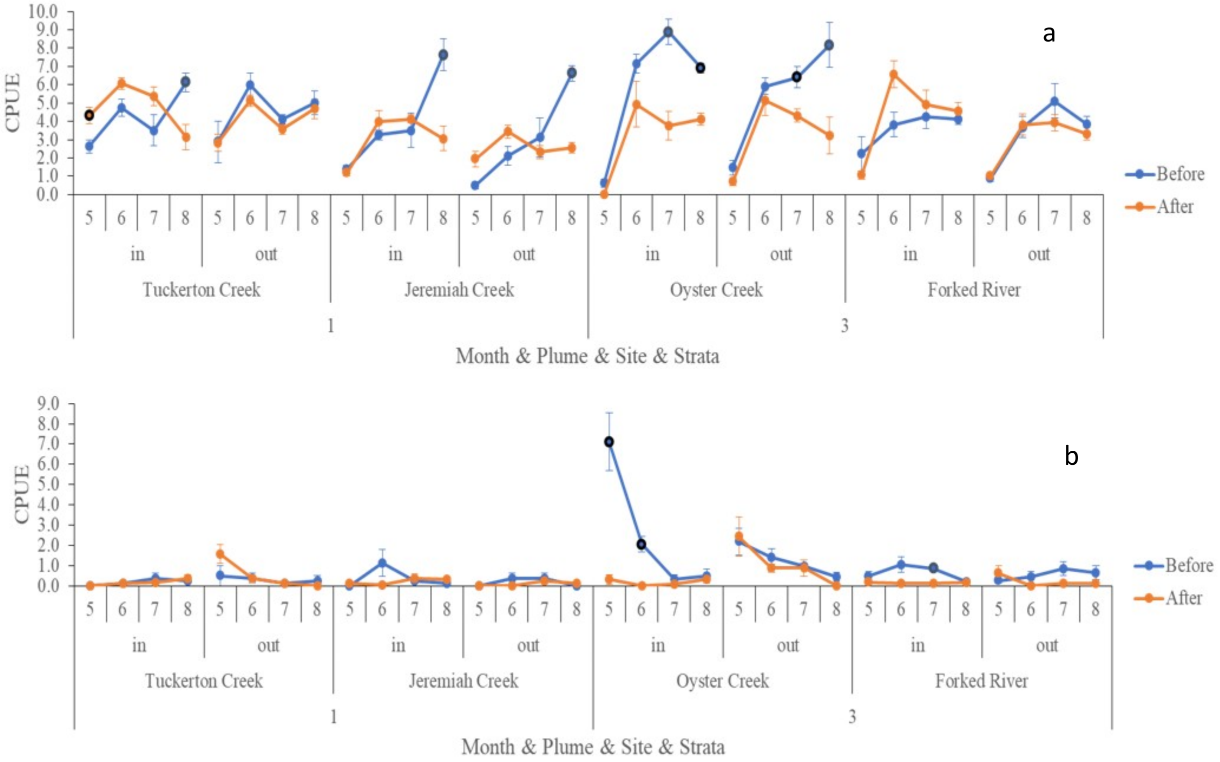


Figure 23. Male (a) and female (b) blue crab abundance over time among sites as sampled by crab trap.

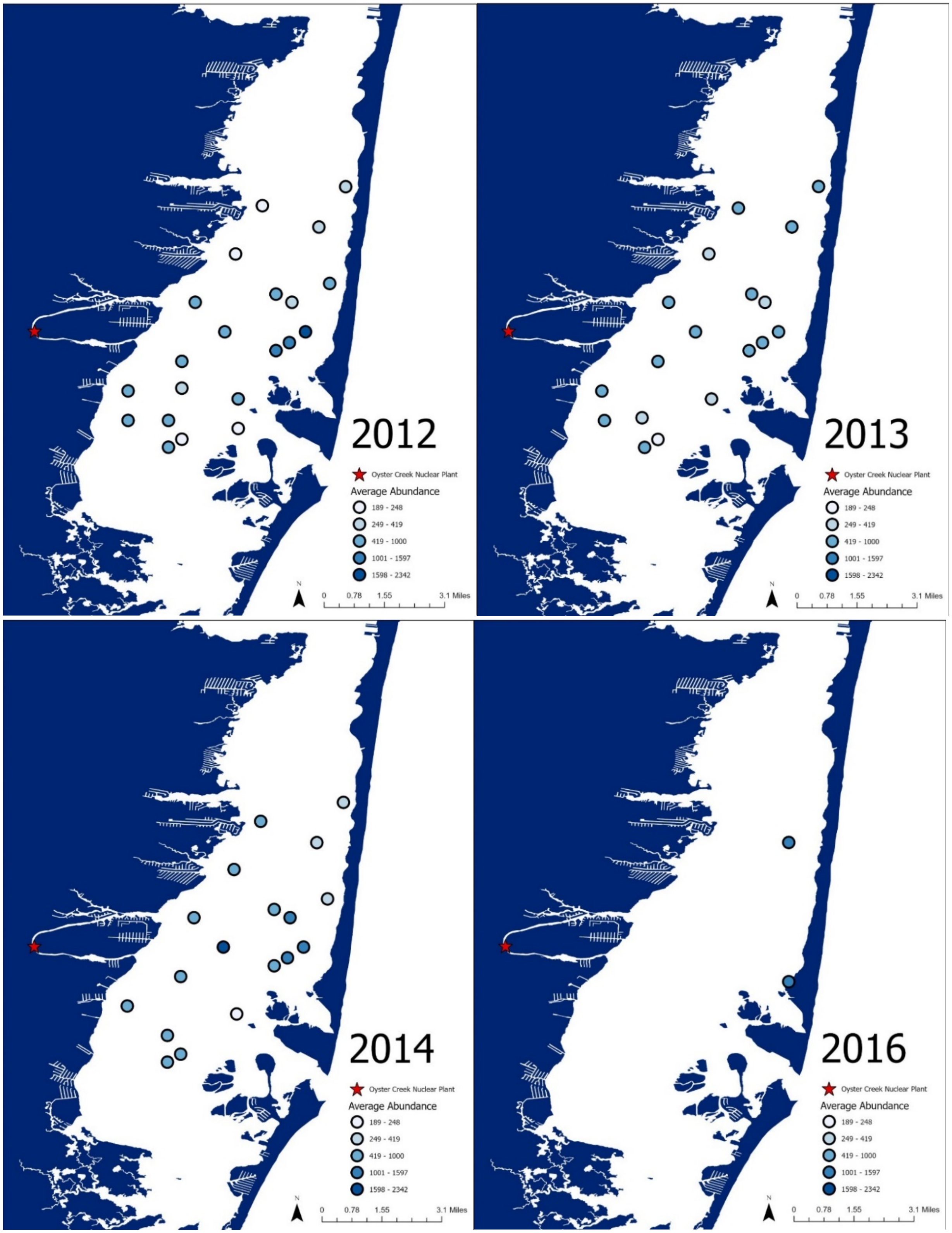


Figure 24. Location of grab sample stations over 8 years of sampling before and after OCNGS closure. Sample marker color indicates abundance of organisms in the sample. Continued on following page.

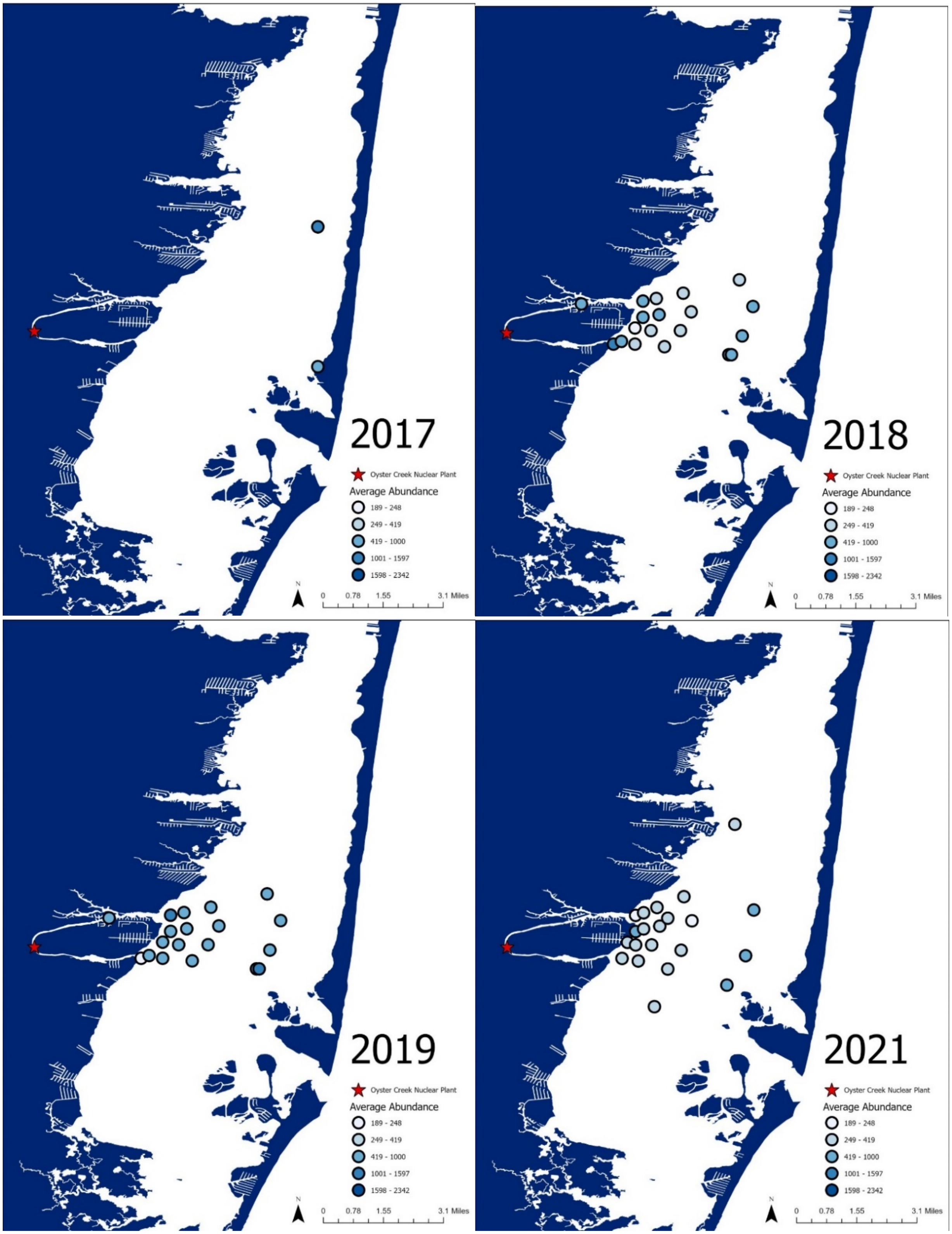


Figure 24 Continued. Location of grab sample stations over 8 years of sampling before and after OCNGS closure. Sample marker color indicates abundance of organisms in the sample.

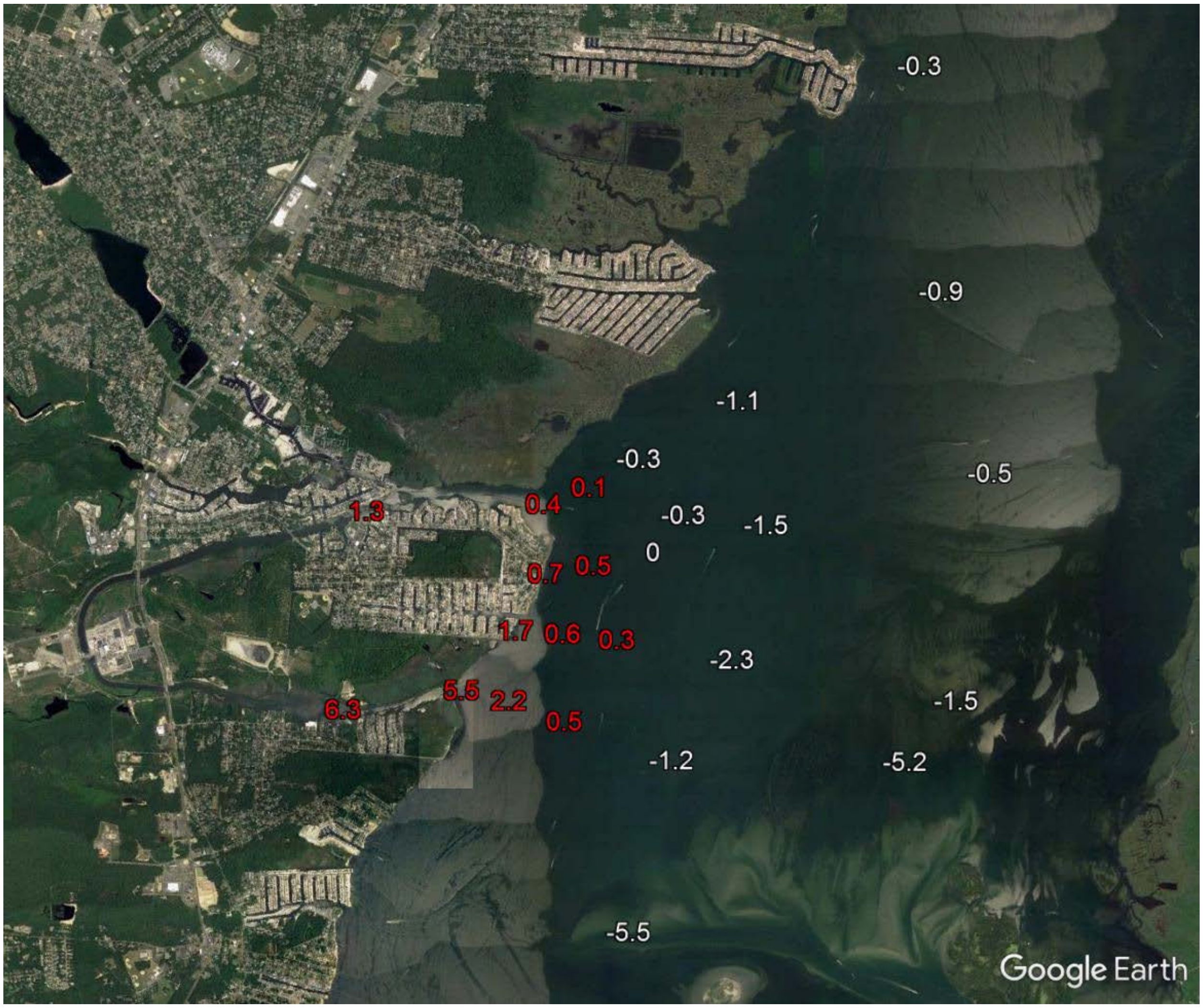


Figure 25. Bottom water temperature (°C) anomalies as measured during grab sampling in 2018 prior to OCNGS closure. Red = degrees above average for all stations, white = degrees below or equal to average for all stations.

Figure 26. Bottom water salinity (ppt) anomalies as measured during grab sampling in 2018 prior to OCNGS closure. Red = value above average for all stations, white = value below or equal to average for all stations.

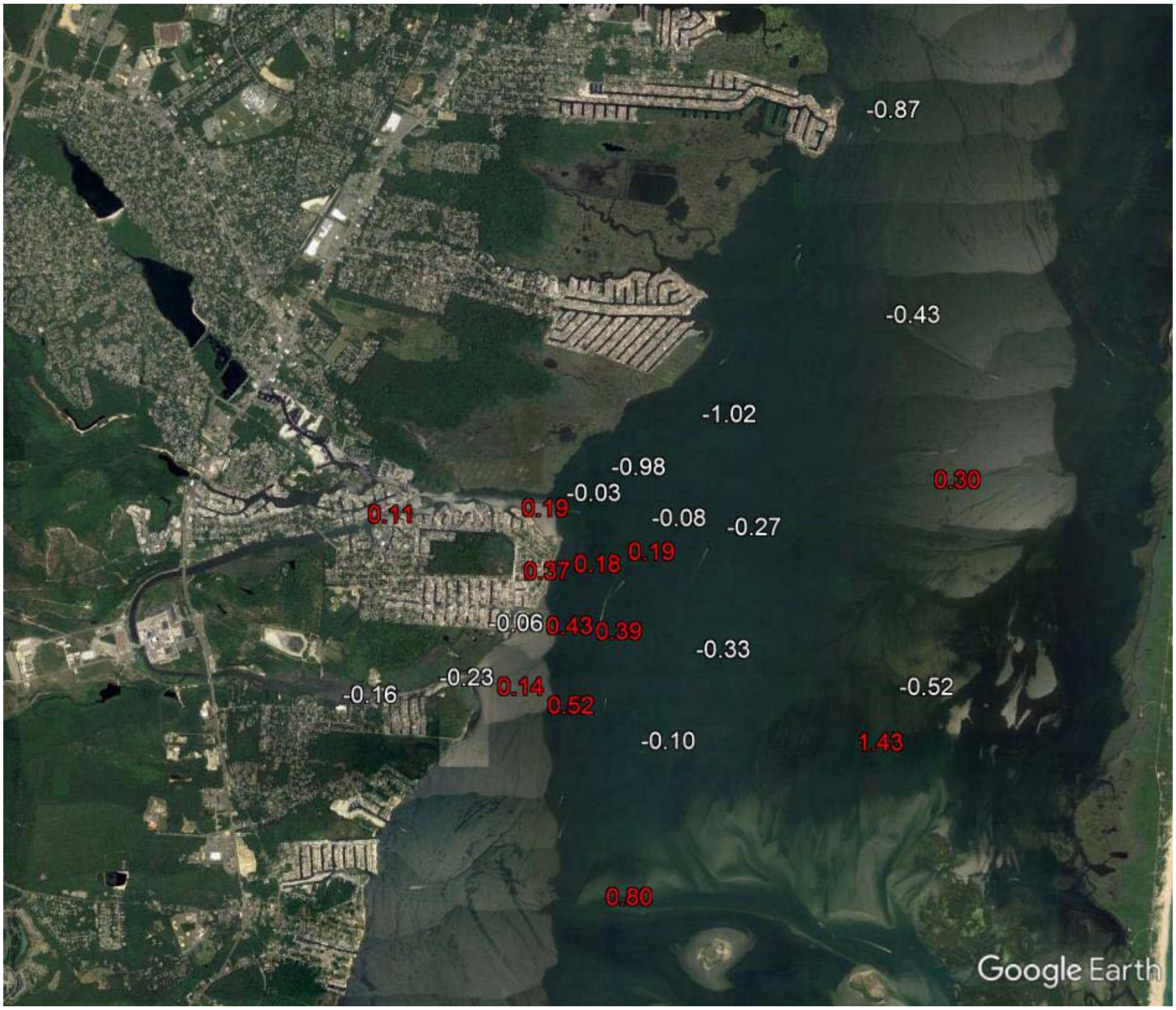


Figure 27. Bottom water dissolved oxygen concentration (mg L^{-1}) anomalies as measured during grab sampling in 2018 prior to OCNGS closure. Red = value above average for all stations, white = value below or equal to average for all stations.

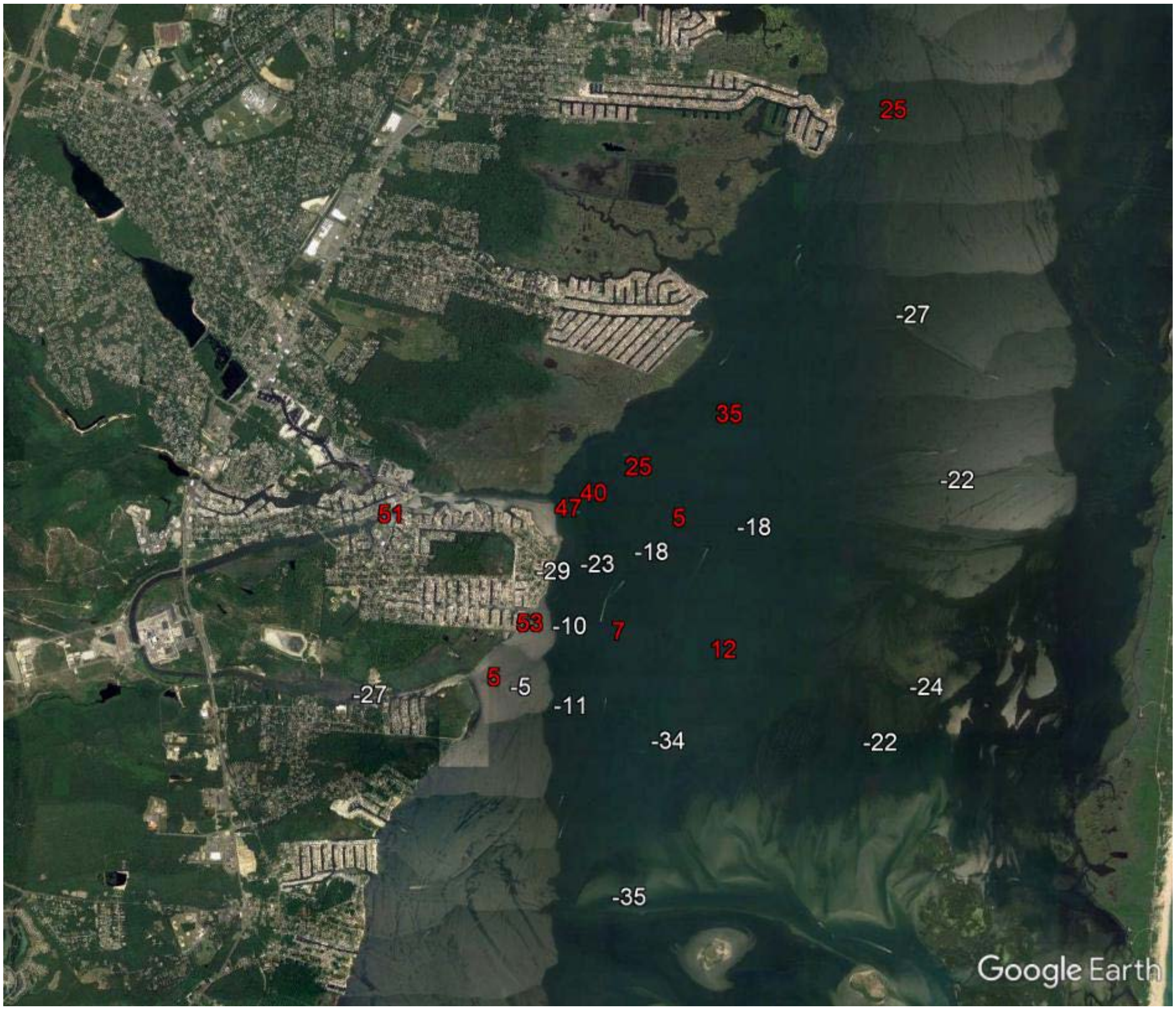


Figure 28. Silt content (percent fraction of total by mass of sediment) anomalies as measured during grab sampling in 2018 prior to OCNGS closure. Red = value above average for all stations, white = value below or equal to average for all stations.

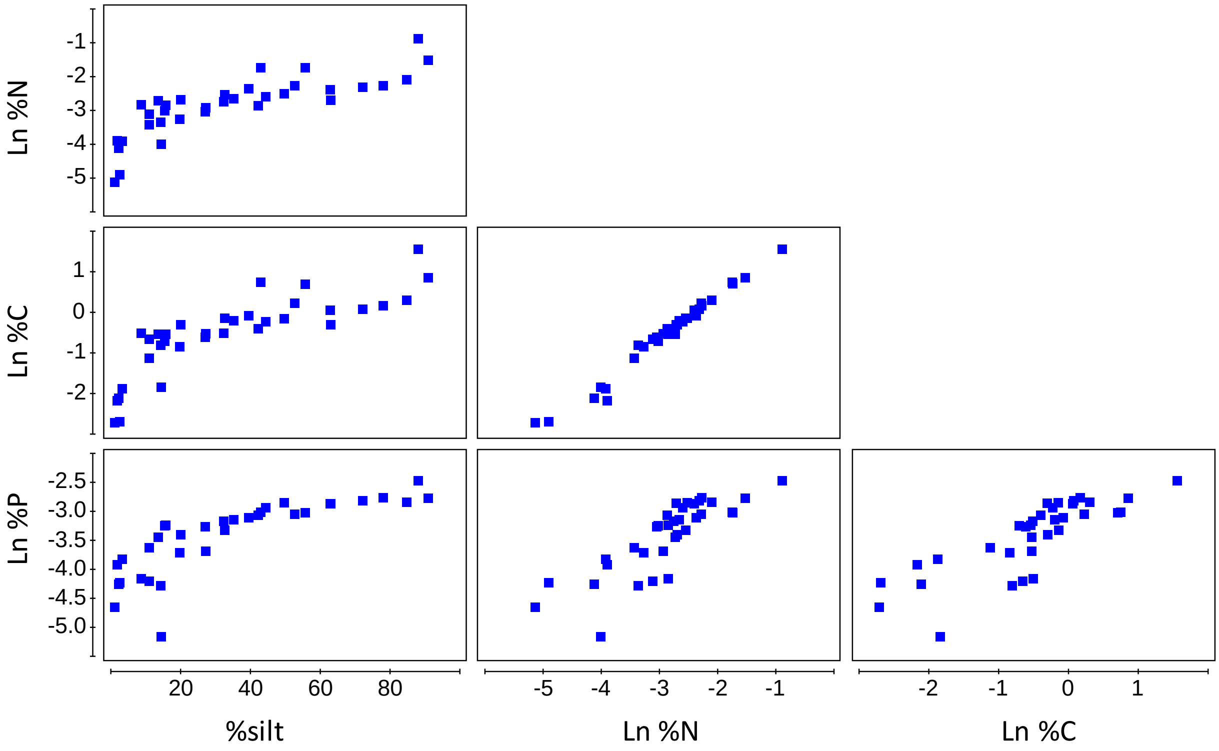


Figure 29. Plots showing the relationship between each pair-wise combination of sediment characters (Carbon, Nitrogen, Phosphate, and silt percent composition). Note that axes are log transformed. The relationship between percent Nitrogen and percent Carbon is particularly tight. The relationships and spread of values show a gradient of sediments from sandy, low organic content to silty, high organic content.

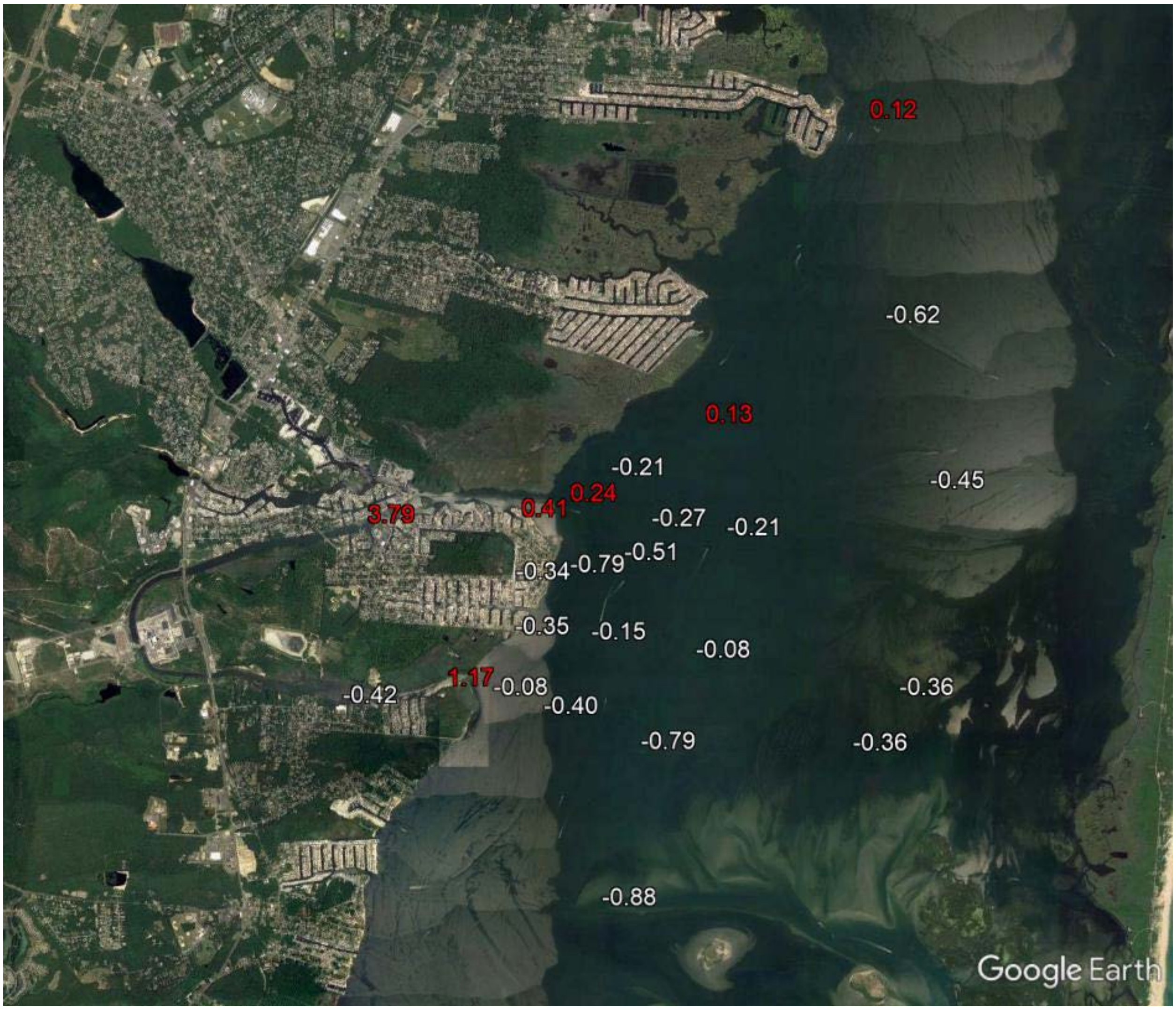


Figure 30. Carbon content (percent of total by mass) sediment anomalies as measured during grab sampling in 2018 prior to OCNGS closure. Red = value above average for all stations, white = value below average for all stations.

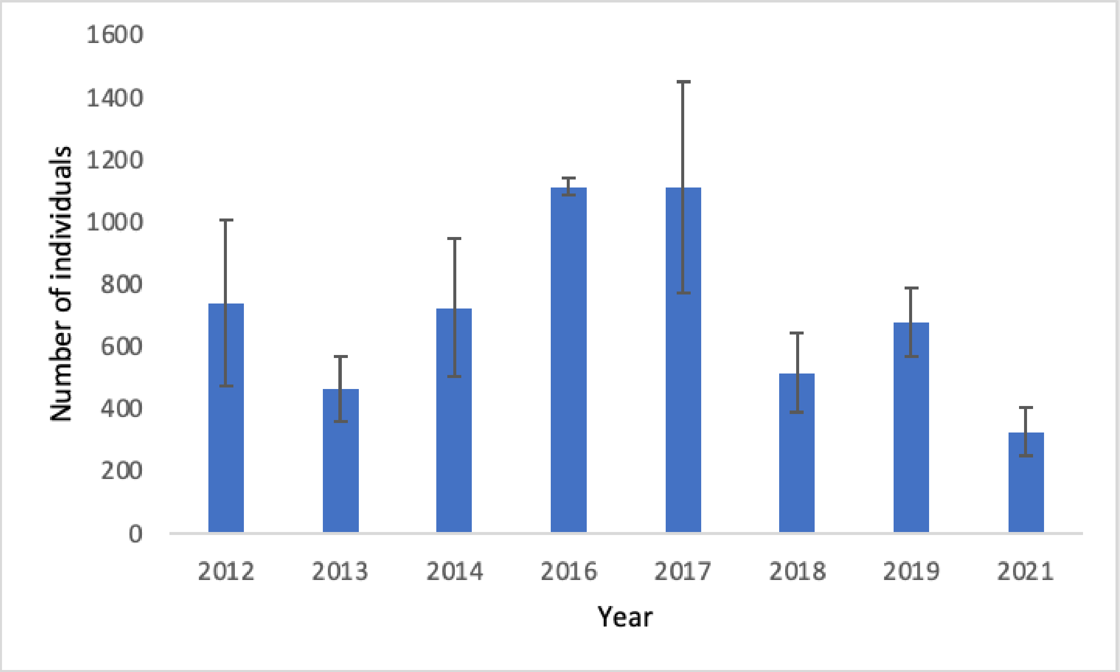


Figure 31. Average and standard error in the number of infaunal invertebrate individuals caught per station each year, using the sum of the mean abundance at each station.

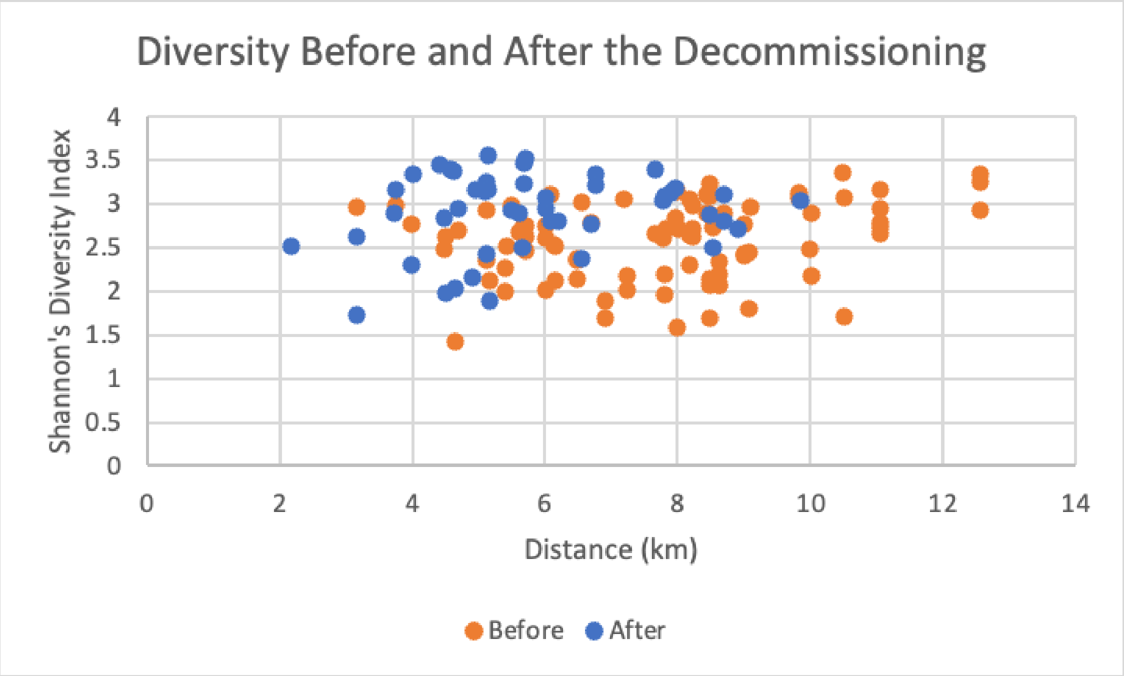


Figure 32. Shannon's diversity (a ratio between species count and dominance in a sample) relative to distance from the OCNGS Before and After closure. Close to the plant, high diversity scores tend to be those from After closure. With increasing distance from the plant this pattern decreases and even samples from Before closure had high diversity.

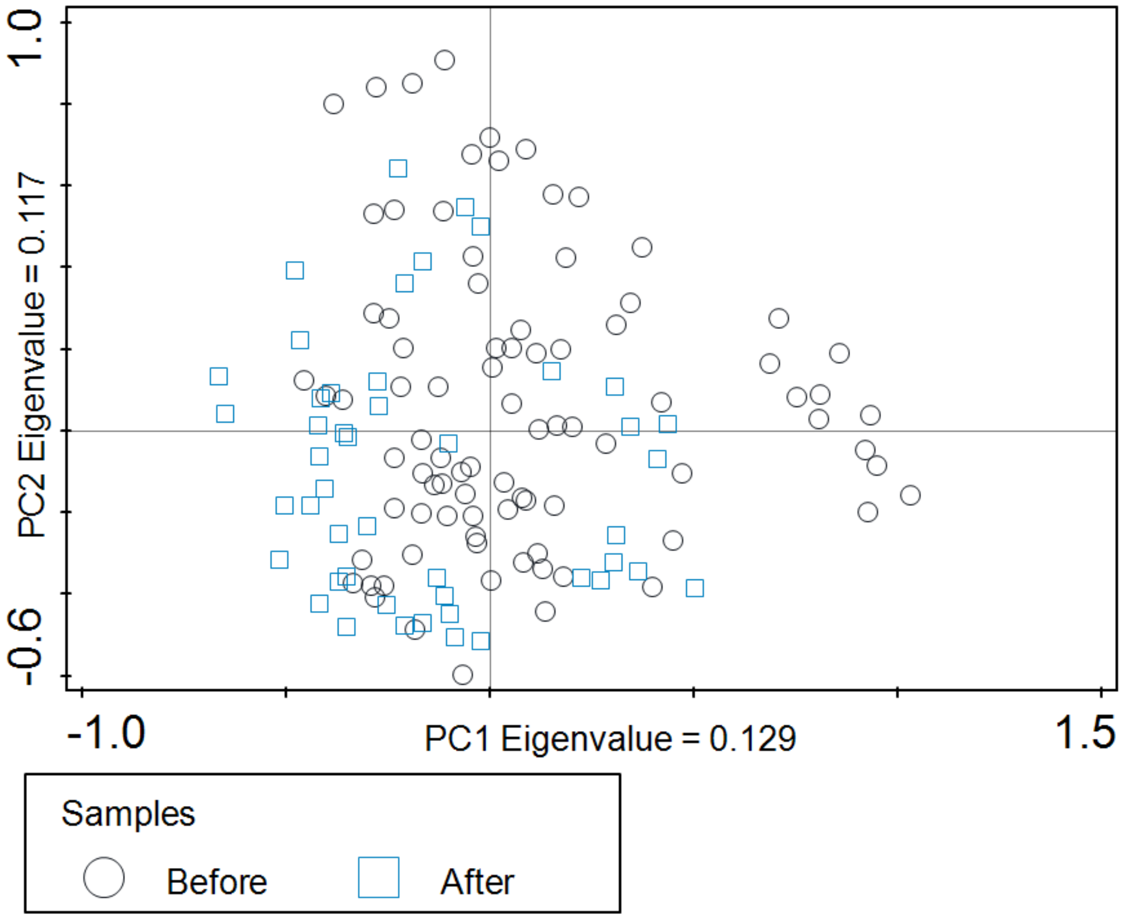


Figure 33. Scatter plots of grab sample ordination scores on the first and second principal component axes. Each plot point represents a sample. Inter-sample distance is χ^2 and indicates similarity in species composition. The trends in composition that account for this spacing are shown in the same plot space in **Figure 34**, but are separated for legibility. Overlaying the sample and species plots shows which species drove sample differentiation and to what extent along either of the two principal component axes. A left (negative) shift in the After sample scores indicates an overall difference, but with substantial overlap, in the composition of infauna in the samples relative to before OCNGS closure (See **Table 25** for test statistics).

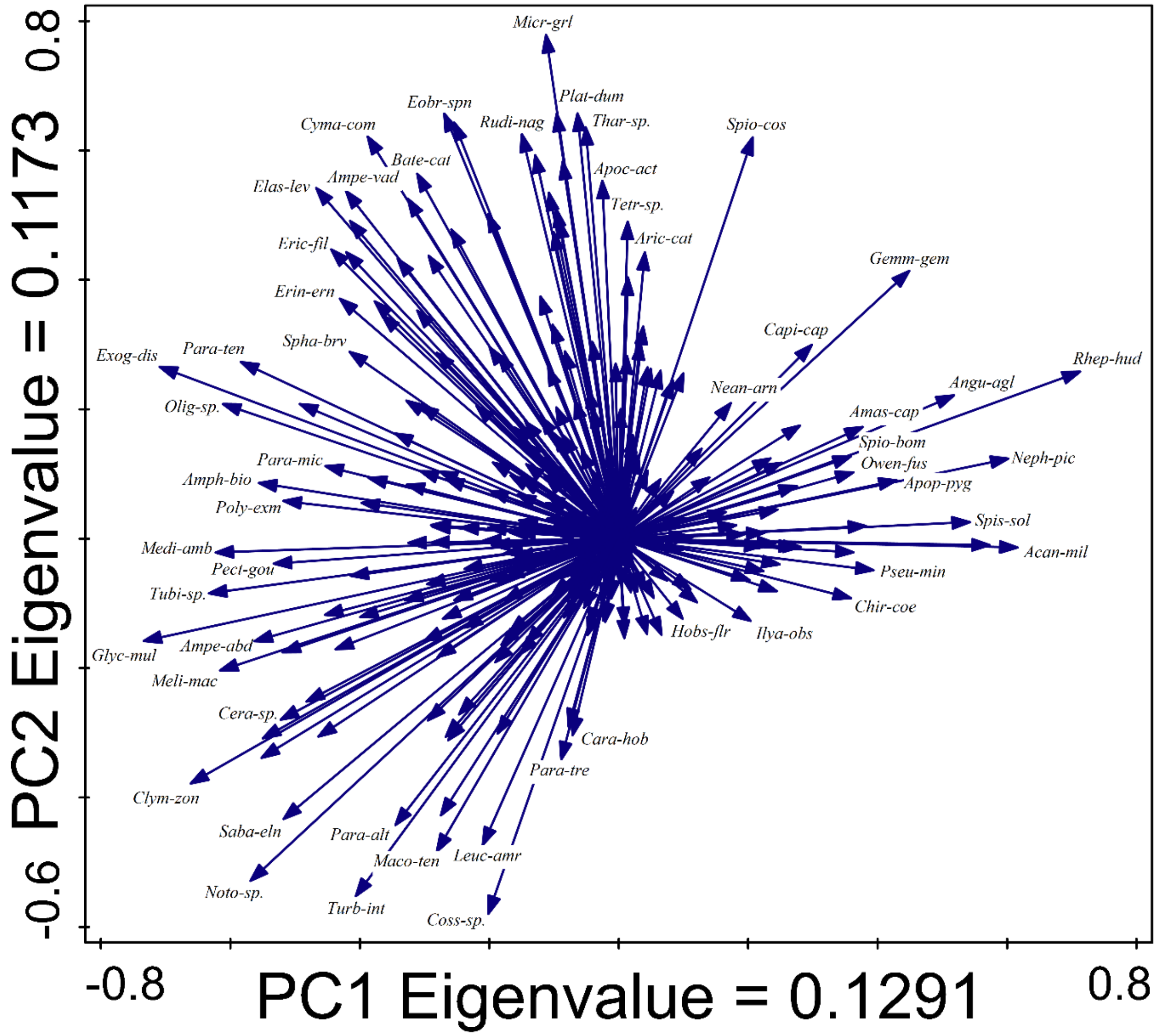


Figure 34. Scatter plot of species abundance trends along the first and second principal components through grab samples. Figure is in the same plot space as **Figure 33**, but separated for legibility. Samples in **Figure 33** are more likely to contain more of the species for which vectors point towards them. Vector length is proportional to the strength of that species abundance gradient. Some species labels are cut for legibility. Cut species labels are generally towards the plot middle and are less important in defining the ordination gradient. Overlaying the sample and species plots shows which species drove sample differentiation and to what extent along either of the two principal component axes. Species to the left bottom of the graph were somewhat more common after After closure than Before. Coefficients, Frequency fitted values, and weights for all species are provided in **Appendix 5**.

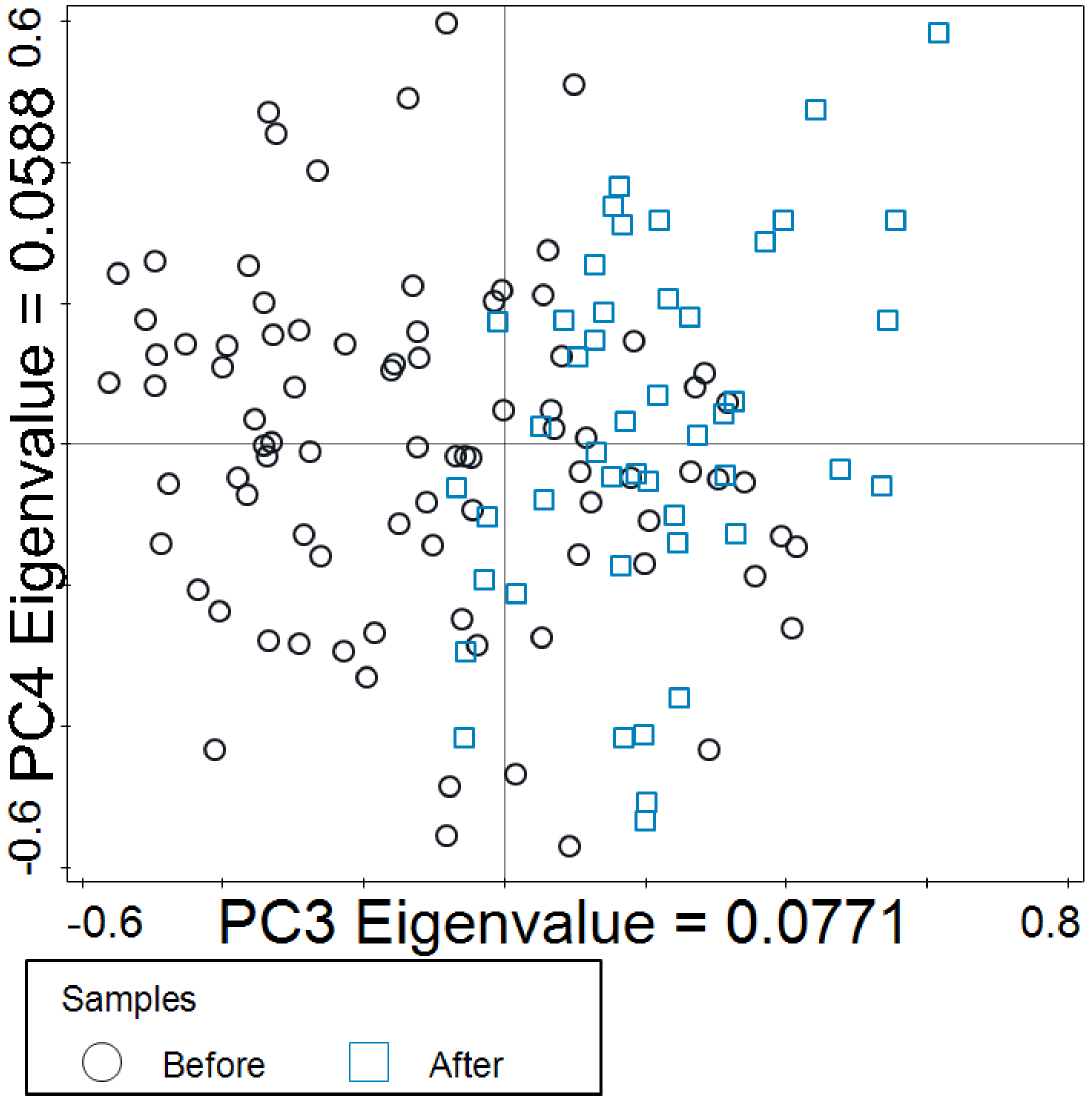


Figure 35. Scatter plots of grab sample ordination scores on the third and fourth principal component axes. Each plot point represents a sample. Inter-sample distance is χ^2 and indicates similarity in species composition. Inter-sample distance is χ^2 and indicates similarity in species composition. The trends in composition that account for this spacing are shown in the same plot space in **Figure 36**, but are separated for legibility. Overlaying the sample and species plots shows which species drove sample differentiation and to what extent along either of the two principal component axes.

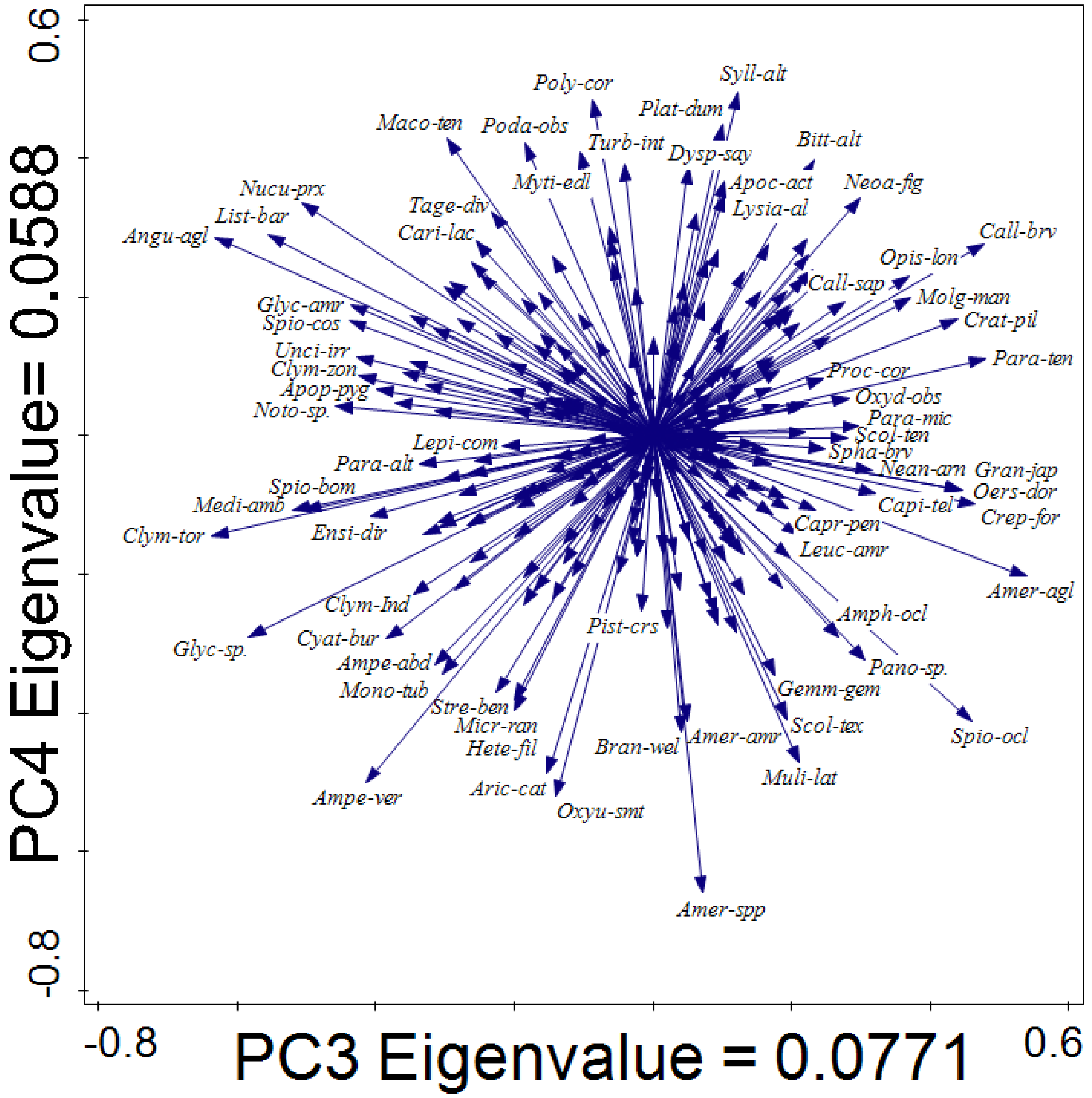


Figure 36. Scatter plot of species abundance trends along the third and fourth principal components through grab samples. Figure is in the same plot space as **Figure 34**, but separated for legibility. Samples in Figure 34 are more likely to contain more of the species for which vectors point towards them. Vector length is proportional to the strength of that species abundance gradient. Some species labels are moved or cut for legibility. Overlaying the sample and species plots shows which species drove sample differentiation and to what extent along either of the two principal component axes. Cut species labels are generally towards the plot middle and are less important in defining the ordination gradient. Coefficients, Frequency fitted values, and weights for all species are provided in **Appendix 5**.